Preferential Flow
in Vertically Oriented,
Unsaturated Soil Layers

A Thesis
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In Partial Fulfillment of the Requirements
For the Degree of Master of Science
in the
Department of Civil Engineering,
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By
Lori L. Newman
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Dedicated in memory of my dad

Arthur Lyle Bell
May 19, 1941 – January 16, 1984
Preferential flow paths develop where particular areas of a geologic profile become more conductive than the surrounding material. Research has been conducted in recent years on preferential flow and the flow of water through unsaturated soils. Unfortunately, the research has been completed by different disciplines of science and engineering, resulting in a wide range of terminology and research objectives.

A field program conducted during the excavation of a large waste rock pile at Golden Sunlight Mine in Montana defined the structure of the pile to consist of steeply-dipping, fine and coarse layers. The fine layers located near the top of the pile were wet and oxidized while the coarse layers were dry and unoxidized. The results of the field program indicated the development of preferential pathways through the fine-grained layers.

A column study was developed to investigate the potential development of preferential flow in vertically layered, unsaturated systems. To achieve this objective, a column was constructed that enabled the amount of lateral flow between two adjacent materials to be quantified and related to the applied surface flux and the hydraulic properties of the individual materials under steady-state conditions.

The results of the column study and subsequent numerical modelling program showed that water prefers to flow where water exists. In unsaturated systems, a fine-grained soil has smaller interparticle voids and is able to maintain fluid-filled pores at suctions greater than that of a coarse-grained material. Once suctions exceed the air entry value of the material the largest voids begin to drain, air enters the system and the hydraulic conductivity decreases. The decrease in hydraulic conductivity with increased

ABSTRACT

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suctions for each material is dependent on the distribution of pore sizes. In an unsaturated system it is this mechanism of decreasing hydraulic conductivity with increasing suction that can result in a fine-grained material becoming more conductive than a coarse-grained material.

When a surface flux is applied to a vertically layered, unsaturated system under steady state conditions, the preferential flow path is determined by the relationship between the applied surface flux rate and the saturated hydraulic conductivity of the fine layer. If the applied flux rate is greater than the saturated hydraulic conductivity of the fine material, the equilibrium suction that forms within the column results in the coarse layer becoming the preferential flow path. Reducing the surface flux to a rate less than the saturated hydraulic conductivity of the fine material results in an equilibrium suction where the fine layer becomes the path of preferential flow. It is critical that the interaction between the hydraulic properties of materials within a system be quantified in order to predict the behaviour of the system.

Following the analysis of the fine and coarse sand column, another column was constructed using fine and coarse waste rock. The results from the second column experiment showed that when the applied surface flux was reduced to a rate of $5.56 \times 10^{-8}$ m/s (i.e., 1753 mm/year), the fine waste rock layer became the path of preferential flow.
In 1993, I was told by two very special people to determine what my family would need so that both my husband and I could return to University and pursue graduate degrees in Civil Engineering. From the very beginning, the positive and supportive attitudes of Drs. Lee Barbour and Ward Wilson have influenced the success of my family. The fundamental support and kindness from both gentlemen will always be remembered with gratefulness. I would also like to acknowledge the support and guidance of Dr. Del Fredlund who became a co-supervisor later in my graduate program.

The support, love and encouragement that I have received throughout my life from my mother and brothers has always been present and is very gratefully acknowledged.

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Without question, the confidence and deep-seated belief that my husband and colleague Greg has in me provides the greatest support of all.
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Chapter 1
Introduction

1.0 BACKGROUND

Mining is an essential component of the Canadian economy and is crucial to the economic well-being of all Canadian provinces. The sustainability of mining in Canada is largely dependent on the mining industry’s ability to balance the economics of ore recovery with the environmental costs associated with mining.

Waste rock piles are commonly constructed in mining operations during the removal of overburden. Infiltrating precipitation is transported through the waste rock piles and discharges as leachate at the bottom. Perhaps the most important environmental issue facing the Canadian mining industry today is the potential generation of an acidic effluent called acid rock drainage, (ARD). The acid is created as a result of the oxidation of sulphide-bearing minerals present in the waste rock. The dissolved minerals and reaction products that can be present in the leachate pose an enormous environmental hazard to the surrounding environment.

Predictions of when a pile may start to generate acid and how long a pile may release contaminants to the environment, are related on a fundamental level to understanding the geochemistry and hydrogeology of waste rock piles. While
geochemical processes are largely understood, there is a serious deficiency regarding the characterization of oxygen and liquid water flow through a waste rock pile. In particular, the role of internal structure within the pile on the transportation and storage of water is poorly understood. The level of uncertainty that currently exists regarding the transport of liquid water within waste rock piles is a serious impediment to predicting the behavior of waste rock piles and the quantity and quality of leachate to be expected.

In 1994, a partial excavation of the existing waste rock pile at Golden Sunlight Mine (GSM) in Montana, USA, revealed a highly stratified environment where fine and coarse-grained waste rock layers were found to be located directly adjacent to each other in sharp contact and steeply dipping at angles consistent with the angle of repose of the material (Herasymuik, 1996). The GSM waste rock pile was also found to contain a wetting front where the moisture existed within the fine-grained layers and the coarse waste rock remained dry, suggesting the formation of preferential flow paths within the pile.

Preferential flow paths develop where particular areas of a geologic profile become more conductive than the surrounding material. In general, there has been significant research conducted on preferential flow and on the flow of water through unsaturated soils in recent years. Unfortunately, the research has been completed by different disciplines of science and engineering, resulting in a wide range of terminology and research objectives.
1.1 RESEARCH OBJECTIVES

Initially the objective of the thesis program was to identify the potential for preferential flow development within waste rock systems as recent research had shown the potential for preferential flow paths to form in these types of environments. However, it became evident during the literature review process that very few hydraulic properties had ever been published with respect to waste rock materials. In addition, there was very little literature available regarding preferential flow paths in any type of vertically layered, unsaturated environments. As a result, the primary focus of the thesis shifted from mining and waste rock piles to a more general study of systems which consisted of vertical layered materials with contrasting hydraulic properties, that is, fine and coarse materials. The thesis was then extended to include a small study regarding preferential flow through waste rock as an application of the fundamental research.

The primary research objective of this thesis was, to investigate the mechanisms for preferential flow in vertically layered, unsaturated systems. To achieve this objective, a single column was constructed, whereby the amount of lateral flow between two adjacent materials could be quantified and related to the applied surface flux and the hydraulic properties of the individual materials under steady-state conditions. A secondary objective of the thesis was to determine the significance of contact length between the two materials on the extent of flow partitioning between the two materials.

Numerical modelling was conducted following the column study in order to identify the critical parameters and mechanisms that governed flow within the system.
1.2 ORGANIZATION OF THESIS

A summary of the research conducted previously on infiltration and transport of liquid water through unsaturated soils is presented in Chapter 2. The summary includes a literature review on the different types of preferential flow. Also included in Chapter 2 is a brief summary of unsaturated flow theory.

Chapter 3 presents the details of the column study including a physical description of the column, design features, procedures used in conducting the study and information regarding the hydraulic properties of the materials. Also included in this chapter is a brief outline of the numerical modelling program that was used during the analysis of the laboratory data.

The results obtained from the laboratory program are presented and interpreted in Chapter 4, independent from the analysis conducted during the numerical modelling program. The numerical modelling results are presented in Chapter 5 as part of the analysis and discussion of the laboratory program. Concluding comments and recommendations for future researchers are provided in Chapter 6.

The extension of this thesis to investigate an application involving waste rock and mining is provided in Appendix A. The format of Appendix A is written as a condensed mini-thesis consisting of an introduction, literature review, a brief summary of the theory regarding unsaturated flow, column study design, results and conclusions.
Chapter 2

Literature Review

2.0 INTRODUCTION

Unsaturated soils are located in the vadose zone, which is the region between the surface of the ground and the top of the water table. The pore-water pressures, \( u_w \), in the vadose zone are negative and when referenced to the pore-air pressure, \( u_a \), are referred to as matric suctions, \((u_a-u_w)\). The matric suctions within a soil profile are controlled by net moisture fluxes across the soil surface as a result of evapotranspiration and precipitation. The purpose of this chapter is to summarize previous research that has concentrated on the infiltration and transport of liquid water through the vadose zone and unsaturated soils.

2.1 INFILTRATION PROCESSES

The process of infiltration into a homogeneous soil has been studied extensively by both soil physicists and hydrologists. In 1933, a hydrologist named R.E. Horton showed that rainfall infilttrates the soil surface at a rate that decreases with time. Horton (1933) also pointed out that for any given soil there was a maximum possible rate of infiltration versus time. This rate was termed the infiltration capacity of the soil and was
considered to be numerically equal to the saturated hydraulic conductivity \( k_{sat} \). Figure 2.1 shows an example of an infiltration curve (Freeze and Cherry, 1979).

All the rain enters the soil when the infiltration capacity of the soil is greater than the rainfall intensity. During heavy rains, actual infiltration follows Horton’s curve. The moisture content of the soil is raised, matric suctions are reduced, the gradient decreases and the hydraulic conductivity increases when water infiltrates the soil. Eventually, the infiltration rate becomes equal to the hydraulic conductivity where the matric suction is dissipated and the hydraulic gradient is equal to unity.

![Infiltration curve](image)

**Figure 2.1:** Infiltration curve (after Freeze and Cherry, 1979).

Tests conducted on various soil types have shown that the rate at which infiltration decreases and the final constant infiltration rate is dependent on the texture of the soil. The rate of decrease is more rapid, and the final rate is lower, for a clay soil than for more open-textured sand soils (Freeze and Cherry, 1979). However, Freeze and Banner
(1970) note that estimates of infiltration properties of a soil can be misleading if only the saturated hydraulic conductivity of the soil and its texture are considered.

