A LABORATORY STUDY OF EVAPORATIVE FLUXES
IN HOMOGENEOUS AND LAYERED SOILS

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By
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ABSTRACT

Many problems faced by geotechnical engineers require the prediction of the water flux boundary condition at the soil surface. Soil covers for the decommissioning of landfills and tailings piles are one of the primary engineering applications in this category.

The purpose of a cover may be to minimize infiltration, reduce radon fluxes, or prevent the generation of acidic leachates. Two cover concepts which are currently being evaluated for various applications are capillary barriers and moisture retaining covers. Both of these concepts involve multi-layered soil covers in which the soils and the layering combinations are chosen to achieve the design requirements.

The processes of evaporation and moisture redistribution in homogeneous and layered soils were studied through the use of column evaporation tests. Six soil columns were tested: three homogeneous profiles, and three layered configurations. The soils used for the column evaporation tests were an aeolian sand (Beaver Creek sand), a natural silt, and a processed silt. The column evaporation tests were conducted with a constant head boundary condition (representing a shallow water table) at the base of the column for 31 days, after which the lower boundary condition was changed to a zero flux condition. The column evaporation tests were continued for approximately 30 days with the zero flux boundary condition at the base of the column. Measurements taken during the column evaporation tests included gravimetric water contents, temperatures, suctions (using tensiometers) and evaporation rates.

A sensitivity analysis was conducted to determine the influence of soil hydraulic properties (saturated hydraulic conductivity, air entry value, and pore size distribution index) on the maximum evaporation rate sustainable from soil profiles corresponding to those used in the column evaporation tests.
The sensitivity analyses indicated that the saturated hydraulic conductivity and the air entry value have a greater effect on the maximum evaporation rate than the pore size distribution index for the soils and layering combinations analyzed.

The column evaporation tests were modelled using the computer program SWIM (Soil Water Infiltration and Movement). SWIM is based on the Richards equation for flow in unsaturated porous media and accounts only for liquid phase flow. The SWIM model was limited by the curve fitting functions used to determine moisture retention curves and hydraulic conductivity functions. The computed moisture contents from SWIM showed reasonable agreement for the natural silt and processed silt. The results for the Beaver Creek sand showed poor agreement due to the steep moisture retention curve for this material.

This thesis indicates that selective layering of multi-layered soil covers has potential in designing capillary barriers or moisture retaining covers where the covers will be subjected to predominantly evaporative conditions.
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Numerous problems faced by geotechnical engineers require the prediction of water fluxes at the soil surface. Problems such as regional groundwater modelling, the design of light structures on expansive clays, seepage analysis through earth structures such as dams and canals, and the evaluation of pore pressure conditions in natural slopes or manmade embankments are examples of this type of problem.

The surface flux boundary condition is the result of two opposing processes: infiltration and exfiltration. Infiltration refers to the movement of water into a soil profile, while exfiltration refers to the movement of water out of a soil profile. Exfiltration thus includes both evaporation (water loss from soils to the atmosphere) and transpiration (water losses from plants to the atmosphere), and is commonly termed evapotranspiration.

The mechanics of infiltration are relatively well understood; however, the mechanics of evaporation from the ground surface are not completely understood (Wilson, 1990). A number of methods are available to predict regional evaporation from saturated surfaces with reasonable accuracy; however, for small areas or unsaturated surfaces the accuracy of these methods is questionable. Since geotechnical engineers frequently deal with projects of limited surface area constructed on or with unsaturated soils, a better understanding of evaporation and improved prediction methods are required.
1.1 The Significance of Evaporation From Soils

Significant portions of the earth's land surface are dominated by climates in which the annual evapotranspiration may be equal to or greater than the annual precipitation. Gray (1970) estimates that on a continental basis, approximately 75 percent of the total annual precipitation is returned to the atmosphere by evaporation and transpiration.

Due to the role of evapotranspiration in the hydrologic cycle, and considering the previously mentioned cases where the surface boundary flux must be calculated, it is obvious that evapotranspiration should be considered in geotechnical engineering design.

The prediction of surface fluxes is important for both naturally occurring soil profiles and man-made earth structures. The primary area of interest involving evaporation from natural soil profiles is agriculture, while for man-made earth structures some of the major areas of concern are projects involving expansive soils, and soil covers.

Conservation of soil moisture from agricultural lands is important in semi-arid and arid regions and an understanding of the process of evaporation in relation to the overall soil moisture balance is necessary. The ability to predict evaporative soil fluxes also plays a role in the operation of irrigation systems. Insufficient irrigation may result in stressed vegetation and reduced crop yields, while overwatering is uneconomical and wastes precious water.
Expansive soils are present in many countries, and are responsible for vast amounts of damage. In the 1970's, the annual damage to light engineered structures in the United States was estimated at 2 billion dollars (Jones and Holtz, 1973; Picornell-Darder, 1985). In terms of 1982 dollars, the loss figure was estimated to be closer to $6 billion annually (Holtz, 1984). These losses are estimated to exceed the combined loss caused by earthquakes, tornadoes, hurricanes and floods (Holtz, 1984).

Generally, the severity of damage to a light engineered structure is determined by the depth of the expansive soil deposit, the type and depth of the foundation, the strength and shape of building construction, and the influence of changes in water content (Longworth et al, 1984). Since evaporation plays a major role in the magnitude of ground water content changes, it must be quantified in order to predict vertical ground movements.

Man's activities have created vast quantities of waste products that require storage or disposal. These waste products include domestic and industrial wastes that are typically disposed in landfills, as well as wastes (tailings) generated from mining processes. The tailings often have undesirable properties, such as being radioactive, acid generating, or environmentally toxic. To illustrate the magnitude of the domestic waste problem, consider that estimates of domestic garbage generation rates in the United States are approximately 3.0 kg/person/day (Peavy et al, 1985). If similar generation rates are applied to Canada, the resultant production of solid waste would be $27.4 \times 10^6$ tonnes per year (based on a population of 25 million). This does not
include industrial waste. As well, there are currently in excess of 200 hundred million tonnes of tailings covering more than 15000 hectares with the potential to produce acidic drainage (Melis, 1983; Filion and Ferguson, 1990). In addition to potentially acidic tailings, significant quantities of radioactive tailings produced by the mining of uranium have the potential to release radon gas to the environment. Mitigation of radon fluxes from uranium mill tailings using multilayered earthen covers has been the subject of a great deal of research (Beedlow, 1982; Beedlow and Carlile, 1984; Kirkham et al, 1982, Gee et al, 1981, 1984; Mayer et al, 1981; Nelson et al, 1980) in the United States, and is also a concern in Canada. In Saskatchewan, there are also millions of tonnes of potash tailings currently stored on the surface. These tailings are primarily composed of sodium chloride (NaCl), and pose major problems such as groundwater contamination and salinization of surrounding land.

Decommissioning of these waste disposal sites must include provisions to minimize or eliminate potential environmental damage. This objective may be accomplished by preventing the generation of leachates, or by isolating the waste from the environment. A major component of the decommissioning strategies for landfills and tailings piles is some type of cover. For landfills, the major environmental concern is the generation of leachate. Mundell and Bailey (1985) state that a final cover is the most effective method for eliminating percolation and is the first line of defense against leachate generation. To minimize infiltration, covers for landfills are generally constructed of materials with low hydraulic conductivities, typically clays. Prevention
of desiccation cracking due to drying is paramount in this application, since cracking can compromise the integrity of the cover. Thus, many cover designs incorporate multiple layers to perform different functions (i.e., erosion control, biological barriers, reduction of infiltration, etc). To determine the amount of drying that will occur under service conditions, evaporation must be considered.

For acid generating wastes, it is desirable to provide a cover that minimizes the supply of oxygen to the tailings, thus suppressing the oxidation reactions that generate the acidic leachates. Oxygen diffusion into the tailings may be reduced by providing a saturated cover over the tailings, since the diffusion coefficient of a saturated soil is much less than for a dry soil. The concept of using multilayered moisture retaining covers (which would limit oxygen diffusion) to reduce acid generation in tailings is currently being evaluated (Yanful, 1991). The same concept has been proposed to reduce radon fluxes from radioactive tailings. Consideration of evaporative fluxes from moisture retaining covers is required, since this concept is based on maintaining high saturation levels in the cover material.

As shown in the preceding paragraphs, understanding evaporation is important in a number of geotechnical applications. In addition to understanding the appropriate mechanisms involved, analytical and predictive methods are also required as design tools. Many of the geotechnical applications which consider natural soil profiles, as well as engineered earth structures (i.e., covers) involve layered soils; thus, it is
important that our understanding of evaporative processes include layered soil systems as well as homogeneous soils.

1.2 Scope and Objectives

This thesis forms a portion of a larger study currently being conducted at the University of Saskatchewan on the subject of evaporation from soils, and the examination of the surface flux condition from a geotechnical engineering perspective. This program has grown from the Ph.D. dissertation by Wilson (1990), which examined the process of evaporation from soil surfaces (particularly unsaturated soil surfaces). Wilson identified the appropriate soil properties and variables that control evaporation from soil surfaces and formulated a theoretical framework for the evaluation of evaporation from soil surfaces. Current areas being studied at the University of Saskatchewan include laboratory testing of evaporation from layered systems (this thesis), numerical modelling of the evaporative process, and predicting the performance of various layered cover systems under evaporative conditions. This thesis extends the laboratory column drying tests performed by Wilson (1990) to include layered soil systems. The general objective of this thesis is to study evaporation rates and moisture redistribution from various soils and layering combinations under controlled conditions, by the use of one-dimensional column evaporation tests. The specific objectives of this research were as follows:
Chapter 1: Introduction

i) To develop a further understanding of the fundamental mechanisms involved in evaporation and moisture redistribution in soils, particularly layered soil systems.

ii) To examine differences in evaporation rates and moisture redistribution patterns from two texturally different soils (i.e. silt and sand) subjected to one-dimensional evaporation under laboratory controlled conditions.

iii) To examine differences in evaporation rates and moisture redistribution patterns between homogeneous soil systems and layered soil systems subjected to one-dimensional evaporation under laboratory controlled conditions.

iv) To determine the sensitivity of evaporation rates to variations in various soil hydraulic properties.

v) To explain the behaviour observed in the laboratory in a manner consistent with the current understanding of unsaturated soil mechanics.

The research in this thesis is restricted to non-vegetated soil surfaces. It is understood that soil moisture losses due to plant uptake (transpiration) may greatly exceed evaporation from a bare soil; however, the primary reason for limiting this thesis to non-vegetated surfaces is the complexity involved in evaluating evapotranspiration from vegetated surfaces. Before evapotranspiration from vegetated surfaces can be examined from a geotechnical engineering perspective, the mechanisms and processes involved in evaporation from bare soil surfaces and layered soil systems must be thoroughly understood. It is hoped that this thesis provides another step in our level of understanding, and that the extension to vegetated surfaces will be accomplished in the near future.
2.0 LITERATURE REVIEW

2.1 Introduction

This chapter provides a review of the evaporation process, measurement of evaporation and important factors involved at the soil-atmosphere boundary. The current relevant literature is summarized, with particular emphasis on current cover design concepts and previous laboratory investigations on evaporation from soils.

2.2 Evaporation and Evapotranspiration

2.2.1 General

The process of evaporation is defined as "the change of state from a liquid to a gas" (Gray, 1970) and usually refers to the process occurring at a free water surface. Evapotranspiration, as defined by Thornthwaite (1948) is "the combined evaporation from the soil surface and transpiration from plants" representing "the transport of water from the earth back to the atmosphere, the reverse of precipitation." The term evaporation is sometimes used synonymously with evapotranspiration in the literature for the sake of simplicity, while other authors prefer the term "exfiltration". This thesis deals specifically with evaporation from non-vegetated surfaces, therefore the term "evaporation" will be used exclusively.

A review on the literature pertaining to the process of evaporation is presented in the following sections.
2.2.2 Factors Affecting Evaporation From Soils

Hillel (1980) states that three conditions must be met for the process of evaporation to occur. First, there must be a continual supply of heat to meet the latent heat requirement (approximately $2.453 \times 10^6 \text{ J/kg at 20 } ^\circ\text{C}$). Second, a vapour pressure gradient must exist between the body and the atmosphere, and the vapour must be transported away by diffusion, convection, or both. Third, a continual supply of water from or through the interior of the body to the site of evaporation is required. The first two conditions are essentially dependent on atmospheric factors, while the third condition is a function of the soil and groundwater conditions. The actual evaporation rate is determined by external evaporativity (i.e. "potential evaporation") or by the soil's ability to deliver water, whichever is less, and therefore the limiting factor.

Gardner (1958) developed solutions to the unsaturated flow equation for the case of steady state flow from a water table. He showed that the maximum evaporation rate from a soil is a function of the hydraulic conductivity of the soil and the depth to the water table. Gardner's (1958) results showed that if the water table is located at a shallow depth, a steady evaporation rate will be attained, and that the greater the depth to the water table, the lower the steady state evaporation rate will be.

If the water table is not located at a shallow depth, which is a more realistic case, the evaporation rate from the soil will not be constant with time. Buckingham (1907)
Chapter 2: Literature Review

noted that the rate of evaporation from soils was rapid at first, but tended to level off with time. Idso et al (1974), Gardner (1974) and Hillel (1980), have described three distinct stages of evaporation from soils: an initial constant rate stage, an intermediate falling rate stage (transition stage), and a residual slow rate stage. These stages are illustrated in Figure 2.1.

![Figure 2.1 Stages of Evaporation From Soils (After Hillel, 1980)](image)

The initial *constant rate stage* occurs while the soil is wet, water is available in storage and its hydraulic conductivity is sufficient to supply enough water to the evaporative front to satisfy the evaporative demand. During this stage, the evaporation rate is
controlled by external meteorological conditions such as incoming radiation, wind, humidity, etc. During the constant rate stage of evaporation, the soil surface gradually dries out and soil moisture is drawn upward in response to steepening evaporation-induced gradients. The rate of evaporation can remain nearly constant as long as sufficient water is available (either from the water table or soil storage) and the increase in gradient near the surface compensates for the decrease in the unsaturated hydraulic conductivity.

The intermediate falling rate stage begins when the soil can no longer supply sufficient water to the evaporative front to satisfy the demand. This stage can also be called the soil profile-controlled stage (Hillel, 1980).

The residual slow rate stage gradually develops as the soil surface becomes desiccated and the primary mode of water movement near the surface is due to vapour diffusion. This stage is sometimes referred to as the vapour diffusion stage. If the evaporative process continues for a sufficient length of time, a "drying front" may develop. This drying front may be characterized by an inflection in the soil moisture content profile, as illustrated in Figure 2.2 (after Hillel, 1980).
Figure 2.2 Hypothetical development of a drying front and its movement into the soil during the course of soil moisture evaporation. (Modified after Hillel, 1980)
2.3 Review of Methods of Calculating Evaporation and Evapotranspiration

Methods for determining evaporation and evapotranspiration rates can be categorized into three groups: direct measurements, micrometeorological methods, and regional climatological methods. Wilson (1990) presented a rather detailed review of all of these categories, thus only a brief review and explanation of these methods will be presented in this thesis.

2.3.1 Direct Measurements of Evaporation and Evapotranspiration

Direct measurements of evaporation are commonly made by meteorologists and hydrologists. Direct measurements typically determine the potential evaporation, the evaporation rate that is controlled by climatic conditions rather than by soil and groundwater conditions. The most common direct measurement methods for evaporation and evapotranspiration are atmometers, evaporation pans and lysimeters.

Atmometers are usually small paper or porous ceramic evaporating surfaces connected to a continuous water supply. Atmometers are portable, inexpensive instruments which provide an indication of potential evaporation.

Evaporation pans are another common method used to determine potential evaporation. Various sizes of pans have been used over the years, with the standard Class A evaporation pan measuring 1219 mm in diameter and 254 mm in depth. The potential rate of evaporation estimated by a method such as Penman, (from an
irrigated field, for example) is often estimated as being a percentage of pan evaporation.

Lysimeters may be used to measure either potential evaporation or actual evaporation. Lysimeters are based on the principle of a water budget. The lysimeter consists of a mass of soil constructed on a balance such that it is hydrologically isolated from the surrounding soil. Precipitation is measured, surface runoff is prevented, and deep drainage may be prevented or measured in a sump. Evaporation is the only unknown in the water budget, and is thus responsible for any net change in the mass of the lysimeter. One of the problems with field lysimeters is the large weight of the soil mass which must be measured with high precision. This problem may be avoided by the use of "microlysimeters", which are short, undisturbed, closed-bottom, removable soil cores that are installed in the soil surface. The change in mass is determined by removing the microlysimeter and oven-drying it to determine the water content. A new, undisturbed microlysimeter is installed in place of the one that is removed. The use of microlysimeters has been analyzed in detail by Boast and Robertson (1982). Microlysimeters have also been used by Walker (1983, 1984) and Lascano and Van Bavel (1986).
2.3.2 Micrometeorological Methods

Micrometeorological methods are used to estimate evaporation or evapotranspiration at a point, or over a very localized area. These micrometeorological methods are based either on the principles of energy balance or mass transfer. The most common micrometeorological methods are the Bowen Ratio Energy Balance Method (BREB), the Aerodynamic Method, and the Mass Transport Method.

2.3.2.1 Bowen Ratio Energy Balance Method (BREB)

Solar energy is the earth's primary source of heat. Incoming shortwave radiation is converted to long-wave radiation, sensible heat or latent heat. Brutsaert (1982) states that the net radiative energy applied to the ground surface is converted into heat fluxes as shown in Equation 2.1.

\[ Q_N = Q_E + Q_H + Q_G \]  

(2.1)

where:
- \( Q_N \) = all net radiation
- \( Q_E \) = Latent heat flux of evaporation
- \( Q_H \) = Sensible heat flux
- \( Q_G \) = Conduction of heat to or from the subsurface soil

The Bowen Ratio Energy Balance Method (BREB) is based on the energy budget, and utilizes the ratio between the sensible heat flux \( Q_H \) and the latent heat flux \( Q_E \) (i.e. the Bowen Ratio \( Q_H/Q_E \)) to calculate the latent heat flux. The latent heat flux is calculated as shown in Equation 2.2 (Oke, 1978):
Chapter 2: Literature Review

The Bowen Ratio is defined as:

\[ Q_E = \left( \frac{Q_N - Q_G}{1 + b} \right) \]  \hspace{1cm} (2.2)

where: \( b \) = The Bowen Ratio

\[ b = \frac{Q_H}{Q_E} = \frac{c_p T}{L_v q} \]  \hspace{1cm} (2.3)

with,

- \( Q_N, Q_E, Q_H \) and \( Q_G \) as defined in Equation 2.1
- \( c_p \) = Specific heat of air
- \( L_v \) = Latent heat of evaporation
- \( T \) and \( q \) = Change in temperature and specific humidity over the same height interval above the soil surface
  
  i.e. \( T = (T_2 - T_1) \); \( q = (q_2 - q_1) \)

Three main assumptions are inherent in the BREB method (Rosenberg et al, 1983; Brutsaert, 1982; Oke, 1978). First, relatively steady atmospheric conditions must prevail during the observation period. Second, energy and mass fluxes must be constant with height. Third, the principal of similarity between the transfer coefficients of eddy conductivity for heat, and eddy diffusivity for water vapour must be valid.
2.3.2.2 Aerodynamic Method

The aerodynamic method computes evaporation using wind speed and relative humidity profiles. The aerodynamic equation presented by Rosenberg et al (1983) is shown as (after Thornthwaite and Holtzman, 1942):

\[
E = \rho_a K^2 \frac{(q_2 - q_1)(U_2 - U_1)}{\ln \left( \frac{z_2}{z_1} \right)^2}
\]  

(2.4)

where:

- \( E \) = Evaporative vapour flux
- \( \rho_a \) = Air mass density
- \( K \) = von Karman's constant
- \( z_1, z_2 \) = Vertical position above the surface
- \( q_1, q_2 \) = Specific humidities at \( z_1, z_2 \)
- \( U_1, U_2 \) = Wind speed at \( z_1, z_2 \)

This method is based on the assumption that the vertical wind speed profile is logarithmic, which requires strict atmospheric conditions that were summarized by Oke (1978) as follows:

1. Atmospheric stability (i.e. neutral stability with respect to buoyancy).
2. Steady atmospheric conditions (i.e. constant radiation and wind speed during the observation interval).
3. Uniform fluxes with height.
2.3.2.3 Mass Transfer Method

The development of the mass transfer method is frequently attributed to Dalton in 1802 (Gray, 1970; Brutsaert, 1982). The mass transfer method, which is essentially a simplification of the aerodynamic method, calculates evaporation based on the vapour pressure gradient between the evaporating surface and the atmosphere. The mass transfer equation may be written as:

\[ E = B ( e_s - e_a ) \]  \hspace{1cm} (2.5)

where:

- \( E \) = Rate of evaporation
- \( e_s \) = Vapour pressure at the temperature of the evaporating surface.
- \( e_a \) = Vapour pressure of the air above the water surface
- \( B \) = A transmission function which depends on mean wind speed and turbulent mixing

2.3.3 Regional Climatological Methods

Regional climatological methods for computing evaporation require only routine climate data such as mean temperature and relative humidity. The most commonly used methods in engineering practice include the Thornthwaite Method, the Penman Method, the Priestley-Taylor Method and the Complementary Relationship.
2.3.3.1 Thornthwaite Method

The Thornthwaite equation for estimating monthly potential evapotranspiration is written as:

\[
E_p = 1.6 \left( \frac{L}{12} \right) \left( \frac{N}{30} \right) \left( \frac{10T_a}{I} \right)^{a_1}
\]  
(2.6)

where:

- \( E_p \) = Monthly potential evaporation in mm
- \( L \) = Length of day in hours
- \( N \) = Number of days per month
- \( T_a \) = Mean monthly air temperature
- \( I \) = The sum of 12 monthly heat indices 'i'

\[
i = \left( \frac{T_a}{5} \right)^{1.514}
\]  
(2.7)

\[
a_1 = \text{A constant}
\]

\[
( a_1 = 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.79 \times 10^{-2} I + 0.49)
\]

The Thornthwaite method is advantageous since it does not require sophisticated data; however, it is not suitable for short term predictions (less than 1 month) since mean monthly temperatures may not accurately represent the amount of incoming solar radiation on any given day. In general terms, the Thornthwaite method is limited to the estimation of potential evapotranspiration of large scale areas over periods of at least a month (Wilson, 1990).
2.3.3.2 Penman Method

The Penman method utilizes the simultaneous solution of the energy balance and mass transfer equations to compute evaporation rates. The Penman Equation is written as:

\[ E_p = \frac{\Gamma Q_N + \nu E_a}{\Gamma + \nu} \]  

(2.8)

where:

- \( E_p \) = Potential evaporation per unit time, mm/day
- \( E_a \) = Actual evaporation = \( f(u) (e_{sa} - e_a) \)
- \( e_{sa} \) = Saturation vapour pressure of the mean air temperature
- \( e_a \) = Vapour pressure of the air above the evaporating surface
- \( f(u) \) = 0.35 \((1 + U_s (9.8 \times 10^{-3}))\)
- \( U_s \) = Wind speed
- \( Q_N \) = Heat budget or all net radiation
- \( \Gamma \) = Slope of the saturation vapour pressure versus temperature curve at the mean air temperature
- \( \nu \) = Psychometric constant
2.3.3.3 Priestley-Taylor Model

This method expresses the potential evapotranspiration as a fraction of the combined latent and sensible heat fluxes as shown below:

\[ E_p = \alpha \frac{\Gamma}{\Gamma + v} \left( Q_E + Q_H \right) = \alpha \frac{\Gamma}{\Gamma + v} \left( Q_N + Q_G \right) \]  

(2.9)

where:

- \( E_p \) = Potential evaporation
- \( Q_E \) = Latent heat flux
- \( Q_H \) = Sensible heat flux
- \( Q_N \) = All net radiation
- \( Q_G \) = Subsurface heat flux
- \( \Gamma \) = Slope of the saturation vapour pressure versus temperature curve
- \( v \) = Psychometric constant
- \( \alpha \) = Empirical constant (equals 1 for equilibrium profiles of specific humidity and temperature, generally ranges from 1.08 to 1.33 (Priestley and Taylor, 1972))

Rosenberg et al (1983) state that the Priestley and Taylor method has been found to give reliable estimates of evapotranspiration in humid areas, but that it has not been sufficiently tested in arid areas.
2.3.3.4 The Complementary Relationship

The complementary relationship between potential and actual evaporation was proposed by Bouchet in 1963. The complementary relationship can be simply written as:

\[ ETP + ETR = 2ETP_0 \]  \hspace{1cm} (2.10)

where:

- \( ETP \) = The potential evapotranspiration which would occur under the given atmospheric conditions if only available energy is limiting.
- \( ETR \) = The actual evapotranspiration over a large uniform region with a characteristic scale in the order of 1 to 10 km.
- \( ETP_0 \) = The rate of evapotranspiration when the actual regional evapotranspiration is equal to the potential evapotranspiration (i.e. wet environment).

This relationship is based on the assumption that any energy which is not consumed in actual evapotranspiration remains available as a potential. The formulations for the complementary relationship given by Bouchet (1963) are hypothetical and have not been completely accepted. Brutsaert (1982) attributes this lack of application to the difficulty in assessing the physical validity of the assumptions adopted by Bouchet (1963).
2.4 Difficulties with the Term "Potential Evaporation"

The term "potential evaporation" (or potential evapotranspiration) is commonly used when discussing, or computing evaporation rates. The climatological methods of determining evaporation that have previously been discussed either calculate the potential evaporation, or include potential evaporation in the equations. The concept of potential evaporation is easy to understand, and it is generally taken as an upper limit to evaporation. In most practical cases, the important parameter is not potential evaporation, but actual evaporation. Actual evapotranspiration can be estimated from computations of potential evapotranspiration and empirical correlations between actual and potential values for evapotranspiration (Granger and Gray, 1989). While this concept seems quite simple, there are a number of difficulties with it.

One of the primary difficulties with the term "potential evaporation" is its definition. Granger (1989) reviewed the concept of potential evaporation and showed that numerous definitions exist. A summary of definitions of potential evaporation is shown in Table 2.1 (after Granger, 1989), and reveals that the calculation of potential evaporation by some of the definitions is indeterminate.
### Table 2.1 Summary of "Potential Evaporation Parameters" (After Granger, 1989)

<table>
<thead>
<tr>
<th>Name</th>
<th>Definition</th>
<th>Calculation</th>
<th>Common Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_p1$</td>
<td>Evaporation rate which would occur if the surface was brought to saturation.</td>
<td>Indeterminate</td>
<td>&quot;definition&quot; of potential evaporation</td>
</tr>
<tr>
<td>$E_p2$</td>
<td>Evaporation rate which would occur if the surface was brought to saturation and the energy supply to the surface was held constant.</td>
<td>Indeterminate. Regression with solar radiation (Priestley and Taylor, 1972)</td>
<td>Wet-environment or equilibrium evaporation. Advection-free evaporation.</td>
</tr>
<tr>
<td>$E_p3$</td>
<td>Evaporation rate which would occur if the surface was brought to saturation and the atmospheric parameters and the energy supply to the surface were held constant.</td>
<td>Energy balance, vapour transfer equations.</td>
<td>Penman potential. Wet-surface evaporation</td>
</tr>
<tr>
<td>$E_p4$</td>
<td>Evaporation rate which would occur if the surface was brought to saturation and the energy supply and the surface temperature were held constant.</td>
<td>Indeterminate.</td>
<td>Not used.</td>
</tr>
<tr>
<td>$E_p5$</td>
<td>Evaporation rate which would occur if the surface was brought to saturation and the atmospheric parameters and the surface temperature were held constant.</td>
<td>Vapour transfer equation (if surface temperature is known)</td>
<td>Potential. (van Bavel, 1966)</td>
</tr>
</tbody>
</table>
The difficulties in defining potential evaporation relate to variables such as air temperature, surface saturation and energy budget. In nature, these variables are intimately dependent on one another and define evaporation as a coupled system. All parameters must be known to define the true rate of evaporation (Wilson, 1990).

2.5 Current Cover Design Concepts

Many of man's activities generate wastes which must be disposed of. A significant portion of the domestic and industrial wastes generated is currently disposed of in landfills, while the majority mining wastes (tailings) are stored in surface containment facilities. As landfills and tailings disposal facilities reach their capacity, they must be decommissioned. Decommissioning of these facilities must ensure that they do not pose environmental hazards for the foreseeable future. Current decommissioning strategies for these types of facilities generally involve some type of cover. Different types of wastes have different decommissioning requirements, and, therefore, the cover designs must also be tailored to the specific facility. Some of the current cover design strategies are discussed in the following sections.

2.5.1 Covers to Limit Infiltration

Leachate generated from landfills is a major concern due to the potential contamination of groundwater supplies. Landfill leachates may contain significant concentrations of dissolved salts and heavy metals, which are unacceptable in
domestic water supplies. A cover designed to limit infiltration is the first line of
defense against the generation of significant quantities of leachate from a landfill
(Mundell and Bailey, 1985). Covers must be able to withstand weathering effects due
to wet/dry cycles and freeze/thaw cycles, deterioration due to settlement, biological
intrusion, etc. If allowed to desiccate, liners may shrink, crack, and lose their integrity
(Kleppe and Olson, 1985). The selective layering of soils in multilayered covers may
be employed to prevent drying due to evaporation, as well as the detrimental effects
of other weathering processes (wet/dry cycles, freeze/thaw cycles). Thus, the final
cover design will likely be a multi-layered system, since it is not probable that any
single layer will meet all of the design criteria.

2.5.2 Capillary Barriers

Capillary barriers, which are also referred to as "wick" covers in the literature are
based on the observation that the presence of a coarse layer below a finer-grained
soil will cause higher moisture retention in the upper layer than if the coarse layer
is not present. Several authors (Corey and Horton, 1969; Frind et al, 1976; Rancon,
1980; Johnson et al, 1983a, 1983b) have demonstrated that this effect can be used to
limit infiltration, and to direct infiltration around buried materials, such as
radioactive wastes.

Various authors have recommended different criteria for the selection of materials
in a capillary barrier system. The ratio of saturated hydraulic conductivities of the
coarse and fine-grained soils has been proposed as a criterion for selecting soils for a wick effect cover. This criterion does not necessarily result in selection of optimum, or even functional soils (Goode, 1986). Goode (1986), states that the performance of a capillary barrier should be based on the reduction of infiltration (evaluated below the coarse-grained layer), and that the important criteria for design is the unsaturated hydraulic conductivity function (i.e. \( k(\psi) \)), particularly at levels of suction where the coarse layer has a lower hydraulic conductivity than the fine grained layer.

The analyses for capillary barriers generally assume that these covers will not be subjected to evapotranspiration (usually due to an assumed topsoil cover); however, there may be applications where subjecting the cover to evapotranspiration may be beneficial and may result in a more efficient and cost-effective cover. For example, if the objective of the cover is to limit infiltration, providing an upper cover layer that possesses high storage capacity, but that would also release a significant portion of its pore-water to the atmosphere by evaporation could reduce the net infiltration through the cover.

In order to utilize this concept in design, evaporative fluxes and moisture redistribution in soils under actual field climatic conditions must be thoroughly understood. Once the processes and mechanisms are understood, predictive design methods can be developed.
2.5.3 Moisture Retaining Covers

Moisture retaining covers are another application where the selective layering of soils can have beneficial effects in a cover design. Moisture retaining covers have been proposed to reduce problems with acidic drainage, which is a major problem with sulphidic mine tailings. Feasby et al (1991) state that acidic drainage is the largest single environmental problem facing the Canadian mining industry today. The acidic drainage produced by these tailings poses a threat to both surface water bodies and groundwater.

It is generally agreed that the production of acid is controlled by the availability of oxygen at the sulphide surface (Shumate et al, 1971; Jaynes et al, 1984; Davis and Ritchie, 1986; Nicholson et al, 1989). This is confirmed by experience which has shown that when fresh, unoxidized tailings are placed under a column of water, sulphide oxidation and acid generation are essentially curtailed (Yanful, 1991). This observation has lead to the so-called "wet cover" tailings disposal scheme, in which potential acid generating tailings are flooded with water to reduce acid generation. In areas where flooding is not acceptable or feasible, other options, such as soil covers will be required. The concept of moisture retaining, or "dry" soil covers is one of the options currently being considered.

The primary mode of oxygen transport in soils and tailings is by molecular diffusion (Kimball and Lemon, 1971; Nicholson et al, 1991; Yanful, 1991). The effective
diffusion coefficient \( (D_e) \) can vary by up to four orders of magnitude with changes in moisture content (Nicholson et al, 1989). Laboratory data has indicated that the diffusion coefficient for oxygen decreases by about two orders of magnitude as moisture saturation increases from 75 to 95 percent (Yanful, 1991). The concept of a moisture retaining cover is that by selective layering of the soil cover, at least one of the soil layers will remain at a high degree of saturation, and thus minimize the transport of oxygen to the sulphide surface.

Nicholson et al (1989) presented a static equilibrium analysis of a moisture retaining cover that utilized a silt layer over a sand (i.e., fine grained over coarse grained soil). The moisture retention curves for these materials are shown in Figure 2.3.
Figure 2.3 Volumetric Water Content (θ) and Pressure Head (ψ) for a sand and a silt loam (Nicholson et al, 1989, modified from Gillham, 1984).

Figure 2.4 presents the hypothetical vertical section of a moisture retaining cover as presented by Nicholson et al (1989). This figure shows the head distribution and expected moisture content at quasi-equilibrium after drainage, and indicates that the silt layer remains saturated even though it may be several metres above the water table. This concept relies on the concept that the sand layer will not drain below its
residual water content, thus the suction (negative pressure head) at the base of the silt layer is independent of the depth to the water table. Based on their analysis, Nicholson et al (1989) showed that for this type of moisture retaining cover to be effective (i.e., the fine layer (silt) remains saturated across its entire thickness), the magnitude of the air-entry value (AEV, shown as $\psi_a$ in Figure 2.3) for the moisture retaining layer must be greater than or equal to the sum of the thickness of the fine layer and the magnitude of the pressure head at which the underlying coarse layer approaches the residual moisture content.

Analyses conducted by Nicholson et al (1989) indicated that the moisture retaining cover concept could be utilized to achieve potential reductions in oxygen flux of about four orders of magnitude for a 1 m thick cover.

The analysis performed by Nicholson et al (1989) assumed static equilibrium conditions and did not consider potential drying of the cover due to evaporation. Barbour (1990) presented an analysis of moisture retaining covers based on a constant infiltration rate. The assumption of a constant infiltration rate may be no more realistic than the static equilibrium conditions assumed by Nicholson et al (1989); however, it provides insight into the potential behaviour of the cover. Barbour (1990) showed that the pressure profiles and resulting moisture contents within the cover under constant infiltration conditions may deviate significantly from those postulated on the basis of static conditions, due to water flux across the cover.
as the result of precipitation or evaporation. In order to properly evaluate the performance of a moisture retaining cover, an analysis using a transient boundary condition at the upper surface (i.e., including both precipitation and evaporation) is required. Before this can be accomplished, the mechanisms of evaporation and moisture redistribution in such a layered system must be understood.
2.6 Previous Laboratory Evaporation Studies

A number of laboratory evaporation studies have been conducted over the years (Shaw and Smith, 1927; Moore, 1939; Staley, 1957; Gardner and Fireman, 1958; Anat et al, 1965; Shimojima et al, 1990; Wilson, 1990). The majority of these investigations have examined steady state flow through homogeneous soils with a water table present, and the main emphasis has been on evaporation rates rather than moisture redistribution.

These previous laboratory investigations have shown that steady state evaporative flow has a limiting value which is a function of the hydraulic conductivity and the depth to the water table.

Staley (1957) investigated the effect of water table depth on the evaporation rate from a fine sand. Staley (1957) used soil columns placed in a wind tunnel, and varied the potential evaporation rate by controlling the wind velocity. He found that a critical water table depth existed, below which the evaporation rates decreased significantly. The critical depth was approximately equal to the head equivalent to the air entry value for the sand used. The sand used had a very steep moisture retention curve in the zone between the air entry value and the residual saturation.

Research by Gardner and Fireman (1958) indicated that the presence of a surface mulch (dry layer) reduces the steady evaporation rate in hyperbolic relation to its thickness as illustrated in Figure 2.5. However, as discussed by Army et al (1961)
mulches effectively reduce evaporation only during the early stages of drying when evaporation is determined primarily by climatic factors. During the falling rate stage of drying, evaporation is determined largely by the soil properties. During this stage, the soil surface dries and forms a "self-mulch" which is a more effective mulch than gravel or straw (Hanks and Woodruff, 1958). In regions of limited rainfall, most evaporation occurs in the falling rate stage. Thus it would appear that any process that would substantially decrease evaporation would necessarily have to decrease evaporation during the falling rate stage of drying (Hanks and Gardner, 1965).

Anat et al (1965) examined steady state upward flow from shallow water tables both experimentally and theoretically under conditions where the flow rate was controlled by the capacity of the soil to transmit liquid to a dry surface layer. They stated that the accurate determination of soil properties such as hydraulic conductivity, air entry value and pore-size distribution index is important for determining maximum evaporation rates.

Willis (1960) studied evaporation rates from layered soils in the presence of a water table. He stated that the difference in evaporation rate from a fine-textured soil overlying a coarse soil compared to a homogeneous profile of fine-textured soil may be relatively small, but a reversal of the layering may have a large effect on evaporation rates. These conclusions may be related to the geometry of the columns and the properties of the soils used. Willis (1960) found poor agreement between
calculated and measured evaporation rates for layered soils. The discrepancy between the calculated and measured values was partially attributed to entrapped air and differences in the degree of packing between the soil in the columns and the soil samples used in the hydraulic conductivity tests.
Wilson (1990) performed tests on thin soil sections to directly measure the evaporative flux from a soil surface as it dried from a saturated state to a completely air-dried state. The saturated soil samples were allowed to evaporate, and evaporation rates and temperatures were measured. The results of these tests indicated that the evaporation rate depended on the total suction in a very thin layer of soil at the surface and began to decline once the total suction at the soil surface exceeded approximately 3000 kPa. This observation was similar for three texturally distinct soils of sand, silt and clay.

Wilson (1990) also performed column evaporation tests on a uniform aeolian sand. The column evaporation tests confirmed that the evaporation rate decreased once the total suction at the soil surface reached approximately 3000 kPa. Wilson (1990) stated that the calculation of the evaporative flux from the soil was sensitive with respect to the accuracy of the moisture retention curves; particularly for high values of suction. Thus, the accuracy of the moisture retention curve is paramount for predicting evaporation rates from soil as suctions increase.
3.0 THEORY

3.1 General

As evaporation from soils occurs, the soil becomes unsaturated, thus an understanding of flow processes in unsaturated soils is important. A brief description of unsaturated soil mechanics and flow in unsaturated soils is presented as background. A detailed treatment of unsaturated soil mechanics is provided by Fredlund (1981).

3.2 Description of an Elementary Soil Volume

The success of the effective stress concept in describing the behaviour of saturated soils has led researchers into a search for a similar statement for unsaturated soils. There have been numerous equations proposed in the literature; however, none has proven completely successful in practice (Fredlund, 1981).

Lambe and Whitman (1969) state that a soil contains three distinct phases: solid (mineral particles), gas and liquid. However, an unsaturated soil can be visualized as having a fourth phase. The fourth phase would be the air-water interface commonly referred to as the "contractile skin" (Fredlund, 1981). An element of an unsaturated soil can therefore be visualized as a mixture with two phases that come to equilibrium under applied stress gradients and two phases that flow under applied stress gradients. In other words, from a continuum mechanics standpoint, two phases can be treated as solids (i.e., the soil structure and the contractile skin) and two
phases can be treated as fluids (i.e., the air and water) (Fredlund, 1981). A conceptual drawing of an elementary soil volume for an unsaturated soil is shown in Figure 3.1.

Figure 3.1 Conceptual Drawing of an Elementary Volume of an Unsaturated Soil (After Fredlund, 1981)
Fredlund and Dakshanamurthy (1982a) defined the independent stress state variables \((\sigma_y - u_a)\) ("net normal stress") and \((u_a - u_w)\) ("matric suction") for the one-dimensional case, where \(\sigma_y\) is the total normal stress in the vertical \(y\)-direction, \(u_a\) is the pore-air pressure and \(u_w\) is the pore-water pressure. These stress state variables were tested using "null type" tests by Fredlund (1973) and have become widely used for describing the behaviour of unsaturated soils. When the soil becomes saturated, \(u_a\) becomes equal to \(u_w\) and a smooth transition to saturated soil mechanics occurs using the remaining variables \(\sigma_y\) and \(u_w\).

3.3 Flow Mechanisms in Saturated-Unsaturated Porous Media

The mechanisms of flow in saturated-unsaturated porous media are described in the following sections, based on the formulations of Dakshanamurthy and Fredlund (1981a and b), and Wilson (1990). Detailed derivations of the governing one-dimensional equations for multiphase transient flow of air, water vapour, liquid water and heat across an elementary soil volume are presented by Wilson (1990) and are not repeated here. Rather, the emphasis will be on the fundamental processes which occur within the elementary soil volume. The individual flux components for the transient flow of mass and heat in an elementary soil volume are illustrated in Figure 3.2.
Figure 3.2 The Individual Flux Components for the Transient Flow of Mass and Heat in an Elementary Soil Volume (After Wilson, 1990)
Air Phase

The air phase is compressible and flow occurs in response to a pressure gradient (Dakshanamurthy and Fredlund, 1981a). Fick’s law is used to describe the net mass flux of air through the elementary soil volume. It is important to realize that the air phase also contains water vapour.

Vapour Phase

The flow of water vapour is a response to pressure gradients in the air phase. The two mechanisms by which water vapour may be transported are:

1. Diffusion of water molecules due to a gradient in the partial pressure of the water vapour.
2. Advection of water molecules in the vapour phase with the bulk pore-air flow caused by a gradient in the total air pressure

Water vapour may also flow between the liquid phase and the vapour phase across the contractile skin. This interphase liquid-vapour water flux must be accounted for in order to maintain mass water balance (Wilson, 1990).

Heat Flow

There are three mechanisms which contribute to heat transfer in soil:

1. Conduction
2. Convection
3. Latent heat due to phase change.
Conduction refers to the transport of heat between soil particles and through the pore fluid. The process of conductive heat transport is independent of mass transport within the soil element.

Convection is the transmission of heat through mass transfer in the fluid phase (air phase, water vapour phase, and liquid water phase).

Latent heat transfer is the energy that is consumed or released due to a phase change in the water phase.

**Flow of Liquid Water in Unsaturated Porous Media**

Flow in saturated porous media is based on Darcy’s Law, named for the French engineer who experimentally determined a relationship between flow rate and hydraulic gradient in sands. Darcy’s Law may be written as (Freeze and Cherry, 1979):

\[ v = -k \frac{dh}{dl} \]  

(3.1)

where:

- \( v \) = Specific discharge
- \( k \) = A constant of proportionality defined as hydraulic conductivity
- \( h \) = Hydraulic head
- \( l \) = Length of flow path
- \( \frac{dh}{dl} \) = Hydraulic gradient

Thus, Darcy’s Law indicates that the driving force for the flow of liquid water is a gradient in the total hydraulic head.
Hydraulic Conductivity of Unsaturated Porous Media

Darcy's law was originally established for saturated soils, but has been extended to unsaturated soils. In 1907, Buckingham proposed that the coefficient of hydraulic conductivity \( k \) was a function of volumetric water content \( \theta \) and in turn negative water pressure \( \psi \).

The unsaturated hydraulic conductivity of a soil may be determined either by direct measurement or by predictive methods based on a water content versus pore-water pressure relationship (also known as a moisture characteristic curve, or a moisture retention curve).

The techniques for directly measuring the unsaturated hydraulic conductivity function have been documented by Klute (1965) and Corey (1957). These techniques are fairly complex and involve difficulties with air diffusion and measuring small flow quantities.

Due to the difficulties associated with the direct measurement of unsaturated hydraulic conductivity, predictive methods based on moisture characteristic curves are often used. Laboratory measurement of moisture characteristic curves is a relatively simple task compared to direct measurement of hydraulic conductivity. A typical moisture characteristic curve is illustrated in Figure 3.3.
Green and Corey (1971) presented a method of predicting unsaturated hydraulic conductivity from moisture characteristic curves as shown in Equation 3.2. Green and Corey (1971), and Elzeftawy and Cartwright (1981) both concluded that this method was sufficiently accurate for most field applications.
Brooks and Corey (1964) also proposed a method of predicting the unsaturated hydraulic conductivity based on the moisture characteristic curve. The Brooks and Corey (1964) method describes the hydraulic conductivity of the soil using Equations 3.3 and 3.4.
\[ k = k_{\text{SAT}} \quad \text{for} \quad (u_a - u_w) \leq (u_a - u_w)_b \quad (3.3) \]

\[ k = k_{\text{SAT}} \left( \frac{(u_a - u_w)_b}{(u_a - u_w)} \right)^\eta \quad \text{for} \quad (u_a - u_w) > (u_a - u_w)_b \quad (3.4) \]

where:

\[ (u_a - u_w) = \text{matric suction} \]
\[ (u_a - u_w)_b = \text{matric suction corresponding to the Air Entry Value (AEV), or bubbling pressure (P_b)} \]
\[ \eta = 2 + 3L \]
\[ L = \text{The pore-size distribution index,} \]
\[ \log S_e = \frac{-d (\log S_e)/d (\log (u_a - u_w))}{2 + 3L} \]
\[ S_e = \text{Effective Saturation} = (S - S_r)/(1 - S_r) \]
\[ S = \text{The degree of saturation} \]
\[ S_r = \text{Residual Saturation} \]

The parameter \((u_a - u_w)_b\) is referred to as the bubbling pressure \((P_b)\) or the air entry value \((\text{AEV})\) by various researchers. The term "air entry value" \((\text{AEV})\) will be used in this thesis, since it is commonly used by geotechnical engineers.

The residual saturation \("S_r\) can be determined using the trial and error method described by Laliberte et al (1968). This method involves choosing a value for \(S_r\), and calculating the associated values of effective saturation \("S_e\). A plot of \(\log S_e\) versus log suction is prepared for several values of \(S_r\), to obtain a linear fit to the data. The AEV is determined by extending the linear portion of the plot to the horizontal line representing 100 percent effective saturation. The point of intersection determines the AEV, while the slope of the linear portion defines the pore-size
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distribution index.

Huston and Cass (1987) state that the parameters AEV and $S_r$ have had physical significance attached, but they are essentially curve-fitting parameters.