Ponding of rainwater occurs if the rate of rainfall at any given time is greater than the infiltration capacity of the soil and if the rainfall duration is long enough for the soil to become saturated at the surface (Rubin et al, 1963, 1964). This unabsorbed excess water becomes runoff and is referred to as Horton overland flow (Dunne, 1978).

2.2 TRANSPORT PROCESSES

There has been disagreement through the years regarding the primary mechanism causing seepage within unsaturated soils. In his book entitled “Soil Physics”, Baver (1956) states that results from “various experiments” indicate that water moves through a soil profile under gravitational forces. Baver also states that the downward movement of water is related to the amount and continuity of the non-capillary pores. The geometry of these pores is a function of the structure and texture of the soil, volume changes and biological channels. Gardner (1960) illustrated in controlled laboratory experiments that when water enters an unsaturated soil, absorptive forces play a greater role in controlling the movement of water than gravitation. It was shown that following infiltration, water will travel through a soil at a rate which is dependant on the amount of water added, the antecedent moisture conditions, the porosity of the soil and the extent of heterogeneity of the soil (Gardner, 1960). Water was shown to move in thin films on the surfaces of the particles and at the points of contact between particles and not through the large, air-filled pores. With a similar concept in mind, Horton and Hawkins (1965) designed a laboratory column study to dispute the widely accepted belief that
rainwater percolated to the water table through the air-filled pores and not the fluid-filled pores which were under negative pore pressures.

The results from Horton and Hawkins (1965) research showed that the transport of water occurs primarily by the downward displacement of water previously held within the soil pores. The term “piston displacement” was used to describe the transportation mechanism. The research showed that groundwater recharge to the water table is from earlier infiltration events. Warrick et al. (1971) confirmed that the location of the wetting front within an unsaturated profile cannot be assumed to be the position of the infiltrating water because of the potential displacement of antecedent water. More recent researchers have qualified these statements by adding that the “piston displacement” mechanism of downward liquid water transport occurs as long as the hydraulic gradient is downward and as long as the hydraulic conductivity of the material is not equal to zero (Stephens, 1994).

The infiltration and transport and flow within an unsaturated soil is not always one-dimensional in nature. The vertical path of seepage through the vadose zone can easily be diverted into zones of preferential flow.

2.3 PREFERENTIAL FLOW

The generic term preferential flow is used to describe a multidimensional flow condition where a particular region of a profile becomes more conductive than the surrounding material. There are many different features within a soil profile that can contribute to the development of preferential flow paths through the vadose zone. These features include changes in surface topography, vegetation, subtle heterogeneities within
an otherwise homogeneous soil, contrasting hydraulic properties, sharp geologic contacts or the presence of macropore structures such as worm holes, abandoned root channels and shrinkage cracks. The most popular terms referring to preferential flow conditions include; finger flow, funnel flow and macropore flow (which also includes the terms bypass flow and short-circuiting).

2.3.1 Finger Flow

Finger flow occurs as a result of an unstable wetting front within a soil profile that exhibits a more or less random distribution of pores (Luxmoore, 1991). However, the profile may consist of vertically layered, homogenous soils. Finger flow can occur when a fine-textured soil overlies a horizontal, coarse-textured soil; a configuration often referred to as a capillary break. When the wetting front approaches the coarse-grained layer, the water concentrates at certain locations, breaking into the coarse-grained layer as fingerlike tongues which are depicted in Fig. 2.3 (Parlange and Hill, 1974, Fetter, 1993).

Finger flow can also occur when an infiltrating front moves through a soil underlain by a relatively impermeable layer. In this situation, the air within the more permeable soil may be temporarily trapped between the wetting front and the less permeable strata. The downward movement of the wetting front becomes impeded as the air ahead of it is compressed (Latifi et al, 1994). As more water enters the soil, the pore pressures within the wetting front decrease and become positive. In response to the increased pore-water pressures, the pressure of the trapped compressed air also increases. This process continues until a condition referred to as 'air counter-flow'
begins and bubbles of the trapped air find their way upward through the water filled pore-spaces. Once the compressed air begins to rise to the surface, the infiltrating water may proceed downward in finger-like pathways (Latifi et al, 1994).

![Figure 2.2 Preferential flow in an unsaturated soil due to finger flow (after Fetter, 1993).](image)

In some instances there are not any physically defined channels to account for the presence of preferential flow fingers within the soil profile. Ritesma and Dekker (1994) found that micro-scale heterogeneities, which naturally occur in seemingly homogeneous dune sand resulted in the formation of preferential flow fingers. Sand dunes are comprised of a series of thin (1-3 mm) sand layers, which have been deposited by successive wind events. The layers may have different densities, texture and pore configurations compared to the layers found above and below. These subtle differences can produce significant changes in unsaturated hydraulic conductivities and an unstable wetting front may form. At one field site, preferential flow paths appeared as sand
columns; resulting from the wind erosion of dry sand located between the wetter and denser preferential flow paths (Ritesma and Dekker, 1994).

In many cases, the preferential flow fingers occupy only a small percentage of the horizontal, cross-sectional area of the porous media. After infiltration ceases, subsequent infiltration events will follow the same finger-like pathways that were developed during the initial infiltration (Stevens, 1994). This has led some researchers to conclude that the recharge of groundwater can occur long before the soil is thoroughly wetted. However, speculation also exists that under deep water table conditions, the fingers may gradually blend together at depth due to moisture diffusion (Stevens, 1994).

2.3.2 Funnel Flow

Another type of preferential flow is called funnel flow (Kung, 1990b). Funnel flow occurs below the root zone and is a large-scale phenomena associated with stratified soils. Sloping coarse-grained layers embedded within fine-grained profiles can impede the downward movement of water. The infiltrating water remains in the fine-grained soil due to the capillary break created between the fine and coarse layers. The water flows along the slope of the interface to the end of the coarse-grained layer, where it then travels vertically through the fine-grained material but in a concentrated volume referred to as column flow (Fig. 2.3).

Kung (1990b) suggests that funnel flow can be expected when the ratio of the infiltrating flux to the saturated hydraulic conductivity of the fine-grained material, is less than 0.38, referring to infiltrating fluxes that are small. It is also suggested that funnel flow may occur if there are bedding planes, clay lenses, or other high-density,
low permeability layers in an otherwise uniform unsaturated soil. This type of funnel flow is not caused by the formation of a capillary break, but rather due to the impedance of downward flow of infiltrating water by the low hydraulic conductivity of the dense material.

![Diagram of preferential flow in an unsaturated soil due to funnel flow](after Fetter, 1993).

**Figure 2.3** Preferential flow in an unsaturated soil due to funnel flow (after Fetter, 1993).

### 2.3.3 Macropore Flow

Macropore flow refers to the rapid movement of infiltrating water through structured soils. The structure within the soil may be a result of large openings at the surface such as gopher holes, shrinkage cracks or abandoned root channels. On a more local scale, macropore flow may occur as a result of disturbance of the soil such as the spaces between adjacent soil clods, which are created after plowing a soil.

There are two general categories of macropore flow presented in the literature. The first category includes the processes known as short-circuiting and bypass flow.
The second category describes a process that combines flow through the macropore structures in the soil as well as flow in the micropores or porous matrix where piston displacement of antecedent water occurs.

### 2.3.3.1 Short-circuiting

The first category, known as short-circuiting or bypass flow, refers to the rapid downward movement of free water through large, continuous macropores that are initially air-filled. Short-circuiting typically occurs in a fine-grained material that has a very low matrix hydraulic conductivity but contains a secondary structure of cracks and fissures, (i.e., heavy clay) (Fig. 2.4).

![Figure 2.4 Preferential flow in an unsaturated soil due to short-circuiting (after Fetter, 1993).](image)

Water will flow preferentially through the macropore structure if the upper surface of the fine-grained matrix cannot conduct all the applied water. At low rainfall intensities, the matrix pores can conduct the applied water if the intensity of the rainfall does not exceed the maximum infiltration rate. Once the maximum infiltration rate is
exceeded, water will pond on the surface of the ground and flow into the macropores after a critical ponding height is exceeded (Bouma and Dekker, 1978, Bouma et al, 1981, Stevens, 1994). The water entering the macropore system is then transported downward having minimal interaction with the water contained within the soil matrix, which may be under negative pore-water pressures.

Short-circuiting can contribute significantly to recharge where the macropores are vertically continuous for significant depths and where the macropores are connected to a free surface, such as ponded water. The downward movement of water within a macropore may be impeded or cease altogether if the air pressure ahead of the wetting front increases significantly (Stevens, 1994).

The phrase “bypass flow” was coined to describe the bypassing of new water past immobile, older water within the soil matrix. This differs significantly from the transport mechanism described earlier as “piston displacement” (Horton and Hawkins, 1965). Short-circuiting or bypass flow cannot be described with the traditional Darcy-type flow theory that can be used successfully for simulation models in homogeneous, non-structured soils.

Short-circuiting causes water to rapidly move beyond the root zone, making it unavailable to the vegetation (Thomas and Phillips, 1979, Bouma et al, 1981). The fresh surface water may also carry surface applied contaminants directly to the water table without utilizing the natural filtration potential of the soil (Stirk, 1953, Bouma et al, 1981).

Thomas and Phillips (1979) note macropores may not have to extend to the soil surface in order to contribute to the downward flow of water, based on field observations
of infiltration into a plowed soil. It was observed that even in a freshly plowed soil, in which the macropores are disrupted in the upper 15 cm of the profile, deep flow through macropores still occurs. It is suggested that the infiltrating water moves in accordance with Darcy's law through the plowed layer of relatively high conductivity material and accumulates at the bottom of the plow layer above the undisturbed soil. Once the pore-water pressures reduce to zero at the interface between the matrix and the macropore, the water then enters the macropore. Gardner (1960) states that, based on his laboratory experiments a channel (or macropore) which is not maintained open to the surface is not effective in transporting infiltrating water.