Governing Equations For Flow of Water

Richards (1931) developed a governing equation for transient flow of liquid water in unsaturated soil by combining Buckingham's concept of a variable hydraulic conductivity with the principle of continuity. The so-called "Richard's Equation" for one-dimensional vertical flow may be written as:

$$\frac{\partial}{\partial z} \left[ k(\psi) \left( \frac{\partial \psi}{\partial z} + 1 \right) \right] = C(\psi) \frac{\partial \psi}{\partial t} \quad (3.5)$$

where:

- $k(\psi)$ = Hydraulic conductivity as a function of negative pressure head or suction
- $C(\psi)$ = Specific moisture capacity = $\partial \theta / \partial \psi$
- $\psi$ = Negative pressure head ($\psi = h - z$) or matric suction
- $z$ = Position (elevation)
- $h$ = Hydraulic head

Philip (1957a) also derived a governing flow equation for unsaturated soils. The Philip equation utilizes the volumetric water content ($\theta$) as the dependent variable instead of pressure ($\psi$). The one-dimensional, vertical form of the Philip Equation is written as:
\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[ D(\theta) \frac{\partial \theta}{\partial z} \right] + \frac{\partial}{\partial \theta} k(\theta) \frac{\partial \theta}{\partial z} \quad (3.6)
\]

where:

\[ D = \text{Diffusivity: } k(\partial \psi/\partial \theta) \]

The formulation based on \( \theta \) has two main advantages over the \( \psi \)-based approach of the Richard equation. First, the volumetric water content, \( \theta \), has a clear finite range between approximately 0 and 0.5 which encourages numerical stability. Secondly, hysteresis in \( k(\theta) \) is much smaller than in \( k(\psi) \).

However, the Philip equation also has some serious disadvantages, particularly for geotechnical engineering use. The Philip equation is fundamentally incorrect, since the volumetric water content, \( \theta \) is not a stress state variable. The use of the Philip equation is limited to homogeneous soil systems due to the use of a \( \theta \)-based formulation rather than a formulation based on the hydraulic head (h). In addition, an important disadvantage of the Philip equation is that the soil structure is assumed to be rigid. For geotechnical engineers, the prediction of volume change is a common requirement, and often the soils are not homogeneous, thus the Philip equation is unacceptable.

Lam (1983) provided a transient flow equation that is more acceptable to geotechnical engineers, shown as Equation 3.7 for the two dimensional transient case.
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The formulation is founded on constitutive relationships for stress and deformation in the air, water and solid phases that were proposed and verified by Fredlund and Morgenstern (1976). The formulation offered by Lam (1983) provides a smooth transition between unsaturated and saturated flow (Lam et al, 1987). Chan (1986) states that the formulation based on the total head ($h$) gives greater stability for numerical solutions than the pressure head ($\psi$) based equation.

\[
\frac{\partial}{\partial x} (k_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y} (k_y \frac{\partial h}{\partial y}) = \rho_w \gamma m^w \frac{\partial h}{\partial t} \quad (3.7)
\]

where:

$k_x$ and $k_y$ = the hydraulic conductivities with respect to the x and y directions as functions of pressure head.

$h$ = total head: \[ h = \left( \frac{u_w}{\rho_w g} + y \right) \quad (3.8) \]

$u_w$ = Porewater pressure
$\rho_w$ = Density of water
$g$ = Gravitational acceleration
$m^w$ = Slope of the $(u_a - u_w)$ versus $\theta_w$ curve when $d(\sigma - u_a)$ is zero.
$u_a$ = Pore air pressure
$\sigma$ = Total stress
$\theta_w$ = Volumetric water content
In one-dimensional form, Equation 3.7 can be written as:

$$\frac{\partial}{\partial z} \left( k_z \frac{\partial h}{\partial z} \right) = \rho_w g m_w \frac{\partial h}{\partial t}$$

(3.9)

3.4 Transient Flow of Liquid Water, Water Vapour and Heat in Soil

Most methods of infiltration analysis assume that precipitation enters the soil as liquid water under isothermal conditions. In contrast, the methods of analysis for evaporation assume water is removed from the ground surface as water vapour. Combining these methods to compute the net flux of water across the soil surface implies that the vapour phase of water only exists in the atmosphere above the soil surface. This is correct for the special case where the soil profile is completely saturated (Wilson, 1990). The previously discussed methods for estimating evaporation work relatively well under saturated conditions, but progressively break down as desaturation of the soil surface continues (Morton, 1969, 1974, 1985; Brutsaert, 1982; Rosenberg et al, 1983; Granger, 1989). Where gradients exist in unsaturated soils, moisture movement occurs in both the liquid and vapour phases. A proper analysis of moisture flow between the atmosphere and soil surface must provide for flow of water vapour and heat along with the flow of liquid water when the soil is unsaturated (Wilson, 1990).
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One of the most widely used methods of describing the one-dimensional flow of liquid water, water vapour and heat in porous materials is that of Philip and de Vries (1957). They presented two non-linear partial differential equations to describe the simultaneous flow of liquid water, water vapour and heat, as shown in Equations 3.10 and 3.11.

The equation for the flow of moisture in both liquid and vapour phases as presented by Philip and de Vries (1957) is:

\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left( D_T \frac{\partial T}{\partial z} \right) + \frac{\partial}{\partial z} \left( D_\theta \frac{\partial \theta}{\partial z} \right) + \frac{\partial k}{\partial z} \tag{3.10}
\]

where:
- \( \partial \theta / \partial t \) = change in volumetric water content with respect to time
- \( D_T \) = Thermal moisture diffusivity (\( D_{T \text{liq}} + D_{T \text{vap}} \))
- \( D_{T \text{liq}} \) = Thermal moisture diffusivity of liquid phase
- \( D_{T \text{vap}} \) = Thermal moisture diffusivity of vapour phase
- \( T \) = Temperature
- \( D_\theta \) = Isothermal moisture diffusivity (\( D_{\theta \text{liq}} + D_{\theta \text{vap}} \))
- \( D_{\theta \text{liq}} \) = Isothermal moisture diffusivity of liquid phase
- \( D_{\theta \text{vap}} \) = Isothermal moisture diffusivity of vapour phase
- \( \theta \) = Volumetric water content
- \( k \) = Unsaturated hydraulic conductivity
- \( z \) = Elevation
- \( D \) = Diffusivity = \( k(\partial \psi / \partial \theta) \)

The differential equation for heat flow under combined temperature and moisture content gradients is given as (de Vries, 1958 and 1987):
\[ Q_H = -\lambda^* \frac{\partial T}{\partial z} + C_w (T - T_o) Q_M - L \rho_w D_{\theta \text{ vap}} \frac{\partial \theta}{\partial z} \]  

(3.11)

\[ \begin{align*} 
Q_H & = \text{Net heat flux} \\
\lambda^* & = \text{Apparent thermal conductivity} \\
C_w & = \text{Specific heat of liquid water} \\
T_o & = 273.16 \text{ K} \\
T & = \text{Temperature} \\
L & = \text{Latent heat of vapourization (2.453 x 10^6 J/kg at 20 °C)} \\
D_{\theta \text{ vap}} & = \text{Isothermal vapour diffusivity} \\
Q_M & = \text{Net mass water flux} \\
\rho_w & = \text{Density of water} \\
\end{align*} \]

Differentiating Equation 3.11, applying the condition of continuity, and neglecting convection leads to:

\[ C \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left( \lambda^* \frac{\partial T}{\partial z} \right) - L \frac{\partial}{\partial z} \left( D_{\theta \text{ vap}} \frac{\partial \theta}{\partial z} \right) \]  

(3.12)

\[ \begin{align*} 
C & = \text{Volumetric heat capacity of the soil} \\
\end{align*} \]

Equation 3.12 accounts only for transfer through conduction and vapourization while ignoring the convective heat transfer terms in Equation 3.11.

The assumptions and limitations of the Philip and De Vries (1957) formulation leave it with several shortcomings for application to geotechnical engineering problems. Wilson (1990) pointed out 5 major deficiencies in this formulation with respect to geotechnical engineering, as listed below:
1. The assumption that the soil matrix is rigid. Prediction of volume change is important in geotechnical analysis.

2. The formulation cannot account for flow induced by changes in total stress.

3. The formulation assumes flow is in response to a gradient in volumetric water content. This is fundamentally incorrect. The flow of liquid water in saturated and unsaturated soil is due to a gradient in total head (Childs and Collis-George, 1950).

4. The model cannot account for pressure changes in the air phase of unsaturated soil. Dakshanamurthy and Fredlund (1981) demonstrated significant changes in pore-air pressures in a clay under conditions of swelling and consolidation.

5. The formulation is only applicable to a homogeneous, isotropic porous medium due to the assumption that liquid flow is in response to a gradient in volumetric water content. Geotechnical engineers are most frequently called upon to analyze multilayered and anisotropic systems.

Wilson (1990) developed a rigorous formulation for the evaluation of evaporation from soil surfaces from a geotechnical engineering perspective. This formulation was based on a continuum mechanics approach, and used principles and conventions commonly used in soil mechanics.

The main assumptions made in Wilson's (1990) formulation were as follows:

1. The soil particles, water and air form a continuum, the behaviour of which may be represented by a representative elementary volume.

2. The flow of liquid water in the soil due to osmotic pressure gradients is neglected.

3. The coefficients of permeability for the water phase and the air phase are functions of the water content, degree of saturation, or matric suction.
4. Hysteresis in the relationships between hydraulic conductivity and matric suction is not taken into account.

5. Local thermodynamic equilibrium prevails at all times at any point in the soil between the liquid water and water vapour phases.

6. The temperature within the soil remains above the freezing point and below the boiling point of water at all times.

7. The effect of double diffuse layer or adsorbed fluid hull around the soil particles is not accounted for.

8. The dissolving of air into the liquid water phase is not considered.

Wilson (1990) also made several other simplifying assumptions to reduce the complexity of the solution. These simplifying assumptions were:

1. Air pressure changes induced by volume change in the liquid water phase and soil structure are small and may be neglected. Wilson stated that this is likely a reasonable solution for most soils which are drying under normal atmospheric conditions, but that it may break down for highly expansive soils undergoing high rates of volume change or in sands exposed to intense and prolonged rainfall events.

2. The interphase vapour flux caused by changes in the air phase volume and/or the partial vapour pressure in the air phase were neglected.

3. The source term due to root uptake was disregarded.

The result of Wilson’s (1990) formulation was two transient coupled partial differential equations to describe the flow of liquid water, water vapour and heat in the soil. These equations are shown below as Equations 3.13 (moisture flow: both liquid and vapour) and 3.16 (heat flow). The formulation also used the widely accepted thermodynamic relationship proposed by Edlefsen and Anderson (1943),
shown as Equation 3.17, to couple the vapour and liquid water phases in the soil. A simple mass transfer equation (Equation 3.19) was used to evaluate the evaporation rate. This simplified formulation was used as a first approximation in the numerical analysis of Wilson’s (1990) column evaporation tests to demonstrate the soil-atmosphere approach to evaluating flux boundary conditions.
Moisture Flow:

\[
\frac{\partial h_w}{\partial t} = c_w^1 \frac{\partial}{\partial y} \left[ k_w \frac{\partial h_w}{\partial y} \right] + c_w^2 \frac{\partial}{\partial y} \left[ D_v \frac{\partial P_v}{\partial y} \right]
\]  \hspace{1cm} (3.13)

where:

\( h_w \) = Total hydraulic head (m)

\( c_w^1 \) = The coefficient of consolidation with respect to the liquid phase

\( \frac{1}{\rho_w g m_w^2} \)

\( c_w^2 \) = The coefficient of consolidation with respect to the vapour phase.

\[
C_w^2 = \left( \frac{P + P_v}{P} \right) \left( \frac{1}{(\rho_w)^2 g m_w^2} \right)
\]  \hspace{1cm} (3.15)

\( m_w^2 \) = The slope of the \((u_a - u_w)\) versus water volume curve when \((\sigma_y - u_a)\) is zero

\( k_w \) = The hydraulic conductivity as a function of matric suction (i.e., \((u_a - u_w))\), m/s

\( D_v \) = The diffusion coefficient of water vapour through the soil, \((\text{kg m})/\text{(kN s)}\)

\( P \) = Total pressure in the bulk air phase \((u_{am} + u_a)\)

\( P_v \) = The actual vapour pressure within the pore air, kPa

\( y \) = position, m
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Heat Flow:

\[
\frac{c_v \rho_s}{\partial t} \frac{\partial T}{\partial y} = \frac{\partial}{\partial y} \left[ \lambda \frac{\partial T}{\partial y} \right] - L_v \left[ \frac{P + P_v}{P} \right] \frac{\partial}{\partial y} \left[ D_v \frac{\partial P_v}{\partial y} \right] \tag{3.16}
\]

where:
- \( c_v \rho_s \): Volumetric specific heat
- \( T \): Temperature (°C)
- \( \lambda \): Thermal conductivity (W/m °C)
- \( P \): Total pressure in the bulk air phase (\( u_{atm} + u_a \))
- \( L_v \): Latent heat of vaporization

Coupling of vapour and liquid water phases:

\[
P_v = P_{vs} h_r \tag{3.17}
\]

where:
- \( P_v \): The actual vapour pressure within the pore-air
- \( P_{vs} \): The saturation vapour pressure of the soil water at temperature, \( T \).
- \( h_r \): Relative humidity = \( \frac{\psi w_v}{e^{\frac{\psi w_v}{RT}}} \) (3.18)

\[
\psi = \text{total potential in the liquid water phase (m), (i.e., matric suction + osmotic suction)}
\]
\[
g = \text{gravitational acceleration (m/s}^2)\]
\[
w_v = \text{molecular weight of water (0.018 kg/mole)}
\]
\[
R = \text{Universal gas constant (8.314 J/mole K)}
\]
\[
T = \text{Absolute temperature (K)}
\]
Evaporation rate:

\[ E = B (e_{\text{soil}} - e_{\text{air}}) \]  \hspace{1cm} (3.19)

where:

- **E** = The rate of evaporation
- **B** = A transmission function which depends on mean wind speed and turbulent mixing
- **e_{\text{soil}}** = Vapour pressure at the ground surface
- **e_{\text{air}}** = Vapour pressure of the air above the ground surface

Wilson (1990) used an explicit forward finite difference technique to simultaneously solve Equations 3.13, 3.16, 3.17 and 3.19, while marching forward in time from a known initial condition. The major drawback of this method was that extremely small time steps were required to maintain numerical stability, which resulted in impractically long solution times.

### 3.5 Kisch (1959) Method of Computing Pressure Profiles

Kisch (1959) proposed a method of computing pressure head profiles in soils under steady state flux conditions. This method assumes that Darcy’s law is valid for both saturated and unsaturated flow, with the hydraulic conductivity taken as a function as a function of the volumetric water content or pressure head. Darcy’s law can be written as shown in Equation 3.20.
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\[ q = -k \frac{dh}{dz} \]  

(3.20)

where:

- \( q \) = unit vertical discharge \((m^3/(s \ m^2))\)
- \( k \) = hydraulic conductivity \((m/s)\)
- \( h \) = hydraulic head \((m)\)
- \( z \) = elevation \((m)\)

The hydraulic head is equal to elevation head, \( z \), plus pressure head, \( p \), as shown in Equation 3.21.

\[ h = z + p \]  

(3.21)

For steady state flow, equations 3.20 and 3.21 can be combined to give Equation 3.22:

\[ dz = \frac{-dp}{\left(\frac{q}{k} + 1\right)} \]  

(3.22)

A pressure profile for a given flux can be calculated by starting at a given pressure (i.e., a water table, with \( p = 0 \)), and selecting a small pressure increment, \( dp \). The hydraulic conductivity over this pressure interval is known, thus the change in elevation \((dz)\) required to reach the new elevation \((p + dp)\) can be calculated. The complete pressure profile can be computed using this incremental technique. This
method was originally proposed for computing pressure profiles under conditions of steady state infiltration; however, it is also applicable for evaporative fluxes.

Gardner (1958) utilized computed steady state pressure profiles to compute the maximum steady state evaporation rate that a soil profile could sustain. Gardner made the assumption that the maximum steady state evaporation rate occurred as the suction at the soil surface approached infinity. Work performed by Wilson (1990) indicated that evaporation rates began to decrease once the total suction at the surface exceeded approximately 3000 kPa. There is a very small difference between the maximum computed evaporation rates determined using the assumptions of Gardner (1958) and Wilson (1990). A similar approach to Gardner’s (1958) will be used to examine evaporation rates for this thesis; however, the point where evaporation rates begin to decrease will be taken as 3000 kPa.
4.0 LABORATORY TESTING

4.1 General

The purpose of the laboratory test program was to make observations of the evaporation process from the selected soils, incorporating various combinations of soil layering, in order to define the factors controlling evaporation rates and moisture redistribution in layered soil systems. The testing program was designed in a similar manner to that of Wilson's (1990) column drying tests, with the extension to additional soil types (i.e., silt) and layered systems.

The laboratory testing program consisted of three phases:

1. Selection and preparation of suitable soils for the proposed testing program.
2. Determination of the basic physical properties of the selected soils.
3. Measurement of evaporative fluxes and moisture redistribution from a vertical soil column in a climatically controlled chamber.

The various phases of the laboratory testing program are discussed in the following sections.
4.2 Selection of the Soils

The relationship between evaporative flux from a soil surface and the available moisture has been recognized by many researchers (Penman, 1948, Idso, 1974; and Morton, 1969, 1971, 1985), but textural considerations have not received the same level of attention. Holmes (1961) presented a qualitative view of differences in the evaporation ratio (actual evaporation/potential evaporation) as a function of moisture availability for sand and clay, as shown in Figure 4.1. Figure 4.1 only provides a qualitative measure of moisture availability, with the soil’s field capacity and permanent wilting point as the respective limits of wet and dry conditions.

Wilson (1990) performed testing to determine the most suitable soil characteristics for a similar laboratory testing program for evaporation from a soil column. He concluded that soils representing the major textural classifications of sand, silt and clay should be tested. Sand was used in Wilson’s column drying test to remove the influence of volume change from the results. It was also expected that a distinct drying front would develop in this soil due to its low air entry value and steep moisture retention curve. To maximize the benefit of the research performed by Wilson (1990), it was decided that similar soils should be used in this testing program; however, clays were excluded due to their undesirable volume change characteristics.
Three soils were selected for the laboratory testing program: a natural silt, a processed silt and Beaver Creek sand. The sand used was obtained from the same aeolian deposit as that used by Wilson (1990); however, it was impossible to use the same silt, since it had been obtained from a borrow pit that had been decommissioned prior to the initiation of this research program. The soils used in this research program are described in the following sections.
4.3 Soil Properties and Preparation

4.3.1 Beaver Creek Sand

The Beaver Creek sand was obtained from a natural aeolian sand deposit located southeast of Saskatoon, Sk., (Twp. 34 Rge. 6-W3) near the Beaver Creek Conservation area. This is the same vicinity as the sand source used by Wilson (1990), which was termed "Beaver Creek sand". The sand is olive brown in colour, is calcareous, oxidized, fine to medium grained, and poorly sorted. The material properties of the soils used in the laboratory testing program are summarized in Table 4.1. The grain size distribution for the Beaver Creek sand used for this thesis is shown on Figure 4.2, along with the grain size curve for the Beaver Creek sand used by Wilson (1990). The extremely close agreement in the two grain size curves is an indication of the uniformity of the Beaver Creek sand deposit, since the two samples were not obtained from exactly the same location. The Beaver Creek sand will also be referred to simply as "sand" when discussing the research performed in this thesis.
4.3.2 Natural Silt

The natural silt used in the laboratory testing program was obtained from a commercial gravel pit east of Saskatoon, Saskatchewan (18-36-3-W3). The pit, owned by Revelstoke Redi-Mix of Saskatoon, Sk., has been designated as Pit No. 48, and is located in a kame and esker complex. The silt occurred as a very uniform layer, approximately 1 m thick, that was exposed in the existing pit wall. The silt was light brown in colour, coarse to medium grained, and very uniform. The grain size distribution for the natural silt is shown in Figure 4.2.

4.3.3 Processed Silt

The processed silt used in the laboratory testing program was obtained by processing the natural silt. The processing of the silt was designed to reduce or eliminate the sand and clay fractions from the natural silt, and leave a clean, relatively uniform silt. The processing was accomplished by a hydrodynamic separation procedure. The initial step in the hydrodynamic separation involved washing the natural silt through a 75 \( \mu \text{m} \) sieve into a container of water to remove the sand sizes. After several kilograms of material had been sieved, the water was agitated to cause the soil to go into suspension. The silt was allowed to settle to the bottom of the container for several hours, and the water was decanted, removing a portion of the clay. This processing resulted in a clean, uniform coarse to medium grained silt. The grain size distributions of the natural and processed silts were determined using hydrometer
tests (ASTM D422). The results of the hydrometer tests are shown on Figure 4.2. The grain size distribution for the "Custom Silt" used by Wilson (1990) is also shown on Figure 4.2 for comparison purposes. Where the word "silt" is used in reference to the work performed for this thesis, it refers to the processed silt.

The difference between the grain size distributions of the natural silt and processed silt are not large, however, the sand component (6.1 %) was essentially eliminated, and the clay size fraction was reduced from 11.0 % in the natural silt to 7.0 % in the processed silt.
Figure 4.2 Grain Size Curves of the Soils Used in the Laboratory Testing Program
Table 4.1  Summary of Material Properties for Soils Used in the Laboratory Test Program

<table>
<thead>
<tr>
<th></th>
<th>Beaver Creek Sand</th>
<th>Natural Silt</th>
<th>Processed Silt</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Sand</td>
<td>96.5</td>
<td>6.1</td>
<td>0.1</td>
</tr>
<tr>
<td>% Silt</td>
<td>3.5 % silt and clay</td>
<td>82.9</td>
<td>92.9</td>
</tr>
<tr>
<td>% Clay</td>
<td></td>
<td>11.0</td>
<td>7.0</td>
</tr>
<tr>
<td>$D_{60}$ (mm)</td>
<td>0.24</td>
<td>0.03</td>
<td>0.028</td>
</tr>
<tr>
<td>$D_{10}$ (mm)</td>
<td>0.093</td>
<td>0.0013</td>
<td>0.0075</td>
</tr>
<tr>
<td>$C_u$</td>
<td>2.58</td>
<td>23.1</td>
<td>3.73</td>
</tr>
<tr>
<td>Atterberg Limits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid Limit</td>
<td>----</td>
<td>20.1</td>
<td>24.0</td>
</tr>
<tr>
<td>Plastic Limit</td>
<td>----</td>
<td>20.1</td>
<td>24.0</td>
</tr>
<tr>
<td>Plasticity Index</td>
<td>NON-PLASTIC</td>
<td>NON-PLASTIC</td>
<td>NON-PLASTIC</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.67</td>
<td>2.71</td>
<td>2.67</td>
</tr>
<tr>
<td>Void Ratio (at 10 kPa Load)</td>
<td>0.532$^1$</td>
<td>0.692$^2$</td>
<td>0.690$^3$</td>
</tr>
<tr>
<td>Porosity (at 10 kPa Load)</td>
<td>0.347$^1$</td>
<td>0.409$^2$</td>
<td>0.408$^3$</td>
</tr>
<tr>
<td>$k_{SAT}$ (m/s) (at 10 kPa Load)</td>
<td>4.26 x 10$^{-6}$</td>
<td>2.07 x 10$^{-8}$</td>
<td>8.36 x 10$^{-9}$</td>
</tr>
</tbody>
</table>

NOTES:  
1. Consolidated from slurry with approx. initial water content = 24 percent  
2. Consolidated from slurry with approx. initial water content = 27 percent  
3. Consolidated from slurry with approx. initial water content = 26 percent  
4. Values obtained from consolidation tests
Wilson (1990) showed that the evaporative flux from a soil is sensitive to the moisture retention curves, particularly at high values of suction, thus the accuracy of the moisture retention curve is paramount for predicting evaporation rates from soil as suctions increase.

Temperature has an effect on the surface tension of water, adsorptive forces in the soil, and osmotic suction in the pore fluid. These temperature effects may influence the moisture retention characteristics of soils. To negate any potential temperature effects on the moisture characteristic curves, all moisture retention testing was performed in the environmental chamber at approximately 35 °C, the same temperature that was used for the column evaporation tests.

4.4 Moisture Retention Characteristics

4.4.1 General

Moisture retention characteristics of the soils used in the laboratory testing program were determined using low pressure (100 kPa) acrylic Tempe cells (manufactured by SoilMoisture Equipment Corp, Santa Barbara, California) and glass desiccators. The desiccators were required to determine the moisture retention curves at high suctions (approximately 5000 to 30000 kPa), where vapour pressure suppression is significant. Detailed testing at low suctions (0 to 10 kPa) was performed on the Beaver Creek sand to accurately determine its low air entry value.
4.4.2 Tempe Cell Tests

The moisture retention curves for matric suctions less than 100 kPa were determined using 1 bar (100 kPa) acrylic Tempe cells manufactured by Soil Moisture Equipment Corp. (Model No. 1400).

Air dried samples were mixed with distilled water to form slurries with water contents of approximately 24, 26, and 27 percent for the Beaver Creek sand, silt and natural silt respectively. The slurried samples were placed in acrylic Tempe cells and were consolidated by static loading. Two samples of each soil type were tested in the Tempe cells, one consolidated to 5 kPa, the other to 10 kPa. Tempe cell testing is often performed on slurried samples; however, Swanson (1991) showed that consolidating the samples prior to testing had a significant effect on the moisture retention curves for fine-grained soils; lowering the volumetric water content at zero matric suction and increasing the air entry value (AEV).

The Tempe cell tests were performed by applying an air pressure to the top of the Tempe cell while maintaining atmospheric pressure at the discharge face of the porous stones. The air pressures applied to the Tempe cells varied from 0 to 100 kPa. The total mass of the soil-filled Tempe cells was monitored during the drainage phase of each pressure increment. When the drainage rate from the Tempe cells decreased to a negligible rate, the air pressure was increased to the next increment. Problems with air leakage from some of the Tempe cells were
encountered, thus some of the tests were terminated before reaching the capacity of the high air entry disks used (100 kPa).

When the Tempe cell samples reached equilibrium at 100 kPa (the upper limit of these cells, based on the air entry value of the high air entry disks), or when air leakage from the cell was detected, the test was terminated. The samples were removed from the Tempe cells and 5 small samples weighing between 1 and 5 grams were trimmed from the samples for use in the vapour equilibrium tests. The remainder of the soil specimen was weighed, then oven dried to determine the final moisture content for the Tempe cell test. The water content at each of the other Tempe cell pressure increments was determined by back-calculation, based on the total mass of dry soil and the change in mass of the sample during previous increments of applied pressure.

4.4.3 Osmotic Desiccation Tests

The osmotic desiccation tests were used to determine the moisture retention characteristics of the soils at high suctions. High total suctions were applied to the samples by allowing them to come to equilibrium at a specified relative humidity in glass desiccators. The relative humidity and vapour pressure in the glass desiccators were controlled using saturated salt solutions. The solutions were selected to give a suitable range of controlled humidities. The salt solutions used and their respective humidities are summarized in Table 4.2.
The samples for the osmotic desiccation testing were weighed to the nearest 0.0001 grams and were placed in the glass desiccators filled with the saturated salt solutions as shown in Table 4.2. The samples were weighed periodically during the osmotic desiccation tests to determine when the samples had reached equilibrium. The gravimetric water content of the osmotic desiccation test samples was determined by oven-drying the samples at 105 °C for at least 24 hours.

Table 4.2 Summary of the Properties of the Saturated Salt Solutions used in the Desiccators (at 35 °C), (After Young, 1967)

<table>
<thead>
<tr>
<th>Saturated Salt Solution</th>
<th>Relative Humidity (Percent)</th>
<th>Equivalent Total Suction (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium Chloride</td>
<td>11.2</td>
<td>317600</td>
</tr>
<tr>
<td>Magnesium Chloride</td>
<td>32.1</td>
<td>164900</td>
</tr>
<tr>
<td>Magnesium Nitrate</td>
<td>49.9</td>
<td>100900</td>
</tr>
<tr>
<td>Sodium Chloride</td>
<td>74.9</td>
<td>41900</td>
</tr>
<tr>
<td>Potassium Sulphate</td>
<td>96.5</td>
<td>5170</td>
</tr>
</tbody>
</table>
4.4.4 Detailed Low Suction Testing

The Beaver Creek sand began to drain after a pressure of 4 kPa was applied during the original Tempe cell tests. The accuracy of the pressure manifold at such low values is suspect, thus detailed moisture retention testing was performed to define the moisture retention curve for the Beaver Creek sand at suctions between 0 and 10 kPa.

The sample preparation for the detailed testing was the same as for the regular Tempe cell testing; however, the method of applying the suction was different. The suction applied to the sample was controlled by varying the outlet elevation of a piece of water-filled Tygon tubing attached to the discharge port of the Tempe cell, while maintaining atmospheric pressure at the upper surface of the soil sample. The discharge from the outlet tube was collected and periodically weighed to determine the water removed from the sample at each suction increment. When the samples achieved equilibrium at a suction of approximately 10 kPa, the cells were dismantled and the soil was oven dried to determine the gravimetric water content. The water content at the lower suction values was determined by back-calculation using the total mass of soil in the cell and the amount of water discharged at each suction increment.
4.5 Consolidation and Saturated Hydraulic Conductivity Testing

Consolidation tests and saturated hydraulic conductivity tests on the soils used in the laboratory test program were performed by Mr. Ning Yang, a research engineer at the University of Saskatchewan. The consolidation permeameter apparatus allowed the consolidation tests and the hydraulic conductivity tests to be performed on the same samples, and allowed the determination of the saturated hydraulic conductivity at various consolidation pressures. The hydraulic conductivity of the samples was determined using a falling head method. The samples were initially slurried into a consolidation ring at water contents of approximately 24, 26 and 27 percent for the Beaver Creek sand, silt and natural silt respectively. The samples were consolidated to the desired total stress prior to performing the hydraulic conductivity test. Hydraulic conductivity tests were performed at consolidation pressures ranging from 5 kPa to 640 kPa.

4.6 One-Dimensional Column Evaporation Tests

The major portion of the laboratory testing program consisted of one-dimensional column evaporation tests, which are described in the following sections.

4.6.1 Criteria and Objective

The objective of the column evaporation tests was to observe evaporation and moisture redistribution from the various soils under controlled climatic conditions.
The column evaporation tests were devised to study both homogeneous samples and layered combinations of the various soils. The tests were also designed to study the effects of two extreme boundary conditions at the lower soil boundary: a shallow water table (located at the base of the column, 600 mm below the soil surface), and a zero flux boundary condition (simulating a water table at a great depth). The columns were tested concurrently to provide identical testing conditions.

An initial "dry run" of a column evaporation test was conducted to test the experimental setup, sampling procedures, and repeatability of measurements. The duplicate samples tested showed close agreement; thus, it was decided that redundant columns would not be used for this study, but that duplicate sampling would be performed at various stages as a check. This decision also allowed the testing of a larger number of columns, since the number that could be tested at one time was severely limited by the size of the environmental testing chamber.

4.6.2 Laboratory Equipment

The equipment used for the column evaporation tests consisted of a climatically controlled environmental chamber (Bally Refrigeration Model 3478-1), 6 soil filled columns, 6 water filled pans for measurement of potential evaporation, 6 - 20 kg capacity triple beam balances (OHAUS heavy duty solution balances), a hygrothermograph, a Vaisala Model HMI-31 moisture/humidity meter equipped with a Vaisala Model HMP-36 probe, a wet-dry psychrometer and a digital thermocouple
(temperature) readout. Some of these items are described in detail in the following sections.

The column evaporation tests were conducted in a Model 3478-1 Bally Refrigeration Environmental Chamber in the Environmental Engineering Laboratory at the University of Saskatchewan. The temperature of the chamber was elevated to approximately 35 °C to accelerate evaporative fluxes. A piece of polyethylene sheeting was suspended below the ceiling fans in the chamber to reduce air currents around the evaporative surfaces of the columns. Unfortunately, this significantly decreased air circulation in the chamber, and resulted in a vertical temperature gradient of approximately 2 to 3 °C/m (temperature increasing with elevation) in the chamber. The temperature at the mid-height of the columns was maintained at approximately 35 ± 0.5 °C. A sheet of polyethylene was also suspended inside the entrance to the chamber to minimize air exchange (and resultant temperature fluctuations) during opening and closing of the chamber door. The relative humidity of the chamber was not directly controlled, and approximately corresponded to the outdoor relative humidity. The average daily relative humidity in the chamber varied from 7.6 to 14 percent, with an average of 11.1 percent. The conditions in the environmental chamber resulted in an actual evaporative flux of approximately 4.5 to 6.5 mm/day from the water filled evaporation pans.

The evaporation columns were constructed from 127 mm (ID) standard PVC well
casing (SDR21) with a wall thickness of 6.7 mm. The columns were 600 mm in height and were placed in lucite bases which contained an O-ring to provide a seal. A bead of silicone sealant was utilized as a secondary seal between the base and the column.

The column bases were provided with drainage grooves on their top surface to permit even drainage from the entire soil surface and an outlet to permit drainage and to control the boundary condition at the bottom of the column. Twelve vertical sets of water content sampling ports, 10 mm in diameter and 20 mm on center were drilled around the circumference of each column. Each sampling port was fitted with a rubber stopper to prevent moisture loss from the column. A schematic diagram of the soil columns is shown in Figure 4.3.

The soils and layering combinations used in the 6 columns are shown schematically in Figure 4.4. Three of the columns were homogeneous, and three of the columns were constructed as layered systems so the effects of layering and layering sequence could both be examined. The full descriptions of the column layering along with a simplified description are shown in Table 4.3.
Table 4.3  Descriptions of Column Layering

<table>
<thead>
<tr>
<th>DETAILED COLUMN DESCRIPTION</th>
<th>SIMPLE COLUMN DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogeneous Beaver Creek Sand</td>
<td>Sand</td>
</tr>
<tr>
<td>Homogeneous Processed Silt</td>
<td>Silt</td>
</tr>
<tr>
<td>0.3 m Processed Silt Overlying 0.3 m Beaver Creek Sand</td>
<td>Silt Over Sand</td>
</tr>
<tr>
<td>0.3 m Beaver Creek Sand Overlying 0.3 m Processed Silt</td>
<td>Sand Over Silt</td>
</tr>
<tr>
<td>Homogeneous Natural Silt</td>
<td>Natural Silt</td>
</tr>
<tr>
<td>Multi-layered Processed Silt and Beaver Creek Sand</td>
<td>Multi-layered</td>
</tr>
</tbody>
</table>
Figure 4.3  Schematic Diagram of a Typical Evaporation Column Used in the Column Evaporation Tests
Chapter 4: Laboratory Testing

Figure 4.4  Schematic Diagram of the Layering Combinations Used in the Column Evaporation Tests.

Thermocouples were used to measure temperature profiles above and within the soil columns. Each column was instrumented with 10 thermocouples, one to measure the air temperature above the column, and nine to measure the temperature profile in the soil. The placement of the thermocouples is summarized in Table 4.4. The
temperature at the base of the column (i.e., a depth of 600 mm below the soil surface) was determined using a thermometer.

The thermocouples were constructed using type T thermocouple wire, and were connected to a rotary switch. Miniature type NMP thermocouple connectors (Omega Engineering Inc., Stamford, CT, USA) were installed between the thermocouples and the rotary switch to allow the thermocouples to be disconnected, thus isolating the column during weighing. This was required to insure accurate weight measurements of the columns. The thermocouples were inserted horizontally in the column by drilling a hole in a rubber stopper, threading the thermocouple through, sealing it with silicone, and inserting the stopper into one of the sampling ports in the column. This arrangement was chosen over the vertical installation used by Wilson (1990) to prevent the potential formation of a preferential vertical flowpath for liquid or vapour flow along the thermocouple wires. Column temperatures were determined by connecting the thermocouples to a digital readout, which had a sensitivity of 0.1 °C. Prior to installation in the columns, the thermocouples were calibrated by checking the measured temperature in an ice bath and in boiling water. All of the thermocouples measured temperatures within 0.3 °C of the actual temperature, thus no correction factor was applied to the temperatures measured during the column evaporation test.

Simple "tube tensiometers" were constructed as shown in Figure 4.3, and were
installed in the columns to provide a direct measurement of suctions along the column profile. The tensiometers consisted of a porous ceramic tip (Soilmoisture Equipment Corp. Part No. 652X03-B1M3) epoxied into one end of a plastic tube, with a rubber septum (Aldrich Chemical Company, Milwaukee, Wisconsin, Part No. Z12,436-2) inserted in the other end of the tube. The tubes were filled with deaired distilled water. The pressure (suction) in the tensiometers was measured using a Tensimeter™ readout gauge manufactured by Soil Measurement Systems of Tucson, Arizona. This gauge utilizes a hypodermic needle connected to a pressure transducer to measure the suction in the tensiometer. This readout was also capable of measuring positive pressures.

The hypodermic needle in the Tensimeter tended to rip the rubber septum after a few readings, thus the interior void of the rubber septum was filled with a flexible silicone (Dow Corning #790 silicone). The durability of the septum was dramatically increased by using the silicone. The interior of the rubber septa were roughened with a drill bit prior to injecting the silicone to increase the bond strength between the silicone and the rubber septum.

The tensiometers were inserted in the column through the sampling ports, and were sealed in place with silicone. The tensiometers were inserted at a slight downward angle to promote migration of any air bubbles from the ceramic tip to the septum end of the apparatus, where they could be removed. The location of the tensiometers
in the soil columns is summarized in Table 4.4. Tensiometers were not installed in the homogeneous natural silt column and the multilayered silt and sand column.

**Table 4.4** Summary of Instrumentation Installed in the Columns Used for the Evaporation Tests

<table>
<thead>
<tr>
<th>Column Description</th>
<th>Thermocouples</th>
<th>Tensiometers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogeneous Beaver Creek Sand</td>
<td>-50*, 1, 10, 25, 50, 120, 280, 320, 400, 500</td>
<td>40, 100, 280, 400</td>
</tr>
<tr>
<td>Homogeneous Natural Silt</td>
<td>-50*, 1, 10, 25, 50, 120, 280, 320, 400, 500</td>
<td>NONE</td>
</tr>
<tr>
<td>Homogeneous Processed Silt</td>
<td>-50*, 1, 10, 25, 50, 120, 280, 320, 400, 500</td>
<td>40, 100, 280, 400</td>
</tr>
<tr>
<td>Processed Silt (300 mm) Over Beaver Creek Sand (300 mm)</td>
<td>-50*, 1, 10, 25, 50, 120, 280, 320, 400, 500</td>
<td>40, 100, 280, 320, 400, 500</td>
</tr>
<tr>
<td>Beaver Creek Sand (300 mm) over Processed Silt (300 mm)</td>
<td>-50*, 1, 10, 25, 50, 120, 280, 320, 400, 500</td>
<td>40, 100, 280, 320, 400, 500</td>
</tr>
<tr>
<td>Multilayered Processed Silt and Beaver Creek Sand</td>
<td>-50*, 1, 10, 25, 50, 120, 280, 320, 400, 500</td>
<td>NONE</td>
</tr>
</tbody>
</table>

* NOTE: -50 mm depth designates a thermocouple positioned approximately 50 mm above the soil surface to measure air temperature. The temperature at a depth of 600 mm was measured using a thermometer on the exterior of the column.
Servicing of the tensiometers was required to reduce the size and number of air bubbles in the tensiometers, and to ensure that the interior surface of the ceramic tip was saturated. Servicing was accomplished by inserting a 150 mm long, 14 gauge hypodermic needle into the tensiometer until the end of the needle was inside the ceramic tip. A second (smaller) hypodermic needle was then inserted through the rubber septa to provide a vent for the air bubbles. Air bubbles were flushed from the system by injecting de-aired water through the needle in the ceramic tip, which forced any air out, and along the plastic tube to the air vent. When the air bubbles were flushed from the system, the hypodermic needles were removed.
4.6.3 Soil Column Preparation

Prior to placing the soil into the PVC columns, a round piece of metal screen (#100 mesh, a screen opening of 0.160 mm) and a single layer of filter paper were placed on the drainage grooves in the base of the column to prevent loss of soil particles during drainage of the columns.

All of the columns were filled and assembled in the environmental chamber, using identical placement techniques. The placement water contents of the dune sand, processed silt and natural silt were approximately 24 percent, 26 percent and 27 percent respectively. Distilled water was used for all samples. The columns were filled in lifts of 25 to 50 mm; the columns were tapped with a rubber mallet to liquefy the soil to ensure the removal of air voids and to obtain consistent, uniform densities. Any excess free water that accumulated after the densification of a lift was carefully removed by suction or by absorbing it with a paper towel. The instrumentation (thermocouples and tensiometers) was installed as the column was filled, filling the column to slightly below the instrument elevation, then installing the instrumentation and carefully filling around and above it.

The tensiometers were inserted through the wall of the column and were sealed in place with silicone sealant. The silicone around each tensiometer was allowed to "skin over" (which required approximately 10 minutes) before filling of the column was resumed.
The thermocouples were threaded through holes drilled in rubber stoppers, and were sealed into the stopper with silicone. This procedure was performed prior to filling the columns so that installation of the thermocouples would not cause undue delays.

An extension (approximately 50 to 75 mm long) was added to the top of the column and soil was placed to the top of this extension as an allowance for consolidation and to add a small amount of surcharge to the soil at the top of the column. After the column had been filled, it was covered with aluminum foil to prevent evaporation while the columns were allowed to come to thermal and hydraulic equilibrium.

Drainage from the column was monitored, and it was assumed that hydraulic equilibrium had been achieved when the measured drainage fell to negligible levels. The tensiometers were also used to monitor the dissipation of positive pore pressures; however, readings below approximately 10 mbar (1 kPa) tended to fluctuate during measurement and thus were not considered to be reliable.

Thermal equilibrium of the columns was determined by monitoring the thermocouples. Thermal equilibrium was achieved when the measured column temperatures stabilized and approximately matched the air temperature in the chamber.

After the columns had achieved thermodynamic equilibrium, they were insulated to minimize lateral heat flow below the evaporating surface. Two layers of insulation
were used. The first layer consisted of narrow strips of R6 (half thicknesses of R12) fibreglass insulation fitted between the stoppers in the sampling ports. The purpose of this layer of insulation was to prevent air gaps between the outer layer of insulation and the column in the area between the rubber stoppers. The outer layer of insulation consisted of R12 fibreglass insulation wrapped around the entire column, and fastened with several pieces of wire.

The soil filled columns were placed on triple beam balances (OHAUS Heavy Duty Solution Balances) that had a capacity of 20 kg, and a readability of ±1 g. The balances were checked prior to the column evaporation test to ensure that small weight changes (1 to 2 grams) could be detected with reasonable reliability.

The water filled reference evaporation pans were placed on stands adjacent to the soil filled columns, at approximately the same elevation as the top of the soil filled columns. The evaporation rate from the reference pans was determined by removing the pans from the stands and weighing them to the nearest 0.01 g to determine the change in mass. After weighing, water was added to the reference pan to maintain a relatively consistent mass. The temperature of the water added to the reference pans was carefully adjusted to match the existing water temperature.
4.6.4 Test Procedure

After the columns achieved thermodynamic equilibrium, as determined by the thermocouple readings, and hydraulic equilibrium, as determined by a cessation of drainage from the outlet port, the initial water content profile of the column was measured.

Water contents were determined by removing one of the rubber stoppers, inserting a 9 mm O.D. glass tube and extracting a small soil sample, generally weighing between 0.5 and 2.0 grams. The soil sample was immediately extruded into an aluminum foil tare and was weighed to the nearest 0.0001 gram using a Mettler A30 electronic balance. The stopper was then replaced, and sampling proceeded vertically down the column. A water content sample was also obtained from the surface of the column, by scraping a small area to a depth of approximately 2 to 3 mm. The soil samples were then oven-dried, and the gravimetric water contents were calculated.

Water content profiles were determined at various times as summarized in Table 4.5. Each subsequent water content profile sampling was determined using a new series of sampling ports, proceeding counterclockwise around the column. On 2 occasions for each column, every second sampling port was sampled, in order to obtain 14 water content profiles from the 12 sets of sampling ports. Duplicate samples were taken (i.e. 1 from a previously used port, and 1 from an unused port) on several occasions to ensure that the water contents were not influenced by the sampling
procedure. These duplicate samples yielded similar results; thus, it was concluded that the sampling procedure did not influence the water content.

After the initial water content profile of the column was determined, the aluminum foil cover and the extension at the top of the column were removed, and the soil surface was trimmed so that it was level with the top of the column. The freshly trimmed soil surface was left exposed to the atmosphere to allow evaporation from the column to proceed. A water reservoir was connected to the outlet port to simulate the presence of a water table at an elevation approximately 0.5 cm above the base of the soil column. This phase of the column evaporation tests will be referred to as the "Constant Head Boundary Condition" (CHBC) Phase.

Throughout the column evaporation tests, measurements of air temperature and relative humidity, soil temperature (from the thermocouples) and soil suction (from the tensiometers) were made at regular intervals. Evaporation rates from the columns and the water filled reference pans were measured on a daily basis.

Potential evaporation was determined by measuring the evaporation rates from the water filled reference pans. A water filled reference pan was placed beside each soil filled column, with the water surface at approximately the same elevation as the soil surface. The reference pans required frequent replenishment to keep the water surface at approximately the same elevation. The reference pans were filled with distilled water, with the temperature of the replenishment water carefully matched.
to the temperature of the water in the reference pan.

The evaporation rate from the soil filled column (i.e. "actual" evaporation) was determined by mass balance using the measured change in mass of the column and the change in mass of the water reservoir during the constant head boundary condition phase of the testing. This provided information regarding the amount of water that was being removed from storage in the soil voids, and how much was being drawn from the "water table".

The temperature and relative humidity in the testing chamber were recorded by the hygrothermograph, with frequent measurements taken using the Vaisala HMI 31 temperature/humidity meter and HMI 36 probe for calibration. The readings obtained by the Vaisala meter were calibrated using an Assman wet-dry psychrometer. The Vaisala meter and the wet-dry psychrometer provided similar results; thus, the Vaisala meter was used as the primary measuring device because it was simpler to use.

The equipment utilized in this testing program was not suitable for automatic data acquisition; therefore, all data was collected manually.

After approximately 31 days of evaporation under the constant head boundary condition, the water reservoir at the base of the column was removed and the outlet port was sealed to change the base of the column to a zero flux boundary condition.
The test was continued for approximately 30 more days in a similar manner to that previously described. Water content profiles were measured at the intervals shown in Table 4.5, with climatic data, soil temperature profiles, and tensiometer readings obtained at various times throughout the duration of the tests. This portion of the column evaporation tests will be referred to as the "Zero Flux Boundary Condition" (ZFBC) Phase.
The column evaporation tests were terminated after a total elapsed time of approximately 60 to 61 days (31 days at the constant head boundary condition, and 29 to 30 days at the zero flux boundary condition). No disruptions or power failures occurred during the test, although one of the triple beam balances was replaced during the testing.
5.0 PRESENTATION OF RESULTS

5.1 Introduction

This chapter presents the experimental results of the laboratory test program described in Chapter 4. The data presented includes the results of the consolidation and hydraulic conductivity tests, moisture retention tests (based on the Tempe cell and osmotic desiccation tests) and the column evaporation tests.

5.2 Consolidation Test Results

Consolidation tests were performed on each of the soils used in the laboratory testing program, as described in Section 4.5. Figure 5.1 shows a plot of the void ratio as a function of the consolidation pressure. The consolidation test results are summarized in Appendix A.