2.3.3.2 Macropore/Micropore Flow

When water enters a macropore, diffusion and adsorption of the water from the macropore into the surrounding porous matrix can occur (Gardner, 1960, Horton and Hawkins, 1965, Skopp et al, 1981, Beven and Germann, 1981, Germann and Beven, 1981). In 1981, Germann and Beven proposed a coupled method for estimating the macropore volume within a profile. A macropore was defined as having an equivalent radius of 0.15 cm. Pores that had a radius smaller than this minimum limit were considered part of the porous matrix (i.e., micropores). It was suggested that a structured soil should be viewed as a two component system with a macropore component superimposed on a micropore component. The two components are considered coupled by the transfer of water between the two systems.

Germann and Beven (1981) proposed two separate modes of flow for the macropore/micropore system. The first mode (mode 1) describes flow through the
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Macropore system under gravitational forces (i.e., free flow). The upper limit of flow
mode 1 is defined as the saturated hydraulic conductivity of the macropores. The lower
limit of flow in mode 1 is defined as the volumetric water content where the movement
of water becomes governed by capillary action. In flow mode 2, the movement of water
is governed by capillary forces within the soil and not by gravitational forces and can be
described using the conventional flow equation for unsaturated porous media (i.e.,
Richards Equation and Darcy’s Law). Gravity flow does still exists within the matrix
under tension saturated conditions or where matric suctions are greater than zero, but it
does not govern the majority of moisture movement in flow mode 2.

In a second paper written the same year, Beven and Germann (1981) present a
one-dimensional model of bulk flow for a macropore/micropore system. The model
presented is based on a domain concept, which includes the flow of water in both the
micropore and macropore system and also considers the potential transfer of flow
between the two systems. In the same paper, Beven and Germann (1981) also
introduced five different stages of flow, which it was believed could occur within a
macropore/micropore system (Figure 2.5).

Figure 2.5a shows water infiltrating and travelling down the walls of an initially
dry macropore. As the water infiltrates the macropore, some of the flow is transferred
from the macropore system into the surrounding micropore system. Figure 2.5b shows a
rising water table within the macropore and absorption of water into the matrix over the
entire depth of the macropore. Figure 2.5c shows a full macropore experiencing surface
runoff. The macropore intercepts the water table within the micropore system. Figure
2.5d shows the response of the water level within the macropore after rainfall cessation.
The final diagram (Fig. 2.5e) shows the inward flow that can occur into a macropore as a result of a rising water table within the micropore system.

Figure 2.5 Stages of water flow in a macropore. R is the rainfall rate, \( \theta_{\text{mi}} \) represents the volumetric water content of the micropore system where 'sat' represents saturated conditions, S is the exchange of flow between the two systems (after Beven and Germann, 1981).

2.3.3.3 Flow from Large to Small Pores

The concept of flow between a macropore/micropore system does not apply only to structured soils containing shrinkage cracks or burrow holes. The transfer of water
from a conceptual large pore to a fine pore was perhaps best demonstrated by the laboratory column study of Horton and Hawkins (1965).

The work by Horton and Hawkins (1965) involved an experiment that was designed to dispute the conventional thinking that water is transported through a soil by large, air-filled pores and not by water-filled pores. A piston displacement mechanism of liquid water transport was confirmed with the use of a tritium tracer applied to the surface of a homogenous column. The results showed that break-through was later than would be expected if movement had been strictly through the large pores.

The second experiment presented in the Horton and Hawkins (1965) paper was a column study constructed using fine and coarse-grained materials. The objective of the column study was to demonstrate how infiltration into a coarse-grained soil could be transferred laterally into an adjacent tension-saturated, fine-grained material before the water penetrated to a significant depth.

The fine-grained soil used in the column study was a sandy clay that had an air entry value of at least 15 kPa (1.5 m of equivalent water pressure) so that it would remain tension saturated over the entire length of the column. The coarse-grained material was coarse sand described as being 10 to 20 mesh (0.85 to 1.98 mm) and was found to have an air entry value of approximately 2 kPa (0.20 m of equivalent water pressure).

The column was constructed to ensure that there was a continuous length of large-pores extending the entire length of the column. This was achieved by placing the fine-grained sandy clay around a coarse sand core. Four column configurations were constructed. To limit the contact length between the two material where lateral transfer of water could occur, each of the four columns had a length of plastic tubing that
extended upward from the bottom of the column and surrounded the sand core. In each of the four columns, the tubing was extended to a different height, as shown in Fig. 2.6. Horton and Hawkins (1965) applied eleven simulated precipitation events to the top of each sand core. Following each application, the columns were allowed to drain and effluent was collected separately from the bottom of each material.

Figure 2.6 Column design for Horton and Hawkins (1965) experiment.

The results of the column study indicated that infiltrating precipitation, which was only applied to the coarse-grained material, transferred over to the fine-grained material in a relatively short distance. There was however, a seemingly contradictory result
between two of the eleven column tests conducted. One column test used an applied precipitation rate of 76 mm/hr for a one hour duration, and a plastic tubing length of 300 mm which allowed the two materials to be in direct contact over the top 1225 mm of the 1550 mm column. For this configuration, 100% of the applied precipitation transferred over to the fine-grained material before the top of the plastic tubing was reached. In a second test, the same precipitation rate was applied to the column where the material was allowed to interact for 1500 mm of the 1550 mm-long column. Instead of 100% of the flow exiting from the fine-grained material, 100% of the flow was collected from the coarse-grained material. Horton and Hawkins (1965) concluded that the infiltrating water must have flowed from the coarse-grained material into the fine-grained material at the top of the column and then transferred back to the coarse-grained material near the bottom of the column. They speculated that the re-cross-over likely occurred at the elevation where the coarse-grained material became tension saturated, approximately 200 mm up from the bottom.

2.4 THEORY OF UNSATURATED SYSTEMS

The theory of classical soil mechanics has been developed to describe and analyse the material properties and the mechanical behavior of saturated soils, however, a large percentage of the world’s surface is unsaturated. In order to predict and describe the flow of water through unsaturated soils, appropriate theory must be applied. The principles of continuum mechanics that have been successfully applied to saturated soils have also become the basis for unsaturated soil mechanics.
The purpose of the rest of this chapter is not intended to be a comprehensive review of either saturated or unsaturated soil mechanics. The key purpose is to highlight the essential theories, parameters and processes, which govern the flow of water through unsaturated environments.

### 2.4.1 Unsaturated Soils

A saturated soil is a soil that contains two distinct phases, solids and water. In a saturated soil, all the interstitial pore spaces between the solid particles are filled with water and the pore-water pressures are positive. An unsaturated soil contains four separate phases: solid particles, water, air and the air-water interface or contractile skin (Fig. 2.7). The presence of even the smallest amount of air renders a soil unsaturated.

![Diagram of unsaturated soil](image)

**Figure 2.7** An element of unsaturated soil showing the presence of four separate phases (after Fredlund and Rahardjo, 1993).

The most important property of the contractile skin is called surface tension, which is the ability of the contractile skin to exert a tensile pull (Fredlund and Rahardjo, 1993). Surface tension is the result of unbalanced forces acting on the water molecules located
on the air-water interface. The surface tension causes the contractile skin to behave like an elastic membrane producing a concave meniscus, which extends from soil particle to soil particle across each pore channel (Freeze and Cherry, 1979). The pressure difference across the contractile skin is referred to as the matric suction, \((u_a - u_w)\), where \(u_a\) is the pore-air pressure and \(u_w\) is the pore-water pressure. As the matric suction within a soil increases (i.e., pore-water pressures become more negative), the radius of curvature of the contractile skin decreases and the meniscus retreats from the larger interstitial pores and re-establishes within the smaller pore channels.

2.5 FLOW OF WATER IN UNSATURATED SYSTEMS

Water flows through a soil as a result of a potential gradient. The driving forces are usually referred to as “heads” so that water is said to flow in response to a hydraulic head gradient. The hydraulic head consists of three components, namely, the gravitation head, the pressure head and the velocity head. The velocity head in a soil is considered negligible so that the hydraulic head at any point within a soil profile simplifies to the following equation total head equation:

\[
h = z + \frac{u_w}{\rho_w g}
\]

where: \(h\) = hydraulic head or total head, m,
\(z\) = elevation head or gravitational head, m,
\(u_w\) = pressure head, m,
\(\rho_w\) = density of water, kg/m\(^3\), and
\(g\) = gravitational acceleration, m/s\(^2\).
In both saturated and unsaturated systems, water will flow from a point of high hydraulic head to a point with low hydraulic head (Fredlund and Rahardjo, 1993). It is important to note that water does not necessarily flow from a high water content to a low water content. It is the total head gradient, which controls the flow within a system.

2.5.1 Flow Laws

The flow of water through a saturated soil is most often described using Darcy’s law. Darcy’s law states that the flow of water through a soil is proportional to the hydraulic head gradient and is written for one-dimensional flow as follows:

$$ q = -k_{sat} \frac{\partial h}{\partial y} \quad (2.2) $$

where:
- $q$ = flow rate of water, (m$^3$/s/m$^2$)
- $k_{sat}$ = saturated hydraulic conductivity, (m/s), and
- $\frac{\partial h}{\partial y}$ = hydraulic head gradient in the y-direction, (m/m).

The proportionality constant is called the saturated hydraulic conductivity ($k_{sat}$), which can vary by several orders of magnitude for a coarse-textured versus a fine-textured soil. In a saturated soil, the hydraulic conductivity of the soil remains constant. However, in an unsaturated soil, both the volumetric water content and the hydraulic conductivity are functions of matric suction, ($\theta_w(u_a-u_w)$ and $k(u_a-u_w)$). Darcy’s law can be applied to unsaturated soils, however, it must be recognized that the magnitude of the hydraulic conductivity will differ for different volumetric water contents (Fredlund and Rahardjo, 1993).
2.5.2 Hydraulic Characteristic Curves

In a saturated soil, all the interstitial pore spaces are filled with water and the volumetric water content is equal to the porosity of the soil. In an unsaturated soil a differential pressure exists across the air-water interface or contractile skin. The pressure difference exists because the air pressure, $u_a$, on one side of the contractile skin is greater than the water pressure, $u_w$, which exists on the other side of the contractile skin. As the matric suction of a soil increases, the radius of curvature of the contractile skin between soil particles decreases. The diameter of the pore spaces able to support the contractile skin become smaller and the larger pores become air-filled. The infiltration of air reduces the total volumetric water content within the soil.

2.5.2.1 Soil-water Characteristic Curves

The soil-water characteristic curve represents the volumetric water content of a particular soil as a function of matric suction. It describes the storage capability of the soil and defines the amount of water that will remain in the pores under increased matric suctions. An important feature of the soil-water characteristic curve is the air-entry value, $(u_a-u_w)_b$, (Fredlund and Rahardjo, 1993). The air-entry value is the value of matric suction that a soil experiences when the largest pores begin to drain and air enters the soil. The air-entry value is a function of the maximum pore size in a soil and can vary significantly based on the pore-size distribution within a soil. A fine-grained soil may have a large air-entry value while a coarse-grained material with large interstitial pores, may start to drain almost immediately once matric suctions are experienced, resulting in an air-entry value which is virtually non-existent.
The change in storage with a change in suction, once the air-entry value is exceeded, is a function of the distribution of pore sizes. Uniform sands will exhibit a greater reduction in storage at suctions greater than the air-entry value as the interstitial pores are all similar in size. A well-graded material with a variety of pore-sizes will have a gentler slope to the soil-water characteristic curve at matric suctions greater than the air-entry value. Figure 2.8 shows two hypothetical soil-water characteristic curves for a uniform sand and a silty sand. Another key feature of the soil-water characteristic curve is the residual water content, which represents the water content of a soil at which further increases in matric suction do not produce significant changes in water content. The residual water content can be called the residual degree of saturation when water contents are converted to degrees of saturation and plotted versus matric suctions.

For a single soil, there can be two soil-water characteristic curves depending on whether the soil is wetting or drying. This duality is known as hysteresis. Figure 2.9 illustrates the hysteresis for a naturally deposited sand.

![Diagram](image)

**Figure 2.8** Hypothetical soil-water characteristic curves showing the air-entry value for a uniform sand and a silty sand.
There are several factors that contribute to hysteresis. These include a non-uniform pore size, a different contact angle of the air-water interface during the wetting and drying processes, entrapped air in the soil during the wetting process and swelling and shrinking of the soil (Hillel, 1971). The size of the smaller pore channels control the drying behaviour of a soil while the wetting behaviour is controlled by the size of the large pores. As a result, coarse textured soils can exhibit strong hysteresis in the soil-water characteristic curve.

2.5.2.2 Hydraulic Conductivity Functions

The hydraulic conductivity of a soil is significantly affected by combined changes in the void ratio and water content of the soil (Fredlund and Rahardjo, 1993). Water flows through an unsaturated soil through the water-filled pores. The pores that are filled with air become non-conductive conduits and serve to increase the tortuosity of
the flow path, reducing the ability of a soil to transport liquid water. As a result, the ability of an unsaturated soil to transport water can be significantly less than that of a saturated soil. Once the air-entry value of a soil is exceeded and significant drainage has begun, the hydraulic conductivity decreases with increased matric suction at a rate dependent on the distribution of pore sizes within the soil. Soils with a uniform distribution of pore sizes exhibit a greater decrease in relative unsaturated hydraulic conductivities with increased matric suction than do soils with a wide distribution of pore sizes. Since the ability of a soil to conduct water is directly related to the amount of water that exists in a soil, it follows that hysteresis can also be a significant feature of the hydraulic conductivity function (Fig. 2.10).

\[
\text{Saturated hydraulic conductivity } k_{\text{sat}} = 4.3 \times 10^{-6} \text{ m/s}
\]

![Graph showing hysteresis in hydraulic conductivity](image)

**Figure 2.10** Hysteresis in the hydraulic conductivity plotted as a function of \((u_a - u_w)\), (after Fredlund and Rahardjo, 1993).

When the unsaturated hydraulic conductivity is plotted against the volumetric water content for a soil, it becomes evident that there is no hysteresis in the relationship between the two functions (Fig. 2.11). The lack of hysteresis in Fig. 2.11 verifies that
the ability of a soil to transport water is truly dependent on the amount of water in the soil.

![Figure 2.11 Lack of hysteresis in the relationship between the hydraulic conductivity and the volumetric water content, (after Fredlund and Rahardjo, 1993).](image)

**Figure 2.11** Lack of hysteresis in the relationship between the hydraulic conductivity and the volumetric water content, (after Fredlund and Rahardjo, 1993).

### 2.6 SUMMARY

Research to date on preferential flow and the flow of water through unsaturated soils, the two sections have, in general, been completed by different research groups. Soil scientists, hydrologists and agronomists have primarily completed the research regarding preferential flow. As a result, the terminology and situations considered differs from those described in the standard geo-environmental engineering journals and reports dealing with flow through unsaturated soils. Most of the research studies summarized in this literature review are empirical in nature and the conclusions apply only for the conditions studied. The theory is typically not reduced to a first principles approach. Another interesting feature in the papers reviewed here is the lack of
information regarding the hydraulic characteristics of the materials being studied. Information is often provided regarding the saturated hydraulic conductivity, and in the case of Horton and Hawkins (1965), the air entry value of the material, but the soil-water characteristic curves of the soils being studied are not presented. In addition, the materials have been relatively fine textured in nature relative to waste rock.

There are many different applications within engineering for which the potential for preferential flow must be evaluated. One application of current interest in the area of geo-environmental engineering is the prediction of seepage rates from waste rock piles. A brief review of the current literature regarding the hydrogeology of waste rock piles is included as Appendix A.
3.0 INTRODUCTION

The excavation of a waste rock pile at Golden Sunlight Mine revealed a highly stratified structure of steeply dipping fine and coarse layers. The fine-grained waste rock had elevated moisture contents that suggested preferential flow had occurred through the fine-grained material Herasymuik (1996). Column studies were proposed to investigate the mechanisms for preferential flow through stratified layers of waste rock. Preliminary numerical modelling was conducted on both a vertically layered system and a steeply inclined system and showed the potential for preferential flow in both environments. A vertically layered column was ultimately selected as it removed the potential for lateral flow enhanced by gravity forces.

3.1 PHYSICAL DESCRIPTION

The research conducted by Horton and Hawkins (1965) provided a basis for the design of the laboratory column study.
3.1.1 Column Design

The column was designed to create an environment where the amount of lateral flow between two vertically layered materials could be quantified and related to the applied surface flux under steady-state conditions. A constant flux rate was applied to the surface and steady-state conditions were established within the column. The resulting discharge from each material was then collected and measured. An adjustable physical barrier, which separated the two materials, was included to investigate the significance of a longer contact length between the layers and the extent of flow partitioning with depth.

Figures 3.1 and 3.2 show detailed drawings of the column design. The column was 1400 mm in height, constructed out of seven sections of clear acrylic. Each section was 200 mm tall with interior, rectangular dimensions of 150 mm by 300 mm (Fig. 3.2). A narrow groove was machined down the inside of the column on both sides to act as a guide for the insertion and adjustment of a thin metal sheet. A quarter-inch flange was placed in each corner to slightly round the square corners and reduce edge effects.

The base plate of the column contained two separate manifold drainage systems, one for either side of the column. Each drainage system measured 150 mm by 150 mm and consisted of a series of radial grooves, which extended outward from a slightly depressed centre outlet. The subtle funnel shape of the drainage system was designed to promote the collection of drainage from each side. Attached to each drainage outlet was a flexible hose approximately 600 mm in length. The hose ends were secured to a metal stand with the outlet of the tubes located 250 mm below the bottom of the soil.
Figure 3.1: Schematic drawing showing the overall design of the laboratory apparatus.
Figure 3.2 Schematic drawing showing the acrylic column and the separate components of the column design.
3.1.2 Surface Flux Application System

The surface flux application system was designed to apply a range of constant flux rates. The system consisted of a DC-electric motor driving two peristaltic pumps (Fig. 3.3). Flexible tubing was used to connect each peristaltic pump to a constant head reservoir. As water from the peristaltic pumps entered each reservoir, an equal amount of water was forced out of the bottom of the reservoir through a myriad of small diameter, flexible tubes held in position over the column's surface using a perforated acrylic sheet (Fig. 3.3). The fluxes were distributed in a raindrop fashion from the end of each tube. For each total flux applied, one-half of the total flux was applied to each material. The acrylic sheet also limited evaporation from the soil surface.

![Diagram of Surface Flux Application System](image)

**Figure 3.3** Surface application system used to evenly distribute a constant flux rate over the surface of the column.
3.2 EXPERIMENTAL PROCEDURE

The following section describes the procedure used to assemble the column and to conduct the laboratory study.

3.2.1 Column Assembly

To assemble the column, a single acrylic section was placed on top of the base plate with the metal cutoff already in position. A layer of coarse gravel, 30 mm in depth was placed at the bottom of the column to avoid clogging of the drainage system by the finer sand material. A wire screen was placed on top of the gravel to inhibit the migration of finer particles into the coarse gravel. The fine and coarse materials were then placed on either side of the cutoff in 100 mm lifts and compacted uniformly using a specially designed compaction hammer. The hammer consisted of a piece of metal sheeting, cut to fit each half of the column with a 150 mm high metal rod welded vertically to the middle of it. A 5 kg circular weight with a 25 mm centre hole was dropped 6 times from a height of 100 mm for each lift.