The consolidation test results show that the Beaver Creek sand and processed silt undergo very small changes in void ratio in comparison to the natural silt. This is to be expected, due to the higher clay content of the natural silt. The similarity in compressibility between the Beaver Creek sand and the processed silt may be an indication that their behaviour may be similar, and somewhat different than that of the natural silt.
Figure 5.1  Void Ratio as a Function of the Applied Consolidation Pressure For the Soils Used in the Laboratory Testing Program.
5.3 Saturated Hydraulic Conductivity Tests

The saturated hydraulic conductivity of each of the three soils used in the laboratory test program was determined at the end of each of the total stress increments used in the consolidation testing, as described in Section 4.5. The saturated hydraulic conductivity was determined using the falling head method. Figure 5.2 shows the variation in saturated hydraulic conductivity as a function of the void ratio determined in the consolidation testing. The saturated hydraulic conductivity of the various soils is also summarized in Appendix A.

Figure 5.2 indicates that the saturated hydraulic conductivity of the Beaver Creek sand and the natural silt decreases as the applied total stress increases. This conforms to the expected behaviour, since the void ratio decreases with increased total stress, reducing the area available for flow. The processed silt results indicate that the saturated hydraulic conductivity increases as the total stress increases, contrary to expected behaviour. The measured increase in hydraulic conductivity is small (8.27 x 10^9 to 9.38 x 10^9 m/s) over the total stress range of 5 to 640 kPa, and may be the result of small piping failures in the sample, although examination of the sample after testing did not reveal any visible piping failures. Another possible explanation may be that the hydraulic conductivity of the porous stone in the test apparatus may have caused some impedance of the flow, thus influencing the results.
5.4 Moisture Retention Characteristics

The moisture retention characteristics for the Beaver Creek sand, natural silt, and processed silt for suctions between 0 and 100 kPa were determined by Tempe cell testing as described in Section 4.4.2. At the completion of the Tempe cell tests,
smaller sub-samples were trimmed from the Tempe cell samples for osmotic desiccation testing, which was described in Section 4.4.3.

Tests were conducted on two sets of samples. Both sets of samples were initially slurried and placed into the Tempe cells. One set of samples was consolidated to 5 kPa while the other set of samples was consolidated to 10 kPa. All testing was performed in the environmental chamber at a temperature of approximately 35 °C, the same temperature used for the column evaporation tests. Temperature variations in the environmental chamber were less than about 0.5 °C over the duration of the testing.

The results of the Tempe cell testing are presented in Table 5.1. The final gravimetric water contents presented in Table 5.1 were determined based on the oven-dried water content determined at the end of the Tempe cell tests, with the water contents at lower values of matric suction back-calculated from the change in mass during the individual pressure increments. The results of the detailed testing to determine the moisture retention characteristics of the Beaver Creek sand at suctions between 0 and 10 kPa, as described in Section 4.4.4 are also included in Table 5.1. The osmotic desiccation test results are shown in Table 5.2. A plot of the moisture retention curves is shown in Figure 5.3.

Air leakage was noted from the some of the Tempe cells at various pressures, as indicated in Table 5.1. Monitoring the sample weight provided an indication of
whether or not leakage was occurring. If the rate of moisture loss from the sample
did not decrease with time at a given pressure increment, leakage was suspected and
the entire cell was immersed in water to determine if leakage was in fact occurring.
If a leak was detected and it could not be stopped, the Tempe cell test was
terminated. The effect of air leakage would be to underestimate the water content
for a given suction.
### Table 5.1 Tempe Cell Test Results, Including Detailed Low Suction Testing on Beaver Creek Sand

| Matric Suction (kPa) | Gravimetric Water Content (Percent) |  |  |  |  |
|----------------------|------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                      | Beaver Creek Sand | Natural Silt | Processed Silt | 5 kPa Load | 10 kPa Load | 5 kPa Load | 10 kPa Load | 5 kPa Load | 10 kPa Load |
| 0                    | 21.23 | 21.18 | 23.78 | 22.78 | 25.48 | 25.47 |
| 1                    | 21.10 | 21.09 | N/M   | N/M   | N/M   | N/M   |
| 2                    | 21.10 | 21.00 | 23.46 | 22.70 | 25.37 | 24.84 |
| 3                    | 21.09 | 20.88 | N/M   | N/M   | N/M   | N/M   |
| 4                    | 20.50 | 20.68 | 23.21 | 22.59 | 25.37 | 24.58 |
| 5                    | 19.21 | 19.07 | N/M   | N/M   | N/M   | N/M   |
| 6                    | 14.99 | 14.93 | 23.11 | 22.53 | 25.35 | 24.58 |
| 7                    | 11.62 | 12.20 | N/M   | N/M   | N/M   | N/M   |
| 8                    | 9.91  | 10.18 | 22.78 | 22.04 | 24.81 | 23.65 |
| 10                   | 9.51  | 8.35¹ | 22.19 | 21.80 | 24.65 | 23.50 |
| 15                   | 8.78  | 6.96  | 21.56 | 21.47 | 24.43 | 23.11 |
| 20                   | 8.36  | 6.53  | 21.26 | 21.17 | 23.70 | 22.91 |
| 30                   | 7.73  | 5.90  | 20.81 | 20.82 | 23.24 | 21.15 |
| 40                   | 7.49  | 5.50  | 20.33 | 20.31 | 21.70 | 14.17¹ |
| 50                   | 7.13  | 5.07  | 18.92 | 18.84 | 18.15 | 10.57 |
| 60                   | 6.68² | 4.97  | 16.26 | 16.16² | 11.66² | 8.17 |
| 70                   |       | 4.72  | 14.12 |       | 7.72   |       |
| 80                   |       | 4.30  | 12.42² |       | 7.08² |       |
| 100                  |       | 4.02  |       |       |       |       |

**NOTES:**

1. Slight air leakage noted, test continued after stopping leakage.
2. Test terminated due to air leakage.

**NOTES:** N/M - Not Measured
Table 5.2 Summary of Osmotic Desiccation Tests

<table>
<thead>
<tr>
<th>Saturated Salt Solution</th>
<th>Relative Humidity (%)</th>
<th>Total Suction (kPa)</th>
<th>Gravimetric Water Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Beaver Creek Sand</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>LOAD (kPa)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Potassium Sulphate</td>
<td>96.5</td>
<td>5170</td>
<td>1.33</td>
</tr>
<tr>
<td>Sodium Chloride</td>
<td>74.9</td>
<td>41900</td>
<td>0.87</td>
</tr>
<tr>
<td>Magnesium Nitrate</td>
<td>49.9</td>
<td>100900</td>
<td>0.65</td>
</tr>
<tr>
<td>Magnesium Chloride</td>
<td>32.1</td>
<td>164900</td>
<td>0.57</td>
</tr>
<tr>
<td>Lithium Chloride</td>
<td>11.2</td>
<td>317600</td>
<td>0.34</td>
</tr>
</tbody>
</table>
Figure 5.3  Moisture Retention Test Results
The moisture retention curves for the two consolidation pressures in the Beaver Creek sand were practically identical in the suction range of 0 to 10 kPa, determined in the detailed low suction testing; however, a consistent water content difference of approximately 2 percent was measured by the Tempe Cell tests in the range of 15 kPa to 100 kPa. This difference may have been due to slight differences in initial sample preparation or air leakage from the Tempe cell. The difference may also be caused by minor errors in the final water content determination. Any error in determining the final water content propagates to all lower suction values since the water contents at lower suctions are determined by back-calculation based on the total mass of dry soil and the amount of water expelled during the suction increment.

The difference between the moisture retention curves for the Beaver Creek sand samples consolidated to 5 kPa and 10 kPa measured by the osmotic desiccation tests (approximately 5000 to 320000 kPa total suction) was small.

The moisture retention curves for the natural silt are essentially identical over the range tested by the Tempe cells, with slight differences at suctions below 10 kPa. The sample consolidated to 10 kPa (total stress) was terminated at a matric suction of 60 kPa due to air leakage from the Tempe cell. The osmotic desiccation test water contents for the sample consolidated to 10 kPa are slightly higher than those for the sample consolidated to 5 kPa, except for the sample at a total suction of 164900 kPa.
The moisture retention curves for the processed silt samples differ slightly at suctions from 0 to 20 kPa, but begin to differ significantly at suctions of 30 to 60 kPa. The maximum water content difference between the two samples is approximately 0.075 at suctions of 40 and 50 kPa, and is likely due to air leakage from the sample consolidated to 10 kPa. The moisture retention curves begin to converge again at a suction of 60 kPa. The osmotic desiccation test water contents for the sample consolidated to 5 kPa are lower than the corresponding water contents for the sample consolidated to 10 kPa, except at a total suction of 41900 kPa, where they are equal. The water contents for the sample consolidated to 5 kPa are slightly lower than those for the sample consolidated to 10 kPa.

The results of the osmotic desiccation tests show that the gravimetric water contents for the samples consolidated to 10 kPa are not always lower than the water content of the sample consolidated to 5 kPa, as was generally the case in the Tempe cell test results. Thus, there is no apparent trend between the samples consolidated to 5 kPa and 10 kPa. This may be due to inaccuracies in the water content, or possibly due to non-equilibrium conditions of the samples with the saturated salt solutions. As well, the water content of the sample will begin to change immediately after removal from the desiccator, as the sample will tend to come to equilibrium at the ambient relative humidity. Thus, the mass of the sample will change slightly before it can be weighed. At high water contents, this is not significant; however, for small samples at low water contents, the difference could be noticeable. The samples were weighed as
soon as physically possible after removal from the desiccators to minimize weight changes; however, slight changes in the sample weight were noted during weighing. This may explain part of the difference in water contents between the samples.

The water content differences measured in the osmotic desiccation tests may also be caused in part by air leakage during the Tempe cell portion of the moisture retention testing. Any water loss from the sample that is not due to the changes in suction (such as water vapour removed by the leaking air) tends to change the moisture retention characteristics at higher suctions. This may help to explain why a number of the water contents for the samples consolidated to 10 kPa were higher than the water contents of the samples consolidated to 5 kPa.

5.5 Column Evaporation Tests

The data collected during the column evaporation tests is presented in the following sections. A preliminary analysis of the data from the column evaporation tests indicated that in general, the behaviour of the columns with silt at the surface was different than the behaviour of the columns with sand at the surface. Three of the columns with silt at the surface (homogeneous natural silt, processed silt over sand and multi-layered silt and sand) maintained relatively high rates of evaporation (greater than 70 percent of the potential evaporation rate) throughout the duration of the Constant Head Phase of the column evaporation tests, and maintained high water contents with depth, except for a shallow zone at the surface. The evaporation
rate for the fourth column with silt at the surface (homogeneous processed silt) decreased to 41 percent of the potential evaporation rate at the end of the CHBC phase of the column evaporation tests. The depth of significant decrease in water content for this column was approximately 60 to 80 mm at the end of the CHBC. In comparison, the evaporation rate for the columns with sand at the surface (homogeneous sand; and sand overlying processed silt) had dropped below 35 percent of the potential evaporation rate by the end of the constant head phase of the column evaporation tests, and significant decreases in water content had occurred throughout the depth of sand in the column.

As mentioned in the previous paragraph, the behaviour of the columns with sand at the surface was different than that of the columns with silt at the surface. However, the behaviour of the homogeneous processed silt column differed from that of the homogeneous natural silt column with respect to evaporation rates. The evaporation rate for the homogeneous processed silt column had dropped to 41 percent of the potential evaporation rate at the end of the constant head boundary condition portion of the column evaporation tests, compared to 74 percent for the homogeneous natural silt column. The differences in behaviour will be described in detail in later sections. This difference in behaviour was unexpected, and a possible explanation of this behaviour is presented below.
During the column evaporation tests it was noted that the water reservoir for the homogeneous natural silt column fell from its support during the Constant Head Phase of the test (cause unknown), shortly before the behaviour of these two columns began to deviate. This may have caused some air-locking of the system, preventing sufficient water from entering the column to supply the evaporative demand. As well, a crack developed at the surface of the processed silt column, in the vicinity of the uppermost tensiometer. It appeared that the soil had consolidated slightly and arched around the tensiometer, causing the crack at the surface. This may have caused the development of a "capillary break" in the column, preventing water from reaching the evaporative surface. These factors would explain the difference in behaviour between the two homogeneous silt columns.

To investigate the observed difference in behaviour between the processed silt column and the natural silt column, two additional, identical homogeneous processed silt columns were prepared in the same manner as described in Section 4.6. The main parameter of concern for these supplementary columns was the evaporation rate. A constant head boundary condition was imposed at the base of the supplementary columns. The applied constant head was maintained approximately 50 mm above the bottom of the soil, in order to prevent air-locking of the system. No instrumentation was installed in the supplementary columns since the presence of the uppermost tensiometer may have caused the formation of a capillary break in the original processed silt column.
The supplementary homogeneous processed silt columns were allowed to evaporate in the environmental chamber under a constant head boundary condition for a period of approximately 30 days. The water content profile in the column was determined at the end of the test. No other water content profile testing was performed on these columns. The results from these supplementary columns are discussed in the subsequent sections, along with the results of the original columns.

The behaviour of the columns was affected by the boundary condition imposed at the base of the column (either constant head, or zero flux). Thus, some of the data from the column evaporation tests will be presented separately for the columns with sand at the surface and those with silt at the surface, with a further distinction made on the basis of the boundary condition (either constant head or zero flux) at the base of the column. It is important to note that since there was continuity between the Constant Head Boundary Condition Phase and the Zero Flux Boundary Condition Phase of the column evaporation tests (i.e. at the end of the constant head phase, the water supply was removed and the zero flux phase was initiated), the final conditions for the Constant Head phase correspond to the initial conditions for the Zero Flux Phase of the tests.
5.5.1 Evaporation Rates

The evaporation rates from the soil filled columns and the water filled reference pans were determined by measuring their change in mass with respect to time. The evaporation from the soil filled columns consisted of two independently measured components: water loss from the constant head reservoir, and water loss from the soil. The change in mass of the water filled reference evaporation pans and the soil filled columns was converted to a daily evaporation rate (mm/day) so that the results from the various columns could be compared directly. The evaporation rates from the various columns ("actual evaporation") and their respective reference pans ("potential evaporation") for the constant head boundary condition and the zero flux boundary condition are summarized in the following sections.

Potential Evaporation Rates

The temperature in the test chamber was maintained at a temperature of approximately 36 ± 1.5 °C during the column evaporation tests. The relative humidity during the column evaporation tests varied from 7.6 to 14 percent, with an average of 11.1 percent. During the supplementary column tests (homogeneous processed silt columns only) the temperature range was 34.6 to 36.1 °C, and the relative humidity range was 10.8 to 19.4 percent. The average daily temperature and relative humidity values are summarized in Appendix B.
The potential evaporation rates (as measured from the change in mass of the water filled pans with respect to time) for the column evaporation tests are shown in Figure 5.4. This figure presents the potential evaporation rates during both the CHBC and ZFBC periods. The average potential evaporation rate for the supplementary columns are also shown on Figure 5.4. The potential evaporation rates are summarized in tabular form in Appendix C.
Figure 5.4 Potential Evaporation Rates (mm/Day) During the Column Evaporation Tests
Figure 5.4 shows that the potential evaporation rates varied from approximately 4.0 mm/day to 6.6 mm/day. The majority of the columns were subjected to a narrow range of potential evaporation rates, ranging from about 4.4 to 5.2 mm/day. The potential evaporation rates for the homogeneous Beaver Creek sand column and the homogeneous processed silt column were consistently higher than the other columns, ranging from approximately 5 mm/day to 6.6 mm/day. This is due to micro-climatic variations within the chamber caused by the presence of a small circulating fan at the back of the chamber. The two columns previously mentioned were located closest to this fan, and the increased air circulation caused the higher potential evaporation rates. The general increase in potential evaporation rates during the zero flux boundary condition phase of the tests is the result of generally lower ambient relative humidities during this period.

Actual Evaporation

The actual evaporation rate data from the column evaporation tests is presented in Figures 5.5 and 5.6. The evaporation rate data is shown as the ratio between the actual evaporation rate (A.E.) and the potential evaporation rate (P.E.) in order to normalize the data. The ratio of actual evaporation to potential evaporation (A.E./P.E.) will be referred to as the "evaporation ratio" in following sections. The data for both the Constant Head Phase and the Zero Flux Phase are shown on the same plot to illustrate the influence of the change in the boundary condition at the
base of the column. The actual evaporation rate is based on the sum of the change in mass from the constant head reservoir and the change in mass from the soil in the column.

Figure 5.5 shows the evaporation ratios for the columns with Beaver Creek sand at the surface. The actual and potential evaporation rates, along with the evaporation ratios are summarized in Appendix C. The evaporation ratios for the columns with silt at the surface (both natural and processed silt), including the supplementary homogeneous processed silt columns are shown in Figure 5.6.

Figures 5.5 and 5.6 illustrate the previously mentioned difference in behaviour between the columns with sand at the surface and those with silt at the surface. The evaporation ratios for the columns with sand at the surface showed a significant decrease in the evaporation ratio at the end of the constant head boundary condition phase of the tests (i.e., A.E./P.E. = 0.2 to 0.3), while those with silt at the surface maintained higher evaporation ratios (approximate A.E./P.E. = 0.8). The exception was the homogeneous processed silt column, in which the evaporation ratio decreased during the constant head boundary condition phase of the tests, although it did not decrease as much as the evaporation ratio for the sand-surfaced columns.
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Figure 5.5  Evaporation Ratio for the Columns with Beaver Creek Sand at the Surface
Figure 5.6 Evaporation Ratio for the Columns with Silt at the Surface
The evaporation ratios for the supplementary homogeneous processed silt columns (Figure 5.6) also decrease under a constant head boundary condition; however, the evaporation ratio at the end of the constant head boundary condition for the supplementary columns was approximately 0.6, compared to approximately 0.4 for the original column. A portion of the difference in evaporation ratios between the original homogeneous processed silt column and the supplementary silt columns is due to the marginally higher water table level for the supplementary columns; however, it is unlikely that this accounts for the entire difference. The results of the supplementary columns confirm that the evaporation ratios for the silt-surfaced columns are different than those for the sand-surfaced columns.

5.5.2 Soil Temperature Measurements

The following sections present the soil temperature measurements obtained from the thermocouples. The temperature measurements for selected thermocouple depths are shown as a function of time in Figures 5.7 to 5.12. Detailed temperature data is included in Appendix D, along with temperature vs depth plots for selected times during the column evaporation tests. Some of the thermocouple wires and/or connectors broke during the column evaporation tests, resulting in some gaps in the data. The thermocouples were repaired whenever possible to minimize the amount of data missed. The temperature data for the various columns indicates that immediately after the start of the test the near-surface temperature decreased due
to the latent heat of evaporation, with a subsequent reduction in temperatures throughout the column as a result of conduction. The temperatures remained depressed, until the soil surface started to dry. As the soil began to dry, the temperatures increased and the evaporation ratio (A.E./P.E.), shown in Figures 5.5 and 5.6 began to decrease.
Figure 5.7  Temperatures at Selected Depths as a Function of Time For the Homogeneous Beaver Creek Sand Column.
Figure 5.8 Temperatures at Selected Depths as a Function of Time For the Column Consisting of 0.3 m Beaver Creek Sand Overlying 0.3 m Processed Silt.
Figure 5.9  Temperatures at Selected Depths as a Function of Time For the Homogeneous Processed Silt Column.
Figure 5.10  Temperatures at Selected Depths as a Function of Time For the Homogeneous Natural Silt Column.
Figure 5.11 Temperatures at Selected Depths as a Function of Time For the Column Composed of 0.3 m Processed Silt Overlying 0.3 m Beaver Creek Sand.
Figure 5.12  Temperatures at Selected Depths as a Function of Time For the Multi-Layered Processed Silt and Sand Column.
5.5.3 Suction Measurements

Suction measurements were obtained from the tensiometers at various times during the column evaporation tests. Unfortunately, a high percentage of the tensiometers failed during the column evaporation tests due to cracking in the plastic tubes, resulting in missing data points. Visible cracks were covered with silicone sealant; however, this did not appear to be very successful in restoring proper tensiometer operation. Although all of the tensiometers did not exhibit visible cracking, their response is also questionable, since the cracks may have occurred inside the column.

It appeared that the residual stresses in the plastic, combined with the stresses imposed as the soil dried (and therefore consolidated) caused the cracking. Researchers using similar tensiometers in subsequent research projects at the University of Saskatchewan have reduced the cracking problems by boiling (annealing) the plastic tubing to remove the residual extrusion stresses.

Obtaining tensiometer readings at very low suction levels (less than approximately 5 kPa) was difficult, since the readings were influenced by small movements of the Tensimeter probe. The Tensimeter probe was inserted in the tensiometers for several minutes in these cases to improve the accuracy of the readings obtained.

The suction measurements from the column evaporation tests are presented in Figures 5.13 to 5.16 as functions of time. The suctions for the columns with sand at the surface are shown in Figures 5.13 and 5.14, with the results for the columns with...
silt at the surface shown in Figures 5.15 to 5.16. As previously described in Section 4.6.2, no tensiometers were installed in the natural silt column or the multi-layered sand and silt column. Therefore, measured suctions are only available for two of the four columns with silt at the surface: the homogeneous processed silt column, and the column composed of processed silt overlying sand. The suction measurements from the tensiometers are included in Appendix E.

The tensiometer located at a depth of 100 mm in the Homogeneous Beaver Creek sand column (Figure 5.13) was visibly cracked; thus, the results are not reliable. The tensiometer at a depth of 40 mm showed a suction increase near the end of the zero flux boundary condition phase of the test; however, it also cracked near the end of the test. The tensiometers at depths of 280 mm and 400 mm were not visibly cracked, and appeared to give reasonable results.
Figure 5.13 Suction Measurements From The Tensiometers as a Function of Time For the Homogeneous Beaver Creek Sand Column.

**NOTE:** DUE TO CRACKING, THE TENSIOMETER READINGS MAY NOT BE RELIABLE
Figure 5.14  Suction Measurements From the Tensiometers as a Function of Time For the Column Composed of 0.3 m Beaver Creek Sand Overlying 0.3 m Processed Silt.
The tensiometers at depths of 40 mm and 100 mm in the sand over silt column (Figure 5.14) developed cracks, thus the readings are not reliable. The rest of the tensiometers appeared to be functional; however, the measured suctions were less than 10 kPa. This creates some question as to the accuracy of the readings, as previously discussed.

The tensiometers in the homogeneous processed silt column (Figure 5.15) showed a good initial response, but the tensiometers at depths of 40 mm, 100 mm and 280 mm failed due to cracking at elapsed times of approximately 30, 10 and 45 days respectively. The tensiometer at a depth of 400 mm was functional throughout the duration of the column evaporation test.

In the column composed of processed silt overlying Beaver Creek sand (Figure 5.16), the tensiometers at depths of 40 mm and 100 mm showed an initial increase in suctions; however, the tensiometer at a depth of 40 mm failed at an elapsed time of approximately 10 days. The septum in the tensiometer at a depth of 100 mm developed a tear at an elapsed time of approximately 20 days, causing the measured suction to become zero. The septum was replaced, and the tensiometer became functional again. The suction measured in the tensiometer at a depth of 100 mm at the end of the zero flux boundary condition phase of the test was approximately 75 percent of the suction determined from the moisture retention curves and the measured water content. The tensiometer at a depth of 280 mm cracked and became
non-functional at an elapsed time of about 5 days. The tensiometers at depths of
320 mm and 500 mm registered suctions throughout the column evaporation tests;
however, the measured suctions were lower than the suctions determined from the
moisture retention curves and the measured water contents. The tensiometer at a
depth of 400 mm cracked at the start of the test, and did not provide any suction
readings.
Figure 5.15 Suction Measurements From The Tensiometers as a Function of Time For the Homogeneous Processed Silt Column.
Figure 5.16 Suction Measurements From the Tensiometers as a Function of Time For the Column Composed of 0.3 m Processed Silt Overlying 0.3 m Beaver Creek Sand.
In summary, the tensiometers provided only limited information due to the high percentage that developed cracks during the test. As a result, the tensiometer readings will not be utilized for further analysis. As previously stated, boiling the plastic tubing prior to fabricating the tensiometers has provided better results in subsequent projects.

5.5.4 Gravimetric Water Content Measurements

The gravimetric water content profiles in the columns were determined at the elapsed times shown in Table 4.4, using the procedure described in Section 4.6. The tares and soil samples were weighed to the nearest 0.0001 gram before and after oven-drying to determine the gravimetric water contents. In addition to the summary plots presented in the following section, the gravimetric water content data is summarized in tabular form in Appendix F. On occasions where water content sampling was performed on alternate sampling ports, values shown on the following gravimetric water content profiles were determined by linear interpolation. Only the measured values are shown in Appendix F.

The initial gravimetric water content profiles from the column evaporation tests indicated that the majority of the measured water contents were higher than the placement water contents. This was probably due to poor initial water content sampling, in which the material at the extreme outside edge of the column was used for the water content sample, to minimize the amount of soil disturbance. It
The gravimetric water content profiles for the columns are shown in Figures 5.17 to 5.28. Two figures are shown for each column; the first one shows the water contents measured during the Constant Head Phase (CHBC), while the second shows the water contents for the same column during the Zero Flux Phase (ZFBC) of the Column evaporation tests. Figures 5.17 to 5.20 show the gravimetric water content profiles for the columns with sand at the surface, while Figures 5.21 to 5.28 show the results for the columns with silt at the surface. The gravimetric water content profiles obtained at an elapsed time of 31 days are shown on both the CHBC plot and the appeared that water content at the extreme edge was higher than near the center of the column due to the presence of free water at the edge of the column upon removal of the rubber stopper. The higher water content at the edge of the column may have been caused by disturbance to the column (vibration) during the sampling process. In addition, due to the high degree of saturation at the start of the column evaporation tests, and the dilative behaviour of the soils used, free water was generated during the sampling process, which caused errors in the measured water contents. Thus, in subsequent water content sampling, extreme care was exercised to minimize vibration to the column during sampling, and the extreme outer edge (approximately 0.5 cm) of material from the column was not used for the water content determination. For the purposes of further analysis, the water content profile obtained at an elapsed time of 1 day into the constant head phase of the column evaporation tests will be utilized as the "initial" water content.

The gravimetric water content profiles for the columns are shown in Figures 5.17 to 5.28. Two figures are shown for each column; the first one shows the water contents measured during the Constant Head Phase (CHBC), while the second shows the water contents for the same column during the Zero Flux Phase (ZFBC) of the Column evaporation tests. Figures 5.17 to 5.20 show the gravimetric water content profiles for the columns with sand at the surface, while Figures 5.21 to 5.28 show the results for the columns with silt at the surface. The gravimetric water content profiles obtained at an elapsed time of 31 days are shown on both the CHBC plot and the
ZFBC plot, to provide a sense of visual continuity. The 31 day profile was the final condition for the CHBC and the initial condition for the ZFBC.

The gravimetric water content profiles for the homogeneous Beaver Creek sand column (Figures 5.17 and 5.18) show a general trend of decreasing water content throughout the depth of the column during the constant head boundary condition phase of the column evaporation tests. A sharp break in the water content profile developed near the surface between an elapsed time of 7 and 14 days, as the water content approaches the residual value and liquid phase flow becomes insignificant. As the surface water content decreases, vapour phase flow becomes dominant. The development of this break in the water content profile approximately corresponds to the decrease in evaporation ratio at approximately 10 days, as shown in Figure 5.17.

During the zero flux boundary condition phase of the column evaporation tests (Figure 5.18), the evaporation rate was less than about 1.5 mm/day, thus the total quantity of water removed from the column during this phase of the test was less than during the constant head boundary condition phase. The gravimetric water content profiles for the zero flux boundary condition phase (Figure 5.18) show small decreases in water content, with the largest changes occurring in the lower portion of the column.
The water content profiles for the homogeneous Beaver Creek sand Column during the ZFBC have anomalously high readings at a depth of 340 mm (see Figure 5.18). It is possible that these anomalous readings are: i) errors in moisture content determination; ii) a thin lense of fines that would naturally have a higher water content than the surrounding sand; or iii) a wet zone caused by leakage from the tensiometer at a depth of 280 mm.

It is unlikely that the anomalous readings are measurement (weighing) errors, since they occurred at the same depth in the column on several different occasions. If tensiometer leakage is the cause, the higher water contents would be expected at a depth of 280 mm (the location of the tensiometer) or 300 mm; and would not be expected at only one elevation. Thus, the most likely explanation is a layer with a higher fines content, or a combination of tensiometer leakage and a higher fines content. However, an examination of the soil from the water content samples, and a visual inspection of the soil from this level at the end of the column evaporation test did not show a distinct lense with a high fines content. Further testing to determine the grain size distribution in this particular zone was not performed.
Figure 5.17 Gravimetric Water Content Profiles For the Homogeneous Beaver Creek Sand Column at Selected Times During the Constant Head Phase of the Column Evaporation Tests.
Figure 5.18 Gravimetric Water Content Profiles For the Homogeneous Beaver Creek Sand Column at Selected Times During the Zero Flux Phase of the Column Evaporation Tests.
The gravimetric water content profiles for the column composed of 0.3 m Beaver Creek sand overlying 0.3 m processed silt (Figures 5.19 and 5.20) showed high initial water contents due to the previously mentioned difficulties in water content sampling. Throughout the constant head boundary condition phase of the tests, only small water content changes occurred in the processed silt, with the majority of the water content change occurring in the Beaver Creek sand layer. A sharp decrease in water content near the surface occurred between elapsed times of 7 and 14 days, as the near-surface water content in the sand approached the residual value. The development of this break corresponds to the decrease in evaporation ratio at an elapsed time of 13 days. At the end of the constant head boundary condition phase of the column evaporation test the water content throughout the Beaver Creek sand layer was less than 10 percent (approaching the residual water content), while the water content in the processed silt was approximately 23 percent, which was only slightly lower than the initial water content of approximately 26 percent.

After the boundary condition at the base of the column was changed to zero flux, the water content throughout the sand continued to decrease, but at a much slower rate than during the constant head boundary condition. The water content in the processed silt remained almost constant, except near the interface with the sand.
Figure 5.19  Gravimetric Water Content Profiles For the Column Composed of 0.3 m Beaver Creek Sand Column Overlying 0.3 m Processed Silt at Selected Times During the Constant Head Phase of the Column Evaporation Tests.
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Figure 5.20  Gravimetric Water Content Profiles For the Column Composed of 0.3 m Beaver Creek Sand Column Overlying 0.3 m Processed Silt at Selected Times During the Zero Flux Phase of the Column Evaporation Tests.
The gravimetric water content profiles for the homogeneous processed silt column show that very small water content changes occurred below a depth of 100 mm during the constant head boundary condition phase of the column evaporation tests (Figure 5.21). A sharp decrease in water content occurred at depths less than 80 mm between an elapsed time of 7 and 14 days, as the water content approached the residual value. Small water content changes occurred throughout the depth of the column between elapsed times of 14 and 31 days during the constant head boundary condition phase of the column evaporation tests.

During the zero flux phase of the test (Figure 5.22), the water content below a depth of approximately 200 mm decreased almost uniformly from 24 percent to approximately 20 percent. At depths above 200 mm, the water contents decreased to a greater degree throughout the zero flux boundary condition phase, indicating the advancement of a drying front.
Figure 5.21 Gravimetric Water Content Profiles For the Homogeneous Processed Silt Column at Selected Times During the Constant Head Phase of the Column Evaporation Tests.
Figure 5.22 Gravimetric Water Content Profiles For the Homogeneous Processed Silt Column at Selected Times During the Zero Flux Phase of the Column Evaporation Tests.
The gravimetric water content profiles for the homogeneous natural silt column showed a decrease from the placement water content to a water content of approximately 20 percent during the constant head boundary condition phase of the test (Figure 5.23). A decrease in water content to approximately 15 percent occurred between the soil surface and a depth of 60 mm. This decrease was not as large as the near-surface water content decrease that occurred in the homogeneous processed silt column during the CHBC. During the zero flux boundary condition phase of the column evaporation test (Figure 5.24), the water content below a depth of 100 mm decreased to consistent water contents between 11 and 13 percent. At depths less than 100 mm, a sharp decrease to a surface water content of approximately 1 percent occurred.
Figure 5.23  Gravimetric Water Content Profiles For the Homogeneous Natural Silt Column at Selected Times During the Constant Head Phase of the Column Evaporation Tests.
Figure 5.24  Gravimetric Water Content Profiles For the Homogeneous Natural Silt Column at Selected Times During the Zero Flux Phase of the Column Evaporation Tests.
The gravimetric water content profiles for the column composed of 0.3 m processed silt overlying 0.3 m Beaver Creek sand show that during the constant head boundary condition phase of the test (Figure 5.25), almost all of the water removed from soil storage came from the sand, since very small water content changes occurred in the processed silt. This trend continued over the first 7 days of the zero flux boundary condition phase of the test (i.e., elapsed time of 31 to 38 days), shown in Figure 5.26. Between elapsed times of 38 and 45 days during the ZFBC, the water content throughout the sand decreased to approximately 8 percent (near the residual water content), and the water content in the processed silt began to decrease. The decrease in the silt water content was sharpest at depths less than 100 mm. The water content in the sand decreased to approximately 5 percent by the end of the ZFBC. The decrease in the evaporation ratio shown in Figure 5.6 occurred at an elapsed time of 45 days, which approximately corresponds to the time when the near surface water content in the silt approached the residual water content.
Figure 5.25  Gravimetric Water Content Profiles For the Column Composed of 0.3 m Processed Silt Overlying 0.3 m Beaver Creek Sand at Selected Times During the Constant Head Phase of the Column Evaporation Tests.
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Figure 5.26 Gravimetric Water Content Profiles For the Column Composed of 0.3 m Processed Silt Overlying 0.3 m Beaver Creek Sand at Selected Times During the Zero Flux Phase of the Column Evaporation Tests.
The gravimetric water contents for the multi-layered silt and sand column showed only small decreases during the constant head boundary condition phase of the column evaporation test (Figure 5.27). During the zero flux boundary condition phase (Figure 5.28), the soil water loss occurred almost entirely from the sand layers. After 7 days at the zero flux boundary condition (i.e., elapsed time of 38 days), the water contents in the sand layers were approaching 10 percent (near the residual water content), and between elapsed times of 38 and 60 days the surficial silt layer began to dry to below the residual water content. The evaporation ratio for this column, shown in Figure 5.6 began to decrease at an elapsed time of approximately 45 days. At the end of the ZFBC, the water content in the lower two silt layers had not decreased significantly from the initial water contents. This is particularly interesting for the silt layer at a depth of 125 mm to 175 mm, which did not dry out even though the sand layers on either side of it were at water contents of approximately 5 percent at the end of the ZFBC phase of the column evaporation test.
Figure 5.27 Gravimetric Water Content Profiles For the Multi-Layered Silt and Sand Column at Selected Times During the Constant Head Phase of the Column Evaporation Tests.
Figure 5.28  Gravimetric Water Content Profiles For the Multi-Layered Silt and Sand Column at Selected Times During the Zero Flux Phase of the Column Evaporation Tests.
5.5.5 Cumulative Flux Components

The design of the column evaporation experiment allowed for the independent determination of the flux from the system as a whole and the flux that was drawn from the constant head water reservoir. The difference between the total system flux and the water reservoir flux is the amount of water removed from soil storage. The amount of water removed from soil storage can also be calculated by multiplying the change in volumetric water content by the total soil volume. This provides a method of checking the reliability of the water content measurements. Figures 5.29 to 5.34 show the cumulative fluxes from the water filled reference pans, the system as a whole, the water reservoir and soil storage. Two curves showing the cumulative loss from soil storage are shown on each plot: one based on the change in column weight, the other based on the change in volumetric water contents. Figures 5.29 to 5.34 are plotted to the same scale to allow easier visual comparison between the various columns.

The plots of cumulative flux components are useful because they illustrate the source of the water that is evaporated from the column (either the water reservoir or soil storage), and they show the development of steady state evaporation conditions as the cumulative flux from soil storage becomes constant. As well, the evaporation rates can be determined from the slopes of the various curves.
The cumulative fluxes in Figures 5.29 to 5.34 show that the reference pan evaporation (potential evaporation) rate was almost constant, since it plots as a straight line. The curves representing the total column (actual evaporation) flux initially plot along the reference pan evaporation line, indicating that the actual evaporation and potential evaporation are approximately equal. As the test progresses and the actual evaporation rate begins to decline, the column flux curves begin to deviate from the reference pan evaporation line. For the columns that showed a significant decrease in the actual evaporation rate, the difference between the potential evaporation curve and the actual evaporation curve continues to increase. However, for the columns where the evaporation rates remained high through the constant head boundary condition portion of the tests, the actual and potential evaporation curves become almost parallel.

For all of the columns except the multi-layered column, the flux from the constant head water reservoir at the base of the column was negligible at the beginning of the test, and the water which evaporated was removed from soil storage. This caused some drying of the soil, increasing the soil suction and resulting in higher upward gradients being established. As evaporation from the column progressed and gradients developed throughout the depth of the column, water was removed from the water reservoir. The flux from the water reservoir increased until it accounted for almost all of the flux from the system, thus the cumulative water loss from the soil
became almost constant (i.e., no additional soil water losses). At this point, the columns were evaporating under (approximately) steady state conditions.

For the multi-layered column, the water loss from soil storage was very small during the CHBC, with almost all of the water lost to evaporation being removed from the constant head reservoir. The multi-layered column achieved steady state evaporation at a shorter elapsed time than the other columns.

The columns were allowed to continue at the steady state evaporation rates for a short period of time before the boundary condition at the bottom of the column was changed from a constant head condition to a zero flux boundary condition.

When the bottom boundary condition was changed from a constant head to a zero flux condition, the water removed from the column by evaporation had to come from soil storage. This resulted in a further decrease in the actual evaporation rate, since as the soil dried, the amount of water available decreased and the hydraulic conductivity decreased. Thus, higher gradients were required to remove water from the soil, gradients that can only be developed by changes in suction. This resulted in even lower hydraulic conductivities, and the evaporation rate continued to decrease.

For the columns that maintained a high evaporation ratio throughout the constant head boundary condition phase of the column evaporation tests (homogeneous natural silt, processed silt overlying Beaver Creek sand, and the multi-layered silt and
sand column), there was a time lag between the imposition of the zero flux boundary condition and the time when the evaporation ratio began to decrease. This was due to the availability of pore water that could be removed from the soil with small changes in suction. Once this readily available water had been removed, large suction increases were required to remove additional pore water. This resulted in surface drying and a decrease in the evaporation ratio.

The two curves representing the cumulative water flux from soil storage (one computed from the measured change in the column weight, the other computed from the change in water content) show reasonably good agreement for all of the columns, although the cumulative losses computed from the change in water content tend to be slightly higher than the measured soil water loss based on the column weight. The difference between the two methods of computing the amount of water loss may be due to small errors in the water content determinations, or variations in void ratio with depth (the void ratio was assumed to be constant in the calculations).

Due to the difficulties encountered in the initial water content sampling (described in Section 5.5.4), the cumulative soil water flux curve calculated from the change in volumetric water content was shifted on the plots to match the curve computed from the change in column weight at an elapsed time of 1 day. The cumulative soil water flux curves for the homogeneous Beaver Creek sand column and the column composed of 0.3 m processed silt overlying 0.3 m Beaver Creek sand were matched.
at an elapsed time of 3 days to obtain good correlation between the two methods for the duration of the column evaporation tests. This indicates that the water content profiles obtained at elapsed times of 0 and 1 day, may not be completely reliable for these two columns.
Figure 5.29  Cumulative Flux Components For the Homogeneous Beaver Creek Sand Column
Figure 5.30  Cumulative Flux Components For the Column Consisting of 0.3 m Beaver Creek Sand Overlying 0.3 m Processed Silt
Figure 5.31 Cumulative Flux Components for the Homogeneous Processed Silt Column
Figure 5.32 Cumulative Flux Components for the Homogeneous Natural Silt Column
Figure 5.33  Cumulative Flux Components for the Column Consisting of 0.3 m Processed Silt Overlying 0.3 m Beaver Creek Sand
Figure 5.34 Cumulative Flux Components for the Multi-Layered Processed Silt and Beaver Creek Sand Column
6.0 ANALYSES AND DISCUSSION

6.1 Introduction

The laboratory testing program was described in Chapter 4, and the results of the testing program were presented in Chapter 5. This chapter presents the analysis and interpretation of the results of the laboratory testing program, and provides a discussion of their significance.

6.2 Moisture Retention Characteristics

Moisture retention curves for the three soil utilized in the laboratory testing program were determined by Tempe cell and osmotic desiccation tests, as described in Section 4.4. Equilibrium water contents for suctions from 0 to 100 kPa were determined by Tempe Cell testing, while osmotic desiccation tests were used to determine the moisture retention characteristics at suctions of approximately 5000 to 320,000 kPa. Moisture retention tests for each soil were performed on samples consolidated to 5 kPa and 10 kPa to assess the effects of preloading. The moisture retention testing was performed in the environmental chamber at the same temperature as the column evaporation tests to minimize temperature effects. The results from the moisture retention testing were presented in Section 5.4. This procedure provided reasonable results; however, a significant gap exists between the highest suction from the Tempe cell tests (100 kPa) and the lowest suction from the vapour equilibrium tests (5170 kPa). This gap could be reduced somewhat by using a porous ceramic with a
higher air entry value, such as 500 kPa in the Tempe cell, or by using a 1500 kPa pressure plate extractor.

It appears that some of the differences between the moisture retention curves for the samples consolidated to 5 kPa and 10 kPa for all three soils used in the laboratory testing program may be due to air leakage from the Tempe cells. Average water contents of the two samples (5 kPa and 10 kPa consolidation pressure) for each soil were used to define the moisture retention curves for further analysis. Due to the air leakage noted in the Tempe cell testing, some potential error exists in the moisture retention curves.

The moisture retention curves that were used for the analysis of the column evaporation tests are shown in Figures 6.1 and 6.2. The values used for the moisture retention curves are included in Appendix A. Moisture retention curves for the Beaver Creek sand, natural silt, and processed silt at suctions less than 100 kPa are shown in Figure 6.1, with moisture retention curves for the entire range of suctions tested shown in Figure 6.2.
Figure 6.1  Moisture Retention Curves for Suctions Less Than 100 kPa
The moisture retention curves have been plotted assuming that the suctions measured in the Tempe cell method represented total suction. In reality, this is not the case, since the suctions determined in the Tempe cell procedure are matric suctions. Thus, the assumption made is that matric suction is equal to total suction.
for the range of 0 to 100 kPa. The points defined by the vapour equilibrium testing represent total suction. The relative components of matric and osmotic suction for the soils were not determined. Krahn (1970) stated that the magnitude of osmotic suction depended on water content and tended to increase as water contents decreased. Wilson (1990), who used an identical approach to determine moisture retention characteristics, noted that it is difficult to predict osmotic suction without direct testing; however, it appears that superimposing osmotic suction on the measured values of matric suction from the Tempe cells would shift the moisture retention curves at low suctions upward slightly.

6.3 Hydraulic Properties of the Soils Used in the Laboratory Testing Program

Several methods have been developed to predict the hydraulic conductivity of a soil as a function of suction by utilizing moisture characteristic curves (i.e., θ (ψ)) (Childs and Collis-George, 1950; Gardner, 1958; Marshall, 1958; Millington and Quirk, 1959, 1960, 1961; Brooks and Corey, 1964; Green and Corey, 1971; Van Genuchten, 1980). The moisture retention curves presented in Figures 6.1 and 6.2, along with the saturated hydraulic conductivity values presented in Section 5.3 (Figure 5.2) were utilized to determine the hydraulic conductivity functions of the soils by the method proposed by Brooks and Corey (1964) (Equations 3.3 and 3.4). The gravimetric water contents on the moisture retention curves were converted to volumetric water contents using the water content at zero matric suction and the specific gravity values
shown in Table 4.1 to calculate the porosity of the soils. The residual saturation \( S_r \) was determined using the trial and error method described by Laliberte et al (1968), which was also discussed in Section 3.3.

Figure 6.3 shows the plots of log effective saturation \( (S_e) \) versus log suction used to determine the AEV and pore-size distribution index for the Beaver Creek sand, natural silt and processed silt. The hydraulic conductivity parameters determined from this analysis are summarized in Table 6.1, with the resulting hydraulic conductivity functions using the Brooks and Corey (1964) method (Equations 3.3 and 3.4) shown in Figure 6.4.

Laliberte et al (1968) point out that the relationship for the hydraulic conductivity of a soil as proposed by Brooks and Corey (1964) is valid only for water contents above the residual saturation \( S_r \). It is important to note that the residual saturation value determined by this method is essentially a curve-fitting parameter.

The hydraulic conductivity computed by the method proposed by Brooks and Corey (1964) accounts only for flow in the liquid phase. Vapour diffusion becomes more significant as the soil becomes progressively drier.
Figure 6.3  Effective Saturation as a Function of Suction for the Soils Used in the Laboratory Testing Program
Table 6.1  Summary of Hydraulic Conductivity Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Beaver Creek Sand</th>
<th>Processed Silt</th>
<th>Natural Silt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturated Hydraulic Conductivity, $k_{SAT}$ (m/s)</td>
<td>$4.26 \times 10^6$</td>
<td>$8.36 \times 10^9$</td>
<td>$2.07 \times 10^8$</td>
</tr>
<tr>
<td>Air Entry Value (kPa)</td>
<td>4.6</td>
<td>34</td>
<td>46</td>
</tr>
<tr>
<td>Pore Size Distribution Index, L</td>
<td>2.5</td>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td>Saturated Water Content (Volumetric)</td>
<td>0.347</td>
<td>0.408</td>
<td>0.409</td>
</tr>
<tr>
<td>Saturated Water Content (Gravimetric)</td>
<td>0.212</td>
<td>0.255</td>
<td>0.233</td>
</tr>
<tr>
<td>Residual Saturation, $S_r$</td>
<td>0.26</td>
<td>0.11</td>
<td>0.10</td>
</tr>
<tr>
<td>Grav. Water Content at $S_r$</td>
<td>0.055</td>
<td>0.028</td>
<td>0.023</td>
</tr>
</tbody>
</table>

NOTE: $S_r$ determined by the method of Laliberte et al (1968)
Figure 6.4  Hydraulic Conductivity Functions of the Soils Used in the Laboratory Testing Program (Based on the parameters shown in Table 6.1)
6.4 Kisch (1959) Method of Computing Pressure Profiles

The Kisch (1959) method of computing steady state pressure profiles (discussed in Section 3.5) was used to perform a sensitivity analysis with respect to evaporation. This method was originally proposed for computing pressure profiles under conditions of steady state infiltration; however, it is also applicable for evaporative fluxes. The condition of steady state evaporative fluxes is unlikely to be met under realistic field conditions; however, this method of analysis can provide valuable insight into the behaviour of various soil systems under long term evaporative fluxes. The condition of steady state evaporative flux can be considered as an extreme boundary condition. Under long term evaporative fluxes, the evaporation rate would likely be controlled by the rate of vapour diffusion through an extremely dry zone at the surface, described as residual rate drying (see Figure 2.1).