Once the first acrylic section was filled to capacity, the next section was lowered into place and fastened to the lower section using screws and butterfly nuts. Subsequent sections were filled using the same procedure as the first. A water tight seal was achieved between each section by the use of greased o-rings, which fit into machined grooves that outlined the base of each section (Fig. 3.2 – Block A: Plan View). The total finished height of the column was 1400 mm, however, the sand was only placed to a height of 1140 mm. The last acrylic section was left unfilled and was used to support the surface flux application system over the top of the column.
The column was saturated prior to conducting the experiment. A water hose was placed at the top of the column and the flow of water was adjusted to maintain a 60 mm free water surface at the top of the column. The outlets at the bottom of the column were left open, which allowed air to escape upon wetting, which in turn promoted the development of an even wetting front. Once the column was completely saturated, the hose was removed and the column was allowed to drain until discharge ceased from both outlet tubes.

3.2.2 Cutoff Heights and Surface Flux Application Rates

The metal sheet, or cutoff, was used to keep the two materials separate during column assembly and to provide a barrier to horizontal flow between the two materials during the experiment. Water flowing in the system above the height of the cutoff was free to move laterally.

Initially, the cutoff extended right to the surface and protruded out the bottom of the base plate. Once the column was completely assembled, the cutoff was lowered to a depth of 550 mm, which placed the top of the metal sheet 590 mm above the base of the gravel. After the cutoff was lowered into position, a series of four surface fluxes were applied to the surface of the column. The first flux rate was determined by adjusting the flow rate on the peristaltic pump until a thin free water surface was maintained on the surface of the fine-grained material. The second flow rate was established by reducing the flow rate just enough so that water no longer appeared on the surface but the indentations formed by the water droplets on the surface of the fine-grained material still remained water filled. The last two fluxes were not chosen visually as the initial two
fluxes, but were chosen by further reducing the flow rate of the pumping system two more times. The choice of the last two flux rates was governed by the need to have two flux rates that were both less than the first two flux rates, but were also able to be applied by the existing surface flux application system without reducing the size of the pump heads. For each applied surface flux, steady-state conditions were established and the percentage of flow discharging from each side of the column was measured and recorded. The cutoff was then lowered to a height of 590 mm (i.e., a contact length of 550 mm) and the four flux rate applications were repeated.

Three times during the experiment the cutoff was further lowered to depths of 750, 1000 and 1100 mm resulting in cutoff heights of 390, 140 and 40 mm respectively. The cutoff was lowered each time by loosening the cutoff holder (Fig. 3.2) and connecting it to a hydraulic jack to ease the cutoff out the bottom of the column. The lowering of the cutoff allowed a greater contact length to exist between the two materials, which provided a greater opportunity for the infiltrating water to transfer laterally under the applied surface flux.

Although efforts were made to ensure that the four surface flux rates were identical for all cutoff heights, slight variations in the applied rates occurred. Table 3.1 provides a summary of the sixteen experimental conditions.

For each experimental condition, the volume of water being supplied by the peristaltic pumps to the top of the column was collected for one minute and converted to a flux rate.
### Table 3.1: Summary of experimental conditions.

<table>
<thead>
<tr>
<th>Cutoff Height (Contact Length) (mm)</th>
<th>Applied Surface Flux Rate (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flux (a)</td>
</tr>
<tr>
<td><strong>Test 1</strong></td>
<td>1.3 x 10^{-5}</td>
</tr>
<tr>
<td>590 (550)</td>
<td></td>
</tr>
<tr>
<td><strong>Test 2</strong></td>
<td>1.3 x 10^{-5}</td>
</tr>
<tr>
<td>390 (750)</td>
<td></td>
</tr>
<tr>
<td><strong>Test 3</strong></td>
<td>1.3 x 10^{-5}</td>
</tr>
<tr>
<td>140 (1000)</td>
<td></td>
</tr>
<tr>
<td><strong>Test 4</strong></td>
<td>1.3 x 10^{-5}</td>
</tr>
<tr>
<td>40 (1100)</td>
<td></td>
</tr>
<tr>
<td><strong>Average flux rate</strong></td>
<td>1.3 x 10^{-5}</td>
</tr>
</tbody>
</table>

#### 3.3 MATERIAL PROPERTIES

The fine-grained material used in the column study was Beaver Creek sand obtained from a local borrow pit near the South Saskatchewan River southwest of Saskatoon. Other researchers at the University of Saskatchewan (Rahardjo 1990, Wilson 1990, Swanson 1996) had previously measured the soil-water characteristic curve for Beaver Creek sand and had identified a range of saturated hydraulic conductivity values.

The average porosity reported by previous researchers for Beaver Creek sand was approximately 0.43 with an approximate air entry value of 3 to 5 kPa. Wilson (1990)
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presented a range of saturated hydraulic conductivity \((k_{sat})\) values for Beaver Creek sand from \(8.1 \times 10^{-5}\) m/s to \(3.9 \times 10^{-6}\) m/s. The first saturated hydraulic conductivity value was predicted using Hazen's formula (Freeze and Cherry, 1979) using a \(D_{10}\) value of 0.09 mm while the second saturated hydraulic conductivity value was measured in the laboratory using a falling head permeameter. As part of the current laboratory program, a second falling head permeameter test was completed on the Beaver Creek sand. The measured value of saturated hydraulic conductivity was \(6.2 \times 10^{-5}\) m/s, which is within the range reported by Wilson (1990).

The coarse-grained material used was a commercially available medium silica sand. The soil-water characteristic curve was measured by Mr. Alex Kozlow at the University of Saskatchewan using a modified pressure plate. As part of the current laboratory program, the saturated hydraulic conductivity for the silica sand was measured using a constant head permeameter to be \(1.5 \times 10^{-2}\) m/s. Silica sand is uniform in gradation with an air entry value of 0.7 kPa. A residual water content of 0.02 is reached at suctions of approximately 4 to 5 kPa. The measured soil-water characteristic curves for the fine and coarse sand are presented in Fig. 3.4.

The hydraulic conductivity functions were generated using the predictive method proposed by Fredlund et al (1994). The predictive method integrates along the measured soil-water characteristic curve and relates hydraulic conductivity to suctions from zero to one million kPa. Figure 3.5 presents the hydraulic conductivity functions for both the Beaver Creek and silica sand.
Figure 3.4 Measured soil-water characteristic curves for the Beaver Creek sand (Wilson, 1990 and Swanson, 1991) and medium silica sand (unpublished).

Note: The shaded area denotes the range of saturated hydraulic conductivity values for Beaver Creek sand identified by Wilson (1990).

Figure 3.5 Hydraulic conductivity functions generated using the soil-water characteristic curves for the fine and coarse-grained sand.
3.4 BASE BOUNDARY CONDITION

In the laboratory experiment, the outlet tubes on both sides of the column were placed 250 mm below the top of the gravel layer. The measured soil-water characteristic curve for Beaver Creek sand presented in Fig. 3.4 shows an air-entry value of approximately 3 to 4 kPa. The maximum suction that could exist at the base of the fine material due to the placement of the outlet hoses would be −2.5 kPa assuming the hoses were water-filled. Under this maximum suction, the Beaver Creek material would be tension saturated. The presence of the unvented coarse drainage layer would not affect the base boundary condition.

The value of matric suction corresponding to an 85% degree of saturation in the coarse silica sand is approximately 0.8 kPa. The maximum possible suction that would form at the base of the coarse material due to the location of the outlet hose under a downward flux would be 0.8 kPa. At suctions exceeding 0.8 kPa, the silica sand would desaturate quickly due to the uniform nature of the material and the air phase would become continuous throughout the height of the column. Once a continuous air phase developed through both the drainage layer and the coarse sand, the presence of the coarse gravel in the drainage layer would control the base boundary condition through the formation of a capillary break. The maximum suction exerted by the coarse gravel layer on the coarse sand above would be equal to the residual suction of the gravel material. The minimum particle size of the drainage material was relatively large (i.e., greater than 10 mm). Although a measured soil-water characteristic curve was not established, it is believed that a material this coarse in nature would exhibit virtually no
air entry value and would have a residual suction of 0.1 kPa. As a result, the suction at
the base of the coarse sand was assumed to be 0.1 kPa.

3.5 WASTE ROCK COLUMN STUDY

At the end of the initial laboratory test consisting of a Beaver Creek and medium
silica sand, the column was dismantled and reconstructed using fine and coarse waste
rock. The waste rock column study extends the laboratory program to an industry
application. A complete description of the waste rock test and the results obtained are
provided in Appendix A.

3.6 NUMERICAL MODELLING PROGRAM

Following the fine and coarse sand laboratory test, a steady-state model study was
completed using SEEP/W (Geo-Slope, 1991). A full description of the numerical
modelling program is presented in Chapter 5: Analysis and Discussion. A sensitivity
analysis was conducted to verify the base boundary condition that existed in the
laboratory program. Numerical modelling was not conducted for the waste rock column
test.
Chapter 4

Presentation and Interpretation of Column Results

4.0 INTRODUCTION

This chapter presents the results of the laboratory column study and provides an interpretation of the laboratory results. A more detailed interpretation of the data based on the numerical modelling program is provided later in Chapter 5: Analysis and Discussion.

4.1 LABORATORY RESULTS

The experimental procedure for the laboratory column study consisted of sixteen different applied flux/cutoff height configurations (Table 3.1). Steady-state conditions were established under each configuration and the effluent from each side of the column was collected, measured and recorded. The volume of effluent collected from each material was compared for the first series of applied fluxes (i.e., Test 1). For the remainder of the laboratory program, the mass of water collected from each material was used to evaluate the partitioning of flow within the column. As a result, the measurements obtained for the last three cutoff heights (Test 2, 3 and 4) are considered more accurate than those obtained for the first cutoff height (Test 1). Each recorded
measurement was converted to a percentage of the total applied flux. Table 4.1 shows the amount of water collected from each side of the column as a percentage of the total effluent collected.

**Table 4.1**: Laboratory column results

<table>
<thead>
<tr>
<th>Cutoff Height (Contact Length) (mm)</th>
<th>Applied Flux Rate (m/s)</th>
<th>Percentage of Total Effluent Discharging from each Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>% Fine</td>
</tr>
<tr>
<td><strong>Test 1</strong> 590 (550)</td>
<td>a) $1.3 \times 10^{-5}$</td>
<td>47%</td>
</tr>
<tr>
<td></td>
<td>b) $9.3 \times 10^{-6}$</td>
<td>44%</td>
</tr>
<tr>
<td></td>
<td>c) $5.2 \times 10^{-6}$</td>
<td>57%</td>
</tr>
<tr>
<td></td>
<td>d) $3.9 \times 10^{-6}$</td>
<td>62%</td>
</tr>
<tr>
<td><strong>Test 2</strong> 390 (750)</td>
<td>a) $1.3 \times 10^{-5}$</td>
<td>35%</td>
</tr>
<tr>
<td></td>
<td>b) $9.3 \times 10^{-6}$</td>
<td>44%</td>
</tr>
<tr>
<td></td>
<td>c) $5.0 \times 10^{-6}$</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>d) $3.7 \times 10^{-6}$</td>
<td>100%</td>
</tr>
<tr>
<td><strong>Test 3</strong> 140 (1000)</td>
<td>a) $1.3 \times 10^{-5}$</td>
<td>25%</td>
</tr>
<tr>
<td></td>
<td>b) $8.7 \times 10^{-6}$</td>
<td>63%</td>
</tr>
<tr>
<td></td>
<td>c) $4.7 \times 10^{-6}$</td>
<td>97%</td>
</tr>
<tr>
<td></td>
<td>d) $3.7 \times 10^{-6}$</td>
<td>100%</td>
</tr>
<tr>
<td><strong>Test 4</strong> 40 (1100)</td>
<td>a) $1.3 \times 10^{-5}$</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>b) $9.5 \times 10^{-6}$</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>c) $5.5 \times 10^{-6}$</td>
<td>64%</td>
</tr>
<tr>
<td></td>
<td>d) $3.9 \times 10^{-6}$</td>
<td>80%</td>
</tr>
</tbody>
</table>

**Note**: The results shaded in grey were obtained with the outlet hoses located at the same elevation as the base of the layered materials. The unshaded results were obtained with the outlet hoses located 250 mm below the base of the materials.
The results obtained from the initial sixteen experiments led to the extension of the laboratory program by changing the base boundary condition for two additional tests. For these two conditions, the outlet hoses were raised 250 mm and placed at the same elevation as the bottom of the layered materials to ensure that the suction at the base of both materials was 0 kPa. The results obtained for these last two configurations are represented by the shaded values in Table 4.1.

A graphical representation of the results from the initial sixteen laboratory conditions is presented as Figure 4.1. Also presented in the figure are the results obtained with a base boundary condition of 0 kPa and a contact length of 1100 mm (i.e., cutoff height 40 mm) for two of the four surface fluxes.

**4.2 INTERPRETATION OF LABORATORY RESULTS**

The purpose of the column study was to investigate the potential for preferential flow within a fine and coarse-grained, vertically layered environment. The study investigated the significance of the contact length between the two layers in addition to the effect of various applied surface fluxes.

**4.2.1 Effect of Applied Surface Flux**

The applied surface fluxes selected at the beginning of the experiment are summarized in Table 3.1 in section 3.2.2, and reproduced as Table 4.2.
The flux rates were selected at the beginning of the study and then reapplied for each column configuration. The first applied surface flux (i.e., \((a) = 1.3 \times 10^{-5} \text{ m/s}\)) resulted in the formation of a thin free water surface on the fine-grained material under steady-state conditions. The thin film of water disappeared when the surface flux application rate was reduced to the value of the second flux rate (i.e., \((b) = 9.3 \times 10^{-6} \text{ m/s}\)); however, water was still visible in small depressions on the surface of the fine-grained material. Ponded water was no longer present on the surface of the fine-grained material under the third applied surface flux (i.e., \((c) = 5.2 \times 10^{-6} \text{ m/s}\)). The fourth applied flux (i.e., \((d) = 3.9 \times 10^{-6} \text{ m/s}\)), was less than the third applied flux.
### Table 4.2: Surface flux rates.

<table>
<thead>
<tr>
<th>Cutoff Height (Contact Length) (mm)</th>
<th>Applied Surface Flux Rate (m/s)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flux (a)</td>
<td>Flux (b)</td>
<td>Flux (c)</td>
<td>Flux (d)</td>
</tr>
<tr>
<td><strong>Test 1</strong></td>
<td>$1.3 \times 10^{-5}$</td>
<td>$9.3 \times 10^{-6}$</td>
<td>$5.2 \times 10^{-6}$</td>
<td>$3.9 \times 10^{-6}$</td>
</tr>
<tr>
<td>590 (550)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Test 2</strong></td>
<td>$1.3 \times 10^{-5}$</td>
<td>$9.3 \times 10^{-6}$</td>
<td>$5.0 \times 10^{-6}$</td>
<td>$3.7 \times 10^{-6}$</td>
</tr>
<tr>
<td>390 (750)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Test 3</strong></td>
<td>$1.3 \times 10^{-5}$</td>
<td>$8.7 \times 10^{-6}$</td>
<td>$4.7 \times 10^{-6}$</td>
<td>$3.7 \times 10^{-6}$</td>
</tr>
<tr>
<td>140 (1000)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Test 4</strong></td>
<td>$1.3 \times 10^{-5}$</td>
<td>$9.5 \times 10^{-6}$</td>
<td>$5.5 \times 10^{-6}$</td>
<td>$3.9 \times 10^{-6}$</td>
</tr>
<tr>
<td>40 (1100)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Average flux rate</strong></td>
<td>$1.3 \times 10^{-5}$</td>
<td>$9.2 \times 10^{-6}$</td>
<td>$5.1 \times 10^{-6}$</td>
<td>$3.8 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Although efforts were made to ensure that the four surface flux rates were identical for all cutoff heights, slight variations existed in the applied rates due to wearing of the flexible tubing in the peristaltic pump and the coarse calibration markings on the dial of the pump motor. The average applied surface fluxes are presented in Table 4.2. Figure 4.2 shows the effect of the applied surface flux rate on the percentage of flow transported through the fine-grained material for each applied surface flux.

The first two applied surface fluxes, (i.e., (a) and (b)), resulted in less than fifty-percent of the water being transported through the fine-grained material for all but one experimental condition (i.e., flux (b) = $8.7 \times 10^{-6}$ m/s with a cutoff of 1000 mm). The preferential flow path that formed for the first two applied surface fluxes was through...
the coarse material with greater than fifty-percent of water being collected from the bottom of the coarse-grained vertical layer.

When the applied surface fluxes were reduced to rates (c) and (d), the path of preferential flow shifted from the coarse-grained material to the fine-grained material with greater than fifty-percent of the water being transported through the fine-grained vertical layer.

![Bar chart](image)

**Figure 4.2** Percentage of total effluent discharging from the base of the fine-grained material compared to the applied surface flux rate for the laboratory results.
4.2.2 Effect of Contact Length

One of the primary objectives of the column study was to determine the significance of increased contact length between the two vertical columns of materials on the partitioning of flow between them. Figure 4.3 shows the effect of increased contact length on the percentage of flow collected from the fine-grained material for the applied surface fluxes, (i.e., (a) and (b)). For these first two flux conditions, the preferential flow path was through the coarse-grained material for all but one experimental condition. Under the first applied surface flux, (i.e., (a), with a contact length of 550 mm), the percentage of water collected from the fine material was 47%. When the contact length increased to 750 mm, 35% of the total applied water was collected from the bottom of the fine-grained material. The percentage of flow decreased to 25% and ~0% with contact lengths of 1000 mm and 1100 mm respectively.

For the first applied surface flux, (a), increasing the contact length between the two materials resulted in a greater opportunity for lateral transfer to occur between the two materials. An increasingly smaller percentage of the total effluent was collected from the fine-grained vertical layer.

The flow partitioning with increased contact lengths for the second applied surface flux, (b), is also shown in Fig. 4.3. The first two contact lengths, (i.e., 550 and 750 mm) both resulted in 44% of the total effluent being collected from the fine-grained material. Lowering the cutoff and increasing the contact length to 1000 mm increased the percentage of flow collected from the fine-grained material to 63%. When the contact length was further increased to 1100 mm, the flow from the fine-grained material decreased to 0% of the collected effluent.
Figure 4.3 The effect of increased contact length on the percentage of total effluent collected from the fine-grained material under the applied surface fluxes, (a) and (b).

The trend in Fig. 4.3 is for more water to transfer laterally from the fine-grained material into the coarse material with increased contact length under the first two applied flux rates. The result obtained with the applied surface flux of $8.7 \times 10^{-6}$ m/s (i.e., flux (b)), and a contact length of 1000 mm contradicts this trend with 63% travelling through the fine layer. The significance of this single laboratory measurement is explained more thoroughly in Chapter 5: Analysis and Discussion.

Figure 4.4 shows the significance of increasing the contact length between the two vertical layers for surface fluxes, (c) and (d). Under these two flux rates, the steady-state preferential flow path was through the fine-grained material (Fig. 4.2). Figure 4.4 shows
that increasing the contact length from 550 mm to 750 mm with an applied surface flux of (c), resulted in a greater percentage of water transferring laterally from the coarse-grained material over to the fine-grained material. Fifty-seven percent of the total effluent was collected from the fine-grained material with a 550 mm contact length and the percentage increased to 100% of the total effluent with a contact length of 750 mm. When the contact length was increased from 750 mm to 1000 mm, the percentage of flow collected from the fine-grained material reduced slightly from 100% to 97% of the total effluent (Fig. 4.4). With a total contact length of 1100 mm, the percentage of total effluent collected from the fine-grained material further reduced from 97% to 64%. The fine-grained material still transported greater than 50% of the total flow.