The Kisch (1959) method of computing pressure profiles was used to perform a series of sensitivity analyses to examine the effects of variations in the hydraulic conductivity function parameters (saturated hydraulic conductivity, $k_{sat}$; air entry value, AEV; and pore size distribution index, L) on evaporative fluxes. The relative effect of changes in individual parameters on soil systems subjected to steady state evaporative conditions was assessed by computing the maximum steady state evaporation rate that could be sustained for a given set of soil parameters. For a true sensitivity analysis, the range of values used for each parameter should be based on statistical analysis or confidence limits to provide a consistent comparison of the
This method was implemented in a spreadsheet, a technique which provided very fast solution times, and made manipulation and graphical output of the results relatively simple.

A "base case" set of parameters for each soil was used to establish a benchmark evaporation rate for each of the soil combinations analyzed. The "base case" parameters were established from the measured laboratory values and are summarized in Table 6.2.

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This method was implemented in a spreadsheet, a technique which provided very fast solution times, and made manipulation and graphical output of the results relatively simple.
b, and n are constants.

maximum evaporation rates from soils; however, he used a limiting condition of

\[ k = a/(S^n + b), \]

where \( k = \) hydraulic conductivity, \( S = \) suction head \((\psi/\rho g)\), and \( a, b, \) and \( n \) are constants.

Figure 6.5 shows a typical steady state pressure head plot for an evaporative flux calculated using the Kisch (1959) method. The pressure head plot shows a sharp break near the soil surface, indicating that the difference in maximum evaporation rates for the assumptions regarding the limiting surface suction made by Wilson (1990) and Gardner (1958) for a given water table depth would be small.

<table>
<thead>
<tr>
<th>Table 6.2</th>
<th>Range of Parameters Used in Sensitivity Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Beaver Creek Sand</td>
</tr>
<tr>
<td>( k_{sat} ) (m/s)</td>
<td>( 1 \times 10^{-6} )</td>
</tr>
<tr>
<td>AEV (kPa)</td>
<td>2</td>
</tr>
<tr>
<td>L</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The maximum evaporation rate, used as the basis for comparison in the sensitivity analyses, was computed based on the observation made by Wilson (1990) that evaporation rates began to decline once the total suction at the surface exceeded approximately 3000 kPa. Gardner (1958) used a similar approach to computing maximum evaporation rates from soils; however, he used a limiting condition of infinite surface suction and a hydraulic conductivity function of the form
Figure 6.5 Typical Pressure Profile Using the Kisch (1959) Method for Evaporative Conditions.

0.3 m SAND OVERLAIN BY SILT:
q (evap) = 4 mm/day

SAND PARAMETERS
k (sat.) = 4.26E-6 m/s
AEV = 3.8 kPa
L = 2.5

SILT PARAMETERS
k (sat.) = 8.36E-9 m/s
AEV = 34 kPa
L = 2.0
Soil layering combinations corresponding to the 6 columns used in the column evaporation tests were analyzed using this procedure. In all cases, the total height of the soil column used in the sensitivity analysis was 0.6 m. A "base case" evaporation rate was computed for each soil configuration using the measured laboratory values of $k_{sat}$, AEV and L for the soils (see Table 6.2). A constant head boundary condition of zero pressure head (i.e., a water table) was imposed at the base of the soil. This method cannot be applied to a zero flux base boundary condition since steady state evaporative conditions will not develop.

The results of this sensitivity analysis are shown in Figures 6.6 to 6.11. These plots are sometimes referred to as "tornado plots", due to the visible funnel shape that results by arranging the order of the results from least sensitivity to greatest sensitivity (vertically ascending). The horizontal lines on the tornado plots show the variation in the maximum evaporation rate for the range of the parameter indicated on the plot, with the other parameters being held constant at the base case values. The tornado plots show an evaporation rate range of 0.1 mm/day to 100 mm/day to illustrate the range obtained from the sensitivity analysis; however, it is important to note that a reasonable range of evaporation rates under natural conditions would be zero to approximately 10 mm/day.
The results of the sensitivity analysis indicate that for the homogeneous Beaver Creek sand column (Figure 6.6), the ranking of parameters in terms of sensitivity from most to least sensitive is AEV, saturated hydraulic conductivity, and pore size distribution index. A variation of 2 kPa (from 4 to 6 kPa) in the air entry value for the Beaver Creek sand has a greater effect on the maximum evaporation rate than an order of magnitude change in the saturated hydraulic conductivity (from $1 \times 10^{-6}$ to $1 \times 10^{-5}$ m/s). The effect of the pore size distribution index (L) on the maximum evaporation rate is significantly less than the effect of the other 2 parameters.

The "base case" maximum evaporation rate for the homogeneous Beaver Creek sand column (24.3 mm/day) is greater than the potential evaporation rate observed during the column evaporation test (approximately 5.5 mm/day). On this basis, it would appear that the homogenous sand column should have been able to sustain an actual evaporation rate equal to the potential evaporation rate. This does not agree with the observed laboratory behaviour, since the actual evaporation rate at the end of the CHBC (which was approximately a condition of steady state evaporation) was 1.66 mm/day, less than the potential evaporation rate. However, if the air entry value and pore size distribution index for Beaver Creek sand measured by Wilson (1990) are used (i.e. $k_{sat} = 3.9 \times 10^{-6}$ m/s, AEV = 3.8 kPa, L = 3.0), the computed maximum evaporation rate is 2.53 mm/day. Based on these parameters, the homogeneous sand column would not sustain the full potential evaporation rate, and the behaviour would be reasonably close to the observed laboratory behaviour. The
difference between Wilson's (1990) moisture retention parameters, and the parameters determined in this research is that Wilson's Tempe cell tests were performed on slurried samples, while the samples used in this research were consolidated prior to testing. If the difference in the measured parameters can be attributed to consolidation, then the parameters measured by Wilson (1990) may be more applicable for this type of analysis, since the Beaver Creek sand at the surface of the soil column was only subjected to a consolidation pressure of about 0.1 kPa, and Wilson (1990) showed that evaporation was controlled by a thin layer at the soil surface. Thus, the observed behaviour of the homogeneous Beaver Creek sand column in the column evaporation test can be reasonably explained using the Kisch (1959) method.
Figure 6.6  Sensitivity Analysis ("Tornado Plot") for Homogeneous Beaver Creek Sand

NOTE: VALUES IN BRACKETS REPRESENT INDIVIDUAL DATA POINTS (FROM LEFT TO RIGHT)  
* INDICATES BASE CASE VALUE

AEV (kPa)  
(2, 3, 3.8, 4, 4.6*, 5, 6)

TO 0.013 mm/DAY  
@ AEV = 2 kPa

SAT. k (m/s)  
(1E-6, 4.26E-6*, 1E-5, 1E-4)

TO 571 mm/DAY  
@ k = 1E-4 m/s

L  
(4, 3, 2.5*, 2, 1.5)

EVAP. RATE AT END OF C.H.B.C.  
= 1.66 mm/DAY

BASE CASE  
(24.3 mm/DAY)

MAXIMUM EVAPORATION RATE (mm/DAY)
For the layered system consisting of 0.3 m Beaver Creek sand overlying 0.3 m processed silt (Figure 6.7), the saturated hydraulic conductivity of the silt has the greatest influence on the maximum evaporation rate, a range of about 3.8 mm/day for the range of \( k_{sat} \) examined. All of the hydraulic properties of the sand (saturated hydraulic conductivity, air entry value, and pore size distribution index) have a noticeable influence on the maximum evaporation rate; however, the range of evaporation rates for these parameters is only about 1 mm/day. The air entry value and pore size distribution index of the silt have essentially no effect on the maximum evaporation rate. The computed range of maximum evaporation rates for this column was very small (approximately 4.0 mm/day) compared to the other columns.

The "base case" evaporation rate for the column consisting of 0.3 m Beaver Creek sand overlying 0.3 m Processed Silt (0.73 mm/day) was less than the potential evaporation rate, thus the surface of the column would be expected to dry and desiccate. This corresponded to the observed behaviour in the column evaporation test, since the evaporation rate at the end of the CHBC was 0.96 mm/day.
Figure 6.7 Sensitivity Analysis ("Tornado Plot") for 0.3 m Beaver Creek Sand Overlying 0.3 m Processed Silt
The sensitivity analysis for the homogeneous processed silt soil profile (Figure 6.8) indicated that variations in the saturated hydraulic conductivity had the greatest effect on the maximum evaporative flux. The effect of the air entry value for the processed silt was much smaller. By varying the air entry value over a range of 30 kPa, the change in maximum evaporative flux was approximately 4 mm/day, compared to a change of more than 40 mm/day for an order of magnitude change in the saturated hydraulic conductivity. Changes in the pore size distribution index for the processed silt caused very small changes in the maximum evaporation rate. The "base case" evaporation rate for the homogeneous processed silt column was 3.78 mm/day, which was less than the potential evaporation rate in the column evaporation tests; therefore, the silt surface would be expected to dry. The evaporation rate at the end of the CHBC was 2.19 mm/day; thus, the base case of the sensitivity analysis agrees rather well with the observed behaviour in the column evaporation tests.

The sensitivity analysis for the homogeneous natural silt column (Figure 6.9) showed the same ranking of parameters in terms of sensitivity as the homogeneous processed silt; however, the base case evaporation rate was 13.74 mm/day. Since this base case evaporation rate is greater than the potential evaporation rate, the homogeneous natural silt column would be expected to maintain a high evaporation rate, as was observed in the column evaporation tests. The observed evaporation rate at the end of the CHBC was 3.59 mm/day.
Figure 6.8 Sensitivity Analysis ("Tornado Plot") for Homogeneous Processed Silt
Chapter 6: Data Analyses and Discussion

Figure 6.9 Sensitivity Analysis ("Tornado Plot") for Homogeneous Natural Silt

**NOTE:** NUMBERS IN BRACKETS REPRESENT INDIVIDUAL DATA POINTS (FROM LEFT TO RIGHT) * INDICATES BASE CASE VALUE

- SAT. k (m/s) 
  - (5E-9, 1E-8, 2.07E-8*, 1E-7)

- AEV (kPa) 
  - (30, 40, 46*, 50, 60)

- L 
  - (3, 2, 1.5*, 1)

- EVAP. RATE AT END OF C.H.B.C 
  - 3.59 mm/DAY

- BASE CASE 
  - (13.74 mm/DAY)
For the layered column consisting of 0.3 m processed silt overlying 0.3 m of Beaver Creek sand (Figure 6.10), the saturated hydraulic conductivity and air entry value of the silt had a noticeable effect on the maximum evaporation rate, while the pore size distribution index of the silt and all of the sand parameters have a negligible effect. The "base case" evaporation rate for this column (7.83 mm/day) was greater than the potential evaporation rate from the column evaporation tests; therefore, the column would be expected to maintain a high evaporation rate, which corresponded to the observed laboratory behaviour (evaporation rate of 3.79 mm/day at the end of the CHBC).

The sensitivity analysis for the multi-layered silt and sand column (Figure 6.11) indicated that the saturated hydraulic conductivity of the silt had the greatest effect on the maximum evaporation rate. The hydraulic properties of the sand also had a noticeable influence on the maximum evaporation rate; however, the air entry value and pore size distribution index of the silt had no effect. The computed range of maximum evaporation rates for this column was approximately 12.5 mm/day, a smaller range than the other columns, except for the column consisting of sand overlying silt.
The "base case" evaporation rate for the multi-layered column was 2.48 mm/day; however, the laboratory evaporation rate at the end of the constant head boundary condition phase for the multi-layered silt and sand column was 3.9 mm/day. The parametric analysis indicated that an evaporation rate of 4 mm/day could be sustained if the saturated hydraulic conductivity of the silt was approximately $1.65 \times 10^{-8}$ m/s, slightly higher than the "base case" value ($8.36 \times 10^{-9}$ m/s). Thus, the behaviour of the multi-layered silt and sand column can also be reasonably explained by the parametric analysis.

The parametric analysis using the Kisch (1959) method of computing pressure profiles was relatively successful at explaining the behaviour observed in the column evaporation tests, even though the method is limited to liquid flux. The parametric analysis indicated that the parameter with the greatest influence on the maximum evaporation rate is the saturated hydraulic conductivity. Part of the reason for this is that the saturated hydraulic conductivity for a given soil type may vary by one or two orders of magnitude, a larger range than the other pertinent variables (air entry value and pore size distribution index). The air entry value of the Beaver Creek sand had a noticeable effect on the maximum evaporation rate for the cases examined.

The geometry of the soil system also plays a significant role in determining the parameters that will effect the evaporation rate. For instance, the analysis for the column consisting of 0.3 m of processed silt overlying 0.3 m of Beaver Creek sand
indicated that the air entry value and pore-size distribution index of the sand had very little influence on the maximum evaporation rate. However, if the soil geometry consisted of a thicker layer of Beaver Creek sand (say 1.0 m) the influence of the sand parameters would be much greater, since the suction in the upper portion of the sand would be greater than the AEV, with a lower degree of saturation (and thus a lower hydraulic conductivity) than a 0.3 m thick layer.
Figure 6.10  Sensitivity Analysis ("Tornado Plot") for 0.3 m Processed Silt Overlying 0.3 m Beaver Creek Sand
Figure 6.11  Sensitivity Analysis ("Tornado Plot") for the Multi-Layered Silt and Sand Column

NOTE: VALUES IN BRACKETS REPRESENT INDIVIDUAL DATA POINTS (FROM LEFT TO RIGHT)
* INDICATES BASE CASE VALUE

MAXIMUM EVAPORATION RATE (mm/DAY)

EVAP. RATE AT END OF C.H.B.C = 3.90 mm/DAY

BASE CASE (2.48 mm/DAY)

TO 0.035 mm/DAY @ AEV = 2 kPa

SAT. k (m/s): (SILT)
(5E-9, 8.36E-9*, 1E-8, 1E-7)

AEV (kPa): (SILT)
(20, 30, 34*, 40, 50)

SAT. k (m/s): (SAND)
(1E-6, 4.26E-6*, 1E-5, 1E-4)

L: (SAND)
(4, 3, 2.5*, 2, 1.5)

AEV (kPa): (SAND)
(2, 3, 3.8, 4, 4.6*, 5, 6)

L: (SILT)
(3, 2*, 1)
6.5 Dominant Flux Mechanism and Drying Front Development

The previous analyses using the Kisch (1959) method considers liquid phase flow only. The analysis presented in this section was performed to determine the thickness and location of the zones dominated by liquid flux and vapour flux for the column evaporation tests. The thickness and location of the transition zone, where both liquid and vapour flux occur was also determined. The zone where vapour flux is dominant can be considered to represent a "drying front".

The dominant flux mechanism was determined using the moisture retention curves and the measured gravimetric water content profiles, along with the temperature profiles. A schematic moisture retention curve can be considered to consist of three zones, as illustrated in Figure 6.12. The first zone (Zone 1) is relatively flat, and extends from zero suction to the air entry value. In this zone, the voids in the soil are full of water, and thus, all flow must occur in the liquid phase. Zone 2 has a relatively steep slope, and extends from the air entry value to a point where the soil begins to approach the residual water content. In Zone 2 the soil voids are rapidly dewatering, thus, it is reasonable to assume that the flux is primarily due to liquid flow. Zone 3 is another relatively flat portion of the moisture retention curve, extending from the end of Zone 2 to very high suctions. In this range the soil is at a low degree of saturation, and flow is occurring in both the liquid and vapour phases (i.e., a transition zone from liquid to vapour flow). At some point in Zone 3, liquid flow essentially ceases, and vapour flow becomes the dominant flux mechanism. This
point can not be exactly defined; however, soil scientists have denoted a suction of 1500 kPa as the "permanent wilting point" for plants, and the majority of flow beyond this suction is due to the vapour phase. Wilson (1990) found that evaporation rates began to decline once the surface suction exceeded approximately 3000 kPa, which is also an indication of vapour dominant flow. For this analysis, it was assumed that vapour flux was dominant at suctions above 3000 kPa. The soil water content at 3000 kPa is not much smaller than the water content at 1500 kPa; therefore the choice of 3000 kPa does not make a significant difference in this analysis.

The analysis was conducted by determining a range of water contents representing a liquid flux zone, vapour flux zone, and a transition zone for each soil based on the moisture retention curves and the previous discussion. The gravimetric water content ranges for the various flux mechanisms are shown in Table 6.3. The measured water content profiles from the column evaporation tests were then used to determine the dominant flux mechanisms with depth through the column profile at the elapsed times corresponding to the water content measurements.
The temperature profiles included in Appendix D were used in conjunction with the water content profiles to determine the location of the drying front. As the flux mechanism changes from liquid flow to vapour flow, the latent heat flux in the vapour dominated zone decreases, with a resultant temperature increase. Due to the spacing of the thermocouples, combined with the late development and shallow depth of the drying front in some of the columns, the temperature profiles were of limited usefulness.
The results of this analysis are shown on Figures 6.13 to 6.18, which show the computed location and thickness of the liquid flux, vapour flux, and transition zones within the soil columns used in the column evaporation tests.

Figures 6.13 to 6.18 indicate that liquid flow was the dominant flux mechanism in the majority of the soil throughout the duration of the column evaporation tests. A vapour flux dominated zone developed in all of the columns by the end of the tests. The vapour flux dominated zone developed earlier in the columns with sand on the surface than the columns with silt at the surface. The thickness of the vapour flux zone ranged from 20 to 60 mm; however, the thickness of the vapour flux zone at the end of the column evaporation tests was not greatly different between the columns.

Table 6.3 Water Content Ranges Used to Determine Dominant Flux Mechanism

<table>
<thead>
<tr>
<th>FLUX MECHANISM</th>
<th>RANGE OF GRAVIMETRIC WATER CONTENTS (PERCENT) FOR GIVEN FLUX MECHANISM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Flow (Zone 1)</td>
<td>W.C. &gt; 7.5</td>
</tr>
<tr>
<td>Transition Zone (Zone 2)</td>
<td>7.5 ≥ W.C. ≥ 2.75</td>
</tr>
<tr>
<td>Vapour Flow (Zone 3)</td>
<td>W.C. &lt; 2.75</td>
</tr>
</tbody>
</table>
with sand at the surface and those with silt at the surface. The thickness of the transition zone from liquid to vapour flux was larger in the sand than in the silt. It is interesting to note that for the layered columns with silt at the surface (i.e. silt overlying sand, and the multi-layered column) transition flux zones developed in the sand layers while the flow in the overlying silt was still primarily dominated by liquid flux.

The development of a vapour flux zone approximately coincided with the time at which the evaporation ratio began to decrease (see Figures 5.5 and 5.6). The columns consisting of homogeneous sand, homogeneous silt, and sand overlying silt developed a vapour flux zone during the constant head boundary condition phase of the column evaporation tests, while the other columns were essentially completely dominated by liquid flux throughout the constant head boundary condition.

During the zero flux boundary condition, the thickness of the vapour flux zone continued to increase. For the columns that did not develop a vapour flux zone during the constant head boundary condition, there was a significant time lapse (10 to 15 days) between the imposition of the zero flux boundary condition and the development of the vapour flux zone.
Figure 6.13 Dominant Flux Mechanisms for the Homogeneous Beaver Creek Sand Column During the Column Evaporation Tests
Figure 6.14 Dominant Flux Mechanisms for the Column Composed of 0.3 m Beaver Creek Sand Overlying 0.3 m Processed Silt During the Column Evaporation Tests
Figure 6.15 Dominant Flux Mechanisms for the Homogeneous Processed Silt Column During the Column Evaporation Tests
Figure 6.16  Dominant Flux Mechanism for the Homogeneous Natural Silt Column During the Column Evaporation Tests
Chapter 6: Data Analyses and Discussion

Figure 6.17 Dominant Flux Mechanisms for the Column Composed of 0.3 m Processed Silt Overlying 0.3 m Beaver Creek Sand During the Column Evaporation Tests
Figure 6.18 Dominant Flux Mechanism for the Multi-layered Processed Silt and Beaver Creek Sand Column During the Column Evaporation Tests
6.6 Evaporation Ratio (AE/PE) Versus Surface Suction

Wilson (1990) observed that evaporative suppression occurred once the total suction at the soil surface exceeded approximately 3000 kPa. This observation was independent of soil type and was similar for three texturally distinct soils (i.e., sand, silt and clay) that he tested. Figure 6.19 shows the relationship between the evaporation ratio and the suction at the surface (determined from the moisture retention curves and the measured water contents) for all of the columns in the laboratory testing program.

Since the temperature of the water in the reference evaporation pan was not the same as the soil surface, the potential evaporation rates were corrected by calculating a mass transfer coefficient (B, Equation 2.5) for the measured water temperature, then substituting it back into Equation 2.5 with the vapour pressure of the water calculated at the temperature of the soil surface. This corrected potential evaporation rate was used to compute the evaporation ratios shown on Figure 6.19.
Due to the direct sampling method used for determining water contents, and the way in which the sampling schedule was set up, there are gaps in the data shown in Figure 6.19. Once the surface began to dry, the suctions increased very rapidly, and
the rate of change of suction with time could not be accurately determined. The use of non-destructive methods of water content determination, such as time domain reflectometry (TDR) combined with automatic data acquisition, would allow more frequent water content measurements, and could provide better definition of the water content (and therefore, suction) as a function of time as the soil surface begins to desiccate.

Figure 6.19 shows that the evaporation ratio at suctions less than 100 kPa ranges from approximately 0.7 to 1.0. At suctions above approximately 100000 kPa, the evaporation ratio drops below 0.5. The data does not show much difference between the columns with sand at the surface and those with silt at the surface. Due to the previously discussed lack of data between suctions of 100 kPa and 10000 kPa, it is not possible to confirm (or dispute) Wilson's (1990) observation that the evaporation ratio begins to decrease once the surface suction exceeds approximately 3000 kPa; however, the sharp break in the curve as the evaporation ratio drops from 0.7 to 0.5 certainly coincides with average suctions of this magnitude.
6.7 Analysis Using The Computer Program "SWIM"

The computer program SWIM (an acronym for Soil Water Infiltration and Movement; Ross, 1990) was used to analyze the column evaporation tests. SWIM is based on a mass-conserving form of Richards' equation for the flow of water in soils.

Richards' equation for one-dimensional flow can be written as:

\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left( k \left( \frac{\partial \psi}{\partial x} + \frac{\partial z}{\partial x} \right) \right) + s 
\]  

(6.1)

where: \( \theta \) = volumetric water content  
\( k \) = hydraulic conductivity  
\( \psi \) = matric suction  
\( z \) = elevation  
\( s \) = rate of addition of water

The SWIM model assumes that the soil matrix is rigid, and ignores soil air flow, vapour flow, temperature effects and hysteresis in the hydraulic conductivity function.

SWIM uses a simplified formulation for calculating hydraulic conductivity. This method is based on a curve fitting method proposed by Huston and Cass (1987) to predict the moisture retention curve. The hydraulic conductivity is computed from the moisture retention data using the functions shown in Campbell (1985).

The evaporation rate from the soil surface is calculated as a fraction of the specified potential evaporation rate using a modification of the Dalton mass transfer equation.
(Equation 2.5). The humidity of the air is assumed to be constant, and the humidity of the soil is calculated from the soil suction using Equations 3.17 and 3.18.

The assumptions made in the SWIM model indicate that it is not ideally suited for detailed geotechnical purposes. Since the soil matrix is assumed to be rigid, the program is not applicable to swelling soils; and the exclusion of vapour flow from the calculations means that predicted water content profiles under evaporative conditions would not be expected to be particularly accurate.

Despite its limitations, SWIM was used to model the column evaporation tests, due to its simplicity and fast execution. The mass-conserving form of Richards' equation used by SWIM allows the use of large time increments in the solution. The result is that solutions with a very small mass balance error can be obtained in a very short time.

The primary results considered from the SWIM modelling were the predicted moisture content profiles, and the predicted evaporation rates. By comparing the SWIM results with the measured values from the column evaporation tests, the effect of the assumptions made in SWIM could be evaluated.

The SWIM analyses was performed using essentially the same parameters as those used for the "base case" of the sensitivity analysis (Section 6.4). The exact properties could not be matched due to the assumptions and curve fitting methods employed
by SWIM. For instance, detailed moisture retention data cannot be input to SWIM. Rather, a curve fitting method is used, based on the method proposed by Huston and Cass (1987). For the soils used in the column evaporation tests, it was very difficult to obtain a reasonable match between the computed and measured moisture retention curves over the entire range of suctions measured in the laboratory testing program. Since vapour flux is not considered in SWIM, the input parameters for SWIM were adjusted to obtain a reasonable fit to the measured moisture retention curve for suctions between 0 and 100 kPa. The measured moisture retention curves and the curves computed using the SWIM curve fitting method are shown in Figure 6.20. The input parameters for SWIM were also modified to match the hydraulic conductivity functions previously shown in Figure 6.4. The hydraulic conductivity functions computed by the Brooks and Corey method are compared to the functions used in the SWIM modelling in Figure 6.21. The hydraulic conductivity functions for the Beaver Creek sand were almost identical, and the discrepancy between the functions for the processed silt and natural silt was relatively small.
Figure 6.20 Comparison of Moisture Retention Curves Measured in the Laboratory, and Used in the SWIM Analysis.
Figure 6.21 Comparison of Hydraulic Conductivity Functions Computed by the Brooks and Corey (1964) Method, and By SWIM (Ross, 1990).
The SWIM modelling was conducted in two stages, to match the physical procedure used for the column evaporation tests. The first stage of the modelling utilized a constant head boundary at the base of the soil profile, simulating the presence of a water table. The initial suction profile required as input to SWIM was specified as hydrostatic (negative), with the pressure at the base of the soil profile equal to zero. The computed suction results from the first stage model were then used as initial conditions for the second stage, where the boundary condition at the base of the soil profile was changed to a zero flux condition.

The computed water contents from the SWIM analysis are shown on Figures 6.22 to 6.27, along with the measured water contents at the end of the Constant Head Phase and the Zero Flux Phase of the column evaporation tests.

In general, the results of the SWIM analyses show the same basic trend in water content profile as that observed in the column evaporation tests for the silt and natural silt, but not for the Beaver Creek sand. The SWIM analyses do not indicate the drying below the surface that was measured in the column evaporation tests. This is not surprising, since SWIM does not account for vapour flow, which is the dominant flow mechanism near the surface once the soil surface begins to dry.
The Beaver Creek sand caused problems in the SWIM analysis, likely due to the narrow range in suction over which the soil goes from saturation to approximately residual water content. The solution for the homogeneous Beaver Creek sand column was numerically unstable, and as shown in Figure 6.22, SWIM indicated a constant water content throughout the profile at the end of each phase of the analysis. Also, the SWIM solution for the column consisting of Beaver Creek sand overlying processed silt resulted in a "numerical underflow" Fortran error during the simulation of the constant head boundary condition, due to the extremely low computed hydraulic conductivity as the sand begins to dry out.
Figure 6.22 Comparison of Measured Water Contents and Computed Water Contents From SWIM Analysis for the Homogeneous Beaver Creek Sand Column.
Figure 6.23 Comparison of Measured Water Contents and Computed Water Contents From SWIM Analysis for the Column Composed of 0.3 m Beaver Creek Sand Overlying 0.3 m Processed Silt.
Figure 6.24  Comparison of Measured Water Contents and Computed Water Contents From SWIM Analysis for the Homogeneous Processed Silt Column.
Figure 6.25 Comparison of Measured Water Contents and Computed Water Contents From SWIM Analysis for the Homogeneous Natural Silt Column.
Figure 6.26 Comparison of Measured Water Contents and Computed Water Contents From SWIM Analysis for the Column Composed of 0.3 m Processed Silt Overlying 0.3 m Beaver Creek Sand.
Figure 6.27 Comparison of Measured Water Contents and Computed Water Contents From SWIM Analysis for the Multi-layered Silt and Sand Column.
Computed Evaporation Rates From SWIM Simulations

As previously stated, SWIM computes the evaporation rate from the soil as a fraction of the specified potential evaporation rate using a modification of the Dalton mass transfer equation (Equation 2.5). The humidity of the air is assumed to be constant, and the humidity of the soil is calculated from the soil suction using Equations 3.17 and 3.18. The computed evaporation ratios from the SWIM simulations are compared to the measured evaporation ratios in Figures 6.28 to 6.30.

Figure 6.28 shows that the evaporation ratio from the SWIM simulation for the homogeneous Beaver Creek sand column remained at 1.0 for the duration of the constant head phase of the simulation, and dropped to zero after 8 days of the zero flux phase of the simulation (i.e., elapsed time of 38 days). This is much different than the measured evaporation ratio, which dropped to approximately 0.29 at the end of the constant head phase of the column evaporation test. As shown in the sensitivity analysis using the Kisch (1959) method of computing pressure profiles (Section 6.4) the air entry value of the sand has a major influence on the maximum evaporation rate from a 0.6 m high homogeneous sand column; thus, small changes in this parameter may provide better agreement between the measured evaporation rates and the SWIM results.

The evaporation ratio computed from the SWIM simulation for the column composed of Beaver Creek sand overlying processed silt (Figure 6.28) decreases to
zero after six days with a constant head boundary condition. This was the point at which the simulation resulted in an Fortran error of "numerical underflow" in the hydraulic conductivity value.

The evaporation ratio computed from the SWIM simulation for the homogeneous processed silt column (Figure 6.29) shows a reasonably good agreement with the values measured in the column evaporation test. A reasonably good agreement was also obtained for the column composed of processed silt overlying Beaver Creek sand (Figure 6.29).

The evaporation ratios computed by SWIM for the homogeneous natural silt column (Figure 6.30) and the multi-layered silt and sand column (Figure 6.30) are reasonable through the first 31 days of the simulation (CHBC), but the computed evaporation ratios decrease sooner than the measured values after the boundary condition is changed to zero flux.

The results of this analysis show that SWIM may be a useful tool for evaluating evaporative fluxes and moisture redistribution; however, it should be used with caution, especially for materials with low air entry values and steep hydraulic conductivity functions, and for situations where a significant zone of vapour-phase flow is expected to develop.
Figure 6.28 Comparison of Measured Evaporation Ratios and Evaporation Ratios From SWIM Simulations For the Columns with Sand at the Surface.
Figure 6.29 Comparison of Measured Evaporation Ratios and Evaporation Ratios From SWIM Simulations For the Homogeneous Silt Column and the Silt Over Sand Column.
Figure 6.30 Comparison of Measured Evaporation Ratios and Evaporation Ratios From SWIM Simulations for the Homogeneous Natural Silt Column and the Multi-layered Column
Chapter 7: Summary and Conclusions

7.0 SUMMARY AND CONCLUSIONS

7.1 Study Objectives

The objectives stated in Chapter 1 of this thesis were as follows:

i) To develop an understanding of the fundamental mechanisms involved in evaporation and moisture redistribution in soils, particularly layered soil systems.

ii) To examine differences in evaporation rates and moisture redistribution patterns from two texturally different soils (i.e. silt and sand) subjected to one-dimensional evaporation under laboratory controlled conditions.

iii) To examine differences in evaporation rates and moisture redistribution patterns between homogeneous soil systems and layered soil systems subjected to one-dimensional evaporation under laboratory controlled conditions.

iv) To determine the sensitivity of evaporation rates to variations in various soil hydraulic properties.

v) To explain the behaviour observed in the laboratory in a manner consistent with the current understanding of unsaturated soil mechanics.

An understanding of the fundamental mechanisms involved in evaporation and moisture redistribution in soils was developed through the literature review provided in Chapter 2 and the theory discussed in Chapter 3. Objectives ii) and iii) were achieved through the laboratory testing program described in Chapter 4, with the results of the testing presented in Chapter 5. The laboratory results presented in Chapter 5 were discussed and analyzed in Chapter 6, and were explained in a manner consistent with the current understanding of unsaturated soil mechanics.
7.2 Conclusions

Column Evaporation Tests

One of the recommendations of Wilson (1990) was that laboratory testing be conducted to verify the development of a steady state evaporation rate from a soil surface with a high water table that was predicted by theoretical calculations. The constant head phase of the column evaporation tests performed for this thesis verified that a (relatively) steady evaporation rate would develop, and that moisture content changes throughout the soil profile would be negligible once this rate was established.

The laboratory column evaporation tests were used to determine differences in evaporation rates and moisture redistribution from various soil layering combinations under controlled laboratory conditions. The column evaporation tests also examined the effect of changing the boundary condition at the base of the soil column from a constant head condition to a zero flux boundary condition. The conclusions from the column evaporation tests are discussed in the following paragraphs.

Actual evaporation rates for the columns with sand at the evaporating surface decreased from 80 percent of the potential evaporation rate to 20 - 30 percent at the end of the constant head boundary condition phase of the column evaporation test (31 days elapsed time). The decrease in evaporation rate from the columns is due to the low air entry value of the Beaver Creek sand, and the steep unsaturated hydraulic
Evaporation rates for three of the four columns with silt at the evaporating surface (homogeneous natural silt, silt over sand; and multi-layered silt and sand) generally remained quite high (approximately 80 percent of the potential evaporation rate) for the constant head boundary condition phase of the column evaporation tests. The columns developed approximately steady state evaporation rates, which were accompanied by essentially constant water content profiles. The evaporation ratio for the homogeneous processed silt column was approximately 40 to 60 percent of the potential evaporation rate at the end of the CHBC. The sensitivity analysis using the Kisch (1959) method of computing pressure profiles provided reasonably good agreement with the observed evaporation rates at the end of the CHBC.

Minor differences in surface hydraulic conductivity and moisture retention characteristics due to sample preparation may have affected the evaporation rates from the columns in the column evaporation tests.

The column evaporation tests provided an indication that the concept of a moisture retaining cover (for reducing acidic drainage or radon fluxes) may be effective under evaporative conditions. The columns tested showed that selective layering of soils can maintain saturated conditions in at least a portion of a cover with a deep water table (or zero flux boundary condition at the base of the cover) under extended evaporative conditions.
Sensitivity Analysis Using Pressure Profiles Computed by Kisch (1959) Method

The sensitivity of variations in soil hydraulic properties ($k_{sat}$, AEV and L) with respect to the maximum steady state evaporation rate from a 0.6 m high soil column was investigated using the method of computing pressure profiles proposed by Kisch (1959) and the observation made by Wilson (1990) that evaporation ratios begin to decrease once total suction at the soil surface exceeds approximately 3000 kPa. This analysis was performed for soil layering combinations identical to those used in the column evaporation tests.

For coarse materials with high saturated conductivities and low air entry values, the air entry value has the greatest effect on the maximum steady state evaporation rate (for the columns analyzed). Thus, accurate moisture retention curves are required to predict evaporation rates from soils. The moisture retention curves must be determined over a wide range of suctions, from less than 10 kPa to several hundred thousand kPa.

The saturated hydraulic conductivity has an important influence on the steady state evaporation rate. If the soil surface is within the zone of capillary rise (i.e., less than the head equivalent to the AEV) the magnitude of the saturated hydraulic conductivity will determine whether the evaporation rate is controlled by the soil or by climatic conditions.
The pore-size distribution index has a small effect on the maximum evaporation rate for the soils, geometry and layering combinations considered in the sensitivity analysis.

As evaporation from a saturated soil surface progresses, upward hydraulic gradients are induced due to increased suctions at the soil surface. If the soil can not deliver sufficient water to the evaporative front to satisfy the potential evaporation rate, surface drying will occur as the suctions (and upward gradients) increase to supply water at the potential evaporation rate. If the total suction at the surface exceeds approximately 3000 kPa, the evaporation ratio will begin to decrease. Further drying results in the formation of a drying front at the soil surface. Flow through the drying front is dominated by vapour flux.

The Kisch (1959) method of computing pressure profiles can provide a good indication of the expected behaviour of a soil system under steady state evaporation conditions with the presence of a water table. Difficulties arise where the maximum steady state evaporation rate is very sensitive to small changes in material parameters. The stress history of the soil samples used to determine moisture retention characteristics for evaporation studies should be similar to the stress history of the soil at the evaporating surface.
Dominant Flux Mechanisms

The dominant flux mechanism (liquid, vapour, or liquid-vapour transition) over the column profile through the duration of the column evaporation tests was determined based on the measured gravimetric water content profiles and the moisture retention curves. Temperature profiles were also used to assist in determining the dominant flux mechanism. The analysis showed that a zone dominated by vapour flow developed as the column evaporation tests progressed. The vapour flux zone developed sooner for the columns with sand at the surface than for those with silt at the surface. A thicker transition zone developed in the sand than in the silt.

7.3 Future Research

The primary objective of this thesis was to examine evaporation and moisture redistribution from layered soils in comparison to homogeneous soils and to explain the results based on the current understanding of unsaturated soil mechanics. Although this objective has been met, further study is required before the contribution made by this thesis may be extended into engineering practice. Some areas where additional research is required are summarized below.

The column evaporation tests conducted for this thesis utilized sand and silt, which exhibited relatively small volume changes during the tests. Since clays are often used for soil liners and covers, this research should be extended to include these soils, which have a greater tendency for volume change. It would also be beneficial to
extend the research to examine the effect of pore-fluid chemistry on the behaviour of soils subjected to evaporative conditions.

The direct sampling method for determining water content samples used in this thesis was relatively simple; however, it required destructive sampling of the soil in the column. The effects of the sampling are likely negligible, but this cannot be conclusively proven. As well, the direct sampling method was time consuming, physically demanding (given the climatic conditions in the test chamber), limited with respect to the number of possible measurements, and was not suited to automated data collection. Non-destructive methods for determining water contents, such as time domain reflectometry (TDR), or a neutron moisture probe would offer significant advantages over direct sampling, and should be explored in further testing.

The samples used in the column evaporation tests were formed by slurrying the soils and consolidating them under very low total stresses. Since materials used for practical engineering applications will be compacted in an unsaturated condition (i.e., near the optimum water content), tests should be carried out on compacted samples to verify the behaviour of layered systems subjected to evaporative conditions.

The moisture retention curves for the soils were determined by Tempe cell testing for suctions of 0 to 100 kPa, and by osmotic desiccation tests for suctions of approximately 5000 to 320,000 kPa. This testing procedure appears to be satisfactory, providing that air leakage from the Tempe cells can be prevented; however, there is
Further research is required with respect to the evaluation of the hydraulic conductivity at water contents near residual saturation to define the relative components of liquid and vapour flow as the soil begins to dry.

The testing performed for this thesis examined evaporation only. For practical application, combined infiltration and evaporation cycles representing typical climatic conditions should be examined both in the laboratory and through numerical simulations to assess the long term behaviour of proposed designs.

The research conducted for this thesis was limited to non-vegetated surfaces, since this was a logical progression from the work performed by Wilson (1990). Another logical, but extremely complex extension is to apply the knowledge gained to vegetated surfaces.

Further research is required with respect to the evaluation of the hydraulic conductivity at water contents near residual saturation to define the relative components of liquid and vapour flow as the soil begins to dry.

A gap in the region of 100 to 5000 kPa. This gap could be reduced by using Tempe cells capable of withstanding pressures of 500 kPa, and using a porous ceramic with an air entry value of at least 500 kPa (5 bars). An alternate approach would be to use a 15 bar pressure plate extractor apparatus. While this would still leave a gap in the data, the soils would be closer to their residual water content, and a smoother transition to the osmotic desiccation test data would be achieved.
Development of an efficient numerical solution based on a geotechnical formulation to the governing equations for liquid water flow, vapour flow and heat flow (such as those proposed by Wilson, 1990) is required to model long term behaviour of various materials and layering combinations under probable climatic conditions.
REFERENCES


References:


References


Fredlund, D.G., 1981. The Behaviour of Unsaturated Soil. Published Course Notes, University of Saskatchewan, Saskatoon, Canada.


Picornell-Darder, M., 1985. The Development of Design Criteria to Select the Depth of a Vertical Moisture Barrier. Ph.D. Dissertation, Department of Civil Engineering, Texas A and M University, Texas, USA.


Ross, P.J., 1990. SWIM - a simulation model for Soil Water Infiltration and Movement. CSIRO Division of Soils, Davies Laboratory, Townsville, Qld 4814, Australia.


References


APPENDIX A: CONSOLIDATION, SATURATED HYDRAULIC CONDUCTIVITY AND MOISTURE RETENTION TEST RESULTS
### TABLE A-1 Summary of Consolidation and Saturated Hydraulic Conductivity Tests

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APPENDIX A:
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MOISTURE RETENTION CURVE FOR BEAVER CREEK SAND

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APPENDIX B: CLIMATIC DATA
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## APPENDIX B: CLIMATIC DATA

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**SUMMARY OF CLIMATIC CONDITIONS FOR SUPPLEMENTARY SILT COLUMNS**

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SUMMARY OF CLIMATIC CONDITIONS FOR SUPPLEMENTARY SILT COLUMNS

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APPENDIX C: COLUMN EVAPORATION TEST DATA
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APPENDIX C: COLUMN EVAPORATION TEST DATA
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**APPENDIX C: COLUMN EVAPORATION TEST DATA**
### TABLE C-1 COLUMN DESCRIPTION: HOMOGENEOUS BEAVER CREEK SAND

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APPENDIX C: COLUMN EVAPORATION TEST DATA

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**APPENDIX C: COLUMN EVAPORATION TEST DATA**
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<th>Column (A.E.)</th>
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**APPENDIX C**: COLUMN EVAPORATION TEST DATA
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APPENDIX C: COLUMN EVAPORATION TEST DATA  
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**TABLE C-3** COLUMN DESCRIPTION: 0.3 m PROCESSED SILT OVERLYING 0.3 m BEAVER CREEK SAND

**EVAPORATION RATE (mm/DAY)**

**CUMULATIVE WATER LOSSES(g)**
## Table C-4: Column Description: 0.3 m Beaver Creek Sand Overlying 0.3 m Processed Silt

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<th>Pan System</th>
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**APPENDIX C: COLUMN EVAPORATION TEST DATA**
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APPENDIX C: COLUMN EVAPORATION TEST DATA
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<th>WATER TEMP. (Deg. C)</th>
<th>EVAPORATION RATE (mm/DAY)</th>
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### TABLE C-5 DESCRIPTION: HOMOGENEOUS NATURAL SILT

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APPENDIX C: COLUMN EVAPORATION TEST DATA
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**APPENDIX C: COLUMN EVAPORATION TEST DATA**
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APPENDIX C: COLUMN EVAPORATION TEST DATA
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**APPENDIX C: COLUMN EVAPORATION TEST DATA**

Page C-22
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APPENDIX C: COLUMN EVAPORATION TEST DATA
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APPENDIX C: COLUMN EVAPORATION TEST DATA
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APPENDIX D:  TEMPERATURE DATA (THERMOCOUPLE READINGS) FOR THE COLUMN EVAPORATION TESTS
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**APPENDIX D: TEMPERATURE MEASUREMENTS**
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APPENDIX D: TEMPERATURE MEASUREMENTS
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**APPENDIX D: TEMPERATURE MEASUREMENTS**
Figure D-1  Temperature Profiles for the Homogeneous Sand Column During the Constant Head Boundary Condition Phase of the Column Evaporation Tests
Figure D-2  Temperature Profiles for the Homogeneous Sand Column During the Zero Flux Boundary Condition Phase of the Column Evaporation Tests

APPENDIX D:  TEMPERATURE MEASUREMENTS  

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APPENDIX D: TEMPERATURE MEASUREMENTS
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**APPENDIX D: TEMPERATURE MEASUREMENTS**

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APPENDIX D: TEMPERATURE MEASUREMENTS
Figure D-3  Temperature Profiles for the Homogeneous Silt Column During the Constant Head Boundary Condition Phase of the Column Evaporation Tests
Figure D-4  Temperature Profiles for the Homogeneous Silt Column During the Zero Flux Boundary Condition Phase of the Column Evaporation Tests
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APPENDIX D: TEMPERATURE MEASUREMENTS
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TABLE D-3 Column Description: 0.3 m PROCESSED SILT OVERLYING 0.3 m BEAVER CREEK SAND
Figure D-5  Temperature Profiles for the Silt Overlying Sand Column During the Constant Head Boundary Condition Phase of the Column Evaporation Tests

APPENDIX D:  TEMPERATURE MEASUREMENTS  

Page D-15
Figure D-6  Temperature Profiles for the Silt Overlying Sand Column During the Zero Flux Boundary Condition Phase of the Column Evaporation Tests
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APPENDIX D: TEMPERATURE MEASUREMENTS
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APPENDIX D: TEMPERATURE MEASUREMENTS
Figure D-7  Temperature Profiles for the Sand Overlying Silt Column During the Constant Head Boundary Condition Phase of the Column Evaporation Tests
Figure D-8  Temperature Profiles for the Sand Overlying Silt Column During the Zero Flux Boundary Condition Phase of the Column Evaporation Tests
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Figure D-9  Temperature Profiles for the Homogeneous Natural Silt Column During the Constant Head Boundary Condition Phase of the Column Evaporation Tests

APPENDIX D:  TEMPERATURE MEASUREMENTS

Page D-25
Figure D-10  Temperature Profiles for the Homogeneous Natural Silt Column During the Zero Flux Boundary Condition Phase of the Column Evaporation Tests
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APPENDIX D: TEMPERATURE MEASUREMENTS
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Figure D-11  Temperature Profiles for the Multi-layered Sand and Silt Column During the Constant Head Boundary Condition Phase of the Column Evaporation Tests
Figure D-12  Temperature Profiles for the Multi-layered Sand and Silt Column During the Zero Flux Boundary Condition Phase of the Column Evaporation Tests
APPENDIX E: SUCTION MEASUREMENTS (TENSIOMETER READINGS) FOR THE COLUMN EVAPORATION TESTS
NOTE: * Denotes Cracked Tensiometer

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APPENDIX E: SUCTION MEASUREMENTS
NOTE: * Denotes Cracked Tensiometer

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<th>Measured Suction (kPa)</th>
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Note: * Denotes Cracked Tensiometer
### APPENDIX E: SUCTION MEASUREMENTS

#### TABLE E-4 Column Description: 0.3 m BEAVER CREEK SAND OVERLYING 0.3 m PROCESSED SILT

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**NOTE:** * Denotes Cracked Tensiometer
APPENDIX F: GRAVIMETRIC WATER CONTENT MEASUREMENTS FOR THE COLUMN EVAPORATION TESTS
## TABLE F-1 Column Description: HOMOGENEOUS BEAVER CREEK SAND

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<th>3</th>
<th>5</th>
<th>7</th>
<th>10</th>
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APPENDIX F: GRAVIMETRIC WATER CONTENTS
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<th>Gravimetric Water Content (Percent)</th>
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### TABLE F-2  Column Description: HOMOGENEOUS BEAVER CREEK SAND

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<th>Elapsed Time (Days)</th>
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APPENDIX F: GRAVIMETRIC WATER CONTENTS
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APPENDIX F: GRAVIMETRIC WATER CONTENTS
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<th>Gravimetric Water Content (Percent)</th>
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APPENDIX F: GRAVIMETRIC WATER CONTENTS
## Table F-6: Column Description: Multi-Layered Processed Silts and Beaver Creek Sand

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<th>Depth (mm)</th>
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