![Figure 4.4](image.png)

**Figure 4.4** The effect of increased contact length on the percentage of total effluent collected from the fine-grained material under the applied surface fluxes, (c) and (d).
Figure 4.4 also shows that increasing the contact length from 550 mm to 750 mm with an applied surface flux of (d), resulted in a greater percentage of water transferring laterally from the coarse-grained material over to the fine-grained material. Sixty-two percent of the total effluent was collected from the fine-grained material with a 550 mm contact length and the amount increased to 100% of the total effluent with a contact length of 750 mm. Increasing the contact length to 1000 mm did not alter the partitioning of flow within the column. One hundred percent of the effluent continued to discharge from the fine-grained material. Once the cutoff was lowered to a height of 40 mm (i.e., a contact length of 1100 mm) the percentage of total effluent collected from the fine-grained material reduced from 100% to 80%. The fine-grained material was still the preferential flow path within the column with approximately 80% of the total flow. However, the reduction in flow that occurred under both of these fluxes with increased contact lengths suggests that the water within the column transferred laterally from the fine-grained material back over to the coarse-grained material at a depth greater than 750 mm.

4.2.3 Effect of Base Boundary Condition

Figure 4.5 shows the effect of raising the outlet hoses to be flush with the base of the column. Raising the hoses ensured the suctions at the base of the column were the same in both materials at 0 kPa. Two steady-state fluxes, (c) and (d), were applied to the column with the cutoff located in the final position, resulting in a contact length of 1100 mm (i.e., cutoff height of 40 mm).
For the applied surface flux (c), the percentage of water collected from the base of the fine-grained material reduced from 64% to 0% when compared with the previous base boundary condition. For the applied surface flux (d), the percentage of water collected from the base of the fine-grained material reduced from 80% to 0% (Fig. 4.5). In effect, all of the effluent collected from the base of the column over the collection time frame for both surface fluxes was from the coarse-grained material when the existing base boundary condition was 0 kPa in both materials.

![Graph showing the effect of reducing the base boundary condition on the percentage of total effluent collected from the fine-grained material under the applied surface fluxes, (c) and (d) with a contact length of 1100 mm.]

**Figure 4.5** The effect of reducing the base boundary condition from -2.5 kPa to 0 kPa on the percentage of total effluent collected from the fine-grained material under the applied surface fluxes, (c) and (d) with a contact length of 1100 mm.
4.3 SUMMARY

In summary, the laboratory program was designed to measure the partitioning of flow between vertically layered, unsaturated materials under a range of applied surface fluxes and with variable contact lengths. The amount of flow travelling through both the fine and coarse-grained material was measured and recorded for eighteen experimental conditions. Sixteen of the conditions had the outlet hoses located 250 mm below the base of the vertically layered materials, and two that had the hoses located at the elevation of the bottom of the two materials.

4.3.1 Column Study Results

The results from the laboratory study indicate that under the first two applied flux conditions (i.e., (a) and (b)), which resulted in visible water in the interstitial pores on the surface of the fine-grained material, the coarse-grained material performed as the preferential pathway. Reducing the applied surface flux to the two lesser rates resulted in the majority of water being collected from the fine-grained material for all contact lengths less than 750 mm. At contact lengths greater than 750 mm and for the two lowest surface fluxes, the fine-grained material became the preferential flow path. The results from the laboratory study also suggest that, to a certain degree, the greater the contact length between two materials, the more opportunity for lateral transfer of water.

4.3.2 Possible Sources of Error

While care was given to obtaining accurate laboratory results, there are a few details that should be noted that may have affected the recorded measurements. The
column was initially saturated by applying a large flux to the surface. The flux resulted in a free water surface on top of the fine sand. The bottom outlet tubes were left open so that air would not be trapped by the wetting front. After 3 days, water was running freely from both outlet tubes and a saturated hydraulic conductivity test was attempted to characterize the materials in situ. A constant head was maintained above the top of the materials and the water flow discharging from each outlet hose was collected over a set length of time. The results were highly variable, the column leaked and the attempt to obtain an insitu saturated hydraulic conductivity was abandoned. The cutoff was drawn down to a height of 590 mm and the first of the four surface fluxes was applied. Steady-state conditions were determined by collecting the water discharging from each outlet hose in a graduated cylinder over a one minute time interval. The volume of water collected from each material was recorded and converted into a percentage of the total flux. It was determined at the end of the first set of tests that a more accurate method of collection and comparison should be used. The results obtained for the remaining three cutoff heights were measured by weighing the water collected from each material over a one-minute time interval.

Each time the cutoff was lowered, the column was gently tapped to ensure that an air gap did not exist between the two materials. With each lowering of the cutoff, some settlement did occur in the coarse-grained material. The coarse sand settled within the column by approximately 15 mm after lowering the cutoff the first time. Some additional coarse sand material was added to the top of the column to ensure that the surface of the column was level. By the end of the test, the total change in height in the coarse-grained material was approximately 20 to 25 mm. As the spaces between the
particles decrease (i.e., a decrease in void ratio), the ability of the soil to conduct liquid water also decreases. This change in density, by adding material to maintain a constant volume, could result in slight changes to material hydraulic properties as the test proceeded.

A peristaltic pump was used to deliver a constant flow rate to two constant head tanks. The tubing that delivered the flux from the pump to the constant head tanks required constant replacement since they would deliver a slightly greater flux when worn. Although the flux applied at the top of the column was checked frequently to ensure consistency, it is possible that the flux varied slightly due to the wearing of the tubes during the first two cutoff heights. For the last two cutoff heights, the tubes were replaced every two days whether wearing was visible or not, in order to reduce this possible variation in delivered fluxes.

Finally, the coarse gravel layer at the base of both materials was not vented throughout the experiment. It was intended at the beginning of the experiment that the interface between the coarse gravel layer and the vertically layered materials would be a drip surface and a zero pressure boundary condition. Near the end of the laboratory program, it became clear that by not venting the coarse drainage material, and with the outlet hoses being located 250 mm below the base of the column, a differential base boundary condition developed between the two vertical layers. The actual suctions at the base of the column were not measured and so a sensitivity analysis was conducted as part of the numerical modelling program in order to define the base boundary condition that existed in the column during the laboratory program.
Chapter 5
Analysis and Discussion

5.0 INTRODUCTION

Numerical modelling was conducted following the laboratory column study in order to identify the critical parameters and mechanisms that governed flow within the system.

5.1 NUMERICAL MODELLING PROGRAM

Steady-state numerical modelling was completed using the two-dimensional, saturated/unsaturated, finite element seepage model SEEP/W (GEO-SLOPE, 1991). Simulations were completed for the four different surface fluxes applied for four different cutoff heights. In addition, a sensitivity analysis was completed to determine the effect of the base boundary condition on calibration of the material properties.

5.1.1. SEEP/W Model

SEEP/W is a two-dimensional finite element software package that can be used to model both saturated and unsaturated flow. The governing differential equation used in the formulation of SEEP/W is as follows:
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\[ \frac{\partial}{\partial x} \left( k_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial h}{\partial y} \right) + Q = \frac{\partial \theta}{\partial t} \]  

[5.1]

where:  
- \( h \) = total head,  
- \( k_x \) = hydraulic conductivity in the x – direction,  
- \( k_y \) = hydraulic conductivity in the y – direction,  
- \( Q \) = applied boundary flux,  
- \( \theta \) = volumetric water content, and  
- \( t \) = time.

For a steady-state analysis, the amount of water entering and leaving an elemental soil volume is the same. As a result, the right hand side of Eq. [5.1] reduces to zero.

5.1.2 Column Mesh Design

A basic mesh was used to model all laboratory conditions. The mesh generated using SEEP/W was 114 cm high and 30 cm wide consisting of two, 15 cm vertically layered materials. The nodal spacing was 2 cm in both the x and y direction. The mesh was altered to represent the presence of the cutoff, which was simulated by incorporating a one-millimeter gap between the two layers over the area where the cutoff existed in the laboratory column. Figure 5.1 shows the four mesh designs created to represent the four different cutoff heights. Four different surface fluxes were applied as the top boundary condition.

Three flux sections were defined within each of the four mesh designs to determine the amount of flow travelling through each vertical layer. One flux section was located above the cutoff and intersected the entire column width. The other two flux sections were located below the height of the cutoff in each material. The flux sections are shown in Fig. 5.1 as solid, horizontal lines.
Figure 5.1 Four meshes used to model the cutoff heights of 590 mm, 390 mm, 140 mm and 40 mm and the flux sections used to determine partitioning.
5.1.3 Calibration of Model

The material properties for the Beaver Creek sand were calibrated using the results obtained for the second cutoff height of 390 mm (Test 2). The results obtained for the first cutoff height of 590 mm (Test 1) were not used because a less accurate technique had been used in the laboratory to determine the partitioning of flow between the two materials. The partitioning of flow in Test 1 had been determined by collecting the amount of water discharging from each material over a one minute interval using graduated cylinders to record the volume of water collected. When the cutoff was lowered to a height of 390 mm, it was decided that a more accurate method of determining the partitioning of flow was needed since the markings on the graduated cylinder were not fine enough for the small sample volume being collected. For the remainder of the laboratory study the amount of water flowing through each material was determined by collecting the water discharging from each outlet tube over a one minute interval and then determining the mass of water collected from each material. As a result, confidence in the laboratory measurements obtained for the last three cutoff heights (Test 2, 3 and 4) is greater than for those measurements obtained for the first cutoff height (Test 1).

Soil-water characteristic curves (SWCC) and saturated hydraulic conductivity values had been previously determined for both of the materials used in the column study. Since storage of water is not considered in steady-state numerical modelling, a hydraulic conductivity function is all that is required for input into the SEEP/W model. The hydraulic conductivity function can be predicted using a measured SWCC and the saturated hydraulic conductivity of a material. The unsaturated hydraulic conductivity
functions presented in Fig. 5.2 for both the Beaver Creek sand and medium silica sand were predicted using the Fredlund and Xing (1994) method using the measured soil-water characteristic curve shown in Fig. 3.4. Saturated hydraulic conductivity values, \( k_{sat} \), were also used in the prediction of the hydraulic conductivity functions. The saturated hydraulic conductivity value used for the silica sand was measured in the laboratory to be \( 1.48 \times 10^{-2} \) m/s. A wide range of saturated hydraulic conductivity values are reported in the literature for Beaver Creek sand as indicated by the shaded area in Fig. 5.2. The single value of saturated hydraulic conductivity used to predict the function presented in Fig. 5.2 was determined through model calibration.

Calibrating the numerical model consisted of adjusting the saturated hydraulic conductivity of the Beaver Creek (fine) sand between subsequent simulations until the best correlation was obtained between the measured and simulated results. The final saturated hydraulic conductivity value used in the model calibration was \( 7.5 \times 10^{-6} \) m/s. The final calibrated saturated hydraulic conductivity value resulted in two of the applied fluxes, (a) and (b), being greater than the saturated hydraulic conductivity of the fine sand and fluxes (c) and (d) being less than the saturated hydraulic conductivity of the fine sand.

Once the model was calibrated, the material properties were held constant and the modelling program was extended to the remaining column configurations and conditions.
Figure 5.2 Predicted unsaturated hydraulic conductivity functions for Beaver Creek Sand and medium silica sand.

5.1.4 Definition of Base Boundary Condition

In the laboratory experiment, the outlet tubes on both sides of the column were placed 250 mm below the top of the gravel layer. The numerical modelling program used a base boundary condition of $-0.25$ m total head (2.5 kPa suction) at the base of the fine material for all simulations. A series of base boundary conditions were applied to the coarse material for each applied flux. The defined total heads were $-0.01$ m, $-0.08$ m, and $-0.25$ m corresponding to matric suction values of 0.1 kPa, 0.8 kPa and 2.5 kPa. More information regarding the choice of base boundary conditions for the sensitivity analysis is provided in section 5.1.6.
The air-entry value of the fine material (Beaver Creek sand) is approximately 3 kPa. The air phase within an unsaturated soil is continuous at a degree of saturation of approximately 80% (i.e., $S < 80\%$). Occluded air bubbles commonly occur at degree of saturation values greater than 90% (i.e., $S < 90\%$). The transition zone between a continuous air phase and occluded air bubbles occurs between 80 to 90% (i.e., $80\% < S < 90\%$), (Fredlund and Rahardjo, 1993). The average value within this defined range is 85% and is approximately where the air phase starts to become continuous. The corresponding suction in the fine material at 85% saturation is approximately 4 kPa. The maximum suction that could have existed at the base of the fine material due to the location of the tubes is 2.5 kPa. Under this suction, the Beaver Creek sand would have remained tension saturated at the base of the column and the air phase would have been discontinuous. As a result, the suction existing at the interface between the coarse drainage layer and the fine material would have been 2.5 kPa.

The air-entry value of the coarse material (medium silica sand) is approximately 0.8 kPa. The placement of the tubes 250 mm below the base of the coarse material exceeded the maximum suction that the coarse material could have withstood and still remain tension saturated. The air phase was therefore continuous through both the coarse sand and the coarse drainage layer. There was no measurement made in the laboratory column to determine the suction that existed at the interface between the coarse sand and the drainage material. In the absence of this data, three base boundary conditions were applied to the coarse material in the numerical modelling program to investigate the influence of the base boundary condition on the partitioning of flow within the column. The first boundary condition assumed a hydrostatic suction profile.
from the outlet of the tubes right up to the base of the coarse material resulting in a total head base boundary condition of $-0.25 \text{ m} (2.5 \text{ kPa suction})$. The second applied base boundary condition corresponded to the maximum suction that could have existed at the base of the coarse material before the air phase became continuous, defined as $-0.08 \text{ m pressure head} (0.8 \text{ kPa suction})$. The third base boundary condition, assumed that the maximum suction that could be exerted by the coarse drainage layer on the interface between the coarse sand and the drainage layer would be equal to the residual suction of the drainage layer, which is assumed to correspond to approximately $-0.01 \text{ m} (0.1 \text{ kPa suction})$.

Two additional simulations were completed which simulated a cutoff height of 40 mm with the two smallest surface fluxes applied (i.e., c and d). A total head base boundary condition of $0 \text{ m}, (0 \text{ kPa suction})$ was applied to the base of both materials to determine what would have happened if the coarse drainage material had been vented resulting in the formation of a drip surface at the bottom of the column.

5.1.5 Numerical Modelling Results

The results from the numerical modelling program are presented in Table 5.1. The numerical modelling results obtained for the last cutoff height (i.e., 40 mm) show that greater than 100% of the applied surface flux exited the base of the fine material for several of the conditions modelled. The reason for this modelling result is due to the limitations of SEEP/W in defining an appropriate base boundary condition and will be explained more fully in the following section.
Table 5.1: Laboratory and numerical modelling results

<table>
<thead>
<tr>
<th>Cutoff Height (Contact Length) (mm)</th>
<th>Applied Flux Rate (m/s)</th>
<th>Percentage of Total Effluent Discharging from Fine Material</th>
<th>% Fine (Lab)</th>
<th>% Fine (Modelling)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Coarse Material Boundary Condition</td>
<td>0.1 kPa</td>
<td>0.8 kPa</td>
</tr>
<tr>
<td>Test 1 590 (550)</td>
<td>a) $1.3 \times 10^{-5}$</td>
<td>47%</td>
<td>32%</td>
<td>32%</td>
</tr>
<tr>
<td></td>
<td>b) $9.3 \times 10^{-6}$</td>
<td>44%</td>
<td>45%</td>
<td>45%</td>
</tr>
<tr>
<td></td>
<td>c) $5.2 \times 10^{-6}$</td>
<td>57%</td>
<td>77%</td>
<td>77%</td>
</tr>
<tr>
<td></td>
<td>d) $3.9 \times 10^{-6}$</td>
<td>62%</td>
<td>91%</td>
<td>91%</td>
</tr>
<tr>
<td>Test 2 390 (750)</td>
<td>a) $1.3 \times 10^{-5}$</td>
<td>35%</td>
<td>34%</td>
<td>34%</td>
</tr>
<tr>
<td></td>
<td>b) $9.3 \times 10^{-6}$</td>
<td>44%</td>
<td>47%</td>
<td>47%</td>
</tr>
<tr>
<td></td>
<td>c) $5.0 \times 10^{-6}$</td>
<td>100%</td>
<td>80%</td>
<td>79%</td>
</tr>
<tr>
<td></td>
<td>d) $3.7 \times 10^{-6}$</td>
<td>100%</td>
<td>93%</td>
<td>93%</td>
</tr>
<tr>
<td>Test 3 140 (1000)</td>
<td>a) $1.3 \times 10^{-5}$</td>
<td>25%</td>
<td>41%</td>
<td>40%</td>
</tr>
<tr>
<td></td>
<td>b) $8.7 \times 10^{-6}$</td>
<td>63%</td>
<td>60%</td>
<td>57%</td>
</tr>
<tr>
<td></td>
<td>c) $4.7 \times 10^{-6}$</td>
<td>97%</td>
<td>97%</td>
<td>88%</td>
</tr>
<tr>
<td></td>
<td>d) $3.7 \times 10^{-6}$</td>
<td>100%</td>
<td>100%</td>
<td>97%</td>
</tr>
<tr>
<td>Test 4 40 (1100)</td>
<td>a) $1.3 \times 10^{-5}$</td>
<td>0%</td>
<td>75%</td>
<td>61%</td>
</tr>
<tr>
<td></td>
<td>b) $9.5 \times 10^{-6}$</td>
<td>0%</td>
<td>101%</td>
<td>80%</td>
</tr>
<tr>
<td></td>
<td>c) $5.5 \times 10^{-6}$</td>
<td>64%</td>
<td>172%</td>
<td>131%</td>
</tr>
<tr>
<td></td>
<td>d) $3.9 \times 10^{-6}$</td>
<td>80%</td>
<td>238%</td>
<td>174%</td>
</tr>
</tbody>
</table>

Note: The italicized group of text indicates the results that were used to calibrate the model by adjusting the saturated hydraulic conductivity of the Beaver Creek sand (fine material).
The results from the additional simulations, completed for a cutoff of 40 mm and fluxes c and d with a base boundary condition of 0 m total head are presented at the end of this chapter in section 5.1.9.

5.1.6 Effect of Base Boundary Condition

Before further analysis can be made regarding the effect of the applied surface flux or the contact length between the two layers, the effect of the base boundary condition on the numerical modelling results must be explored.

The inclusion of a vent within the coarse drainage material on both sides of the laboratory column would have resulted in the formation of a drip surface at the bottom of the column. The base boundary condition for both materials in the numerical modelling program would have been 0 m total head or 0 kPa suction. However, locating the outlet tubes 250 mm below the base of the vertical layers resulted in a differential base boundary condition across the base of the column.

The base boundary condition for the fine material was held constant throughout the numerical modelling program at a total head of -0.25 m (2.5 kPa suction) which corresponds to the base boundary condition that is assumed to have existed in the laboratory column.

The base boundary condition for the coarse sand cannot be as clearly defined since the larger pores present in the coarse sand would not have sustained a suction of 2.5 kPa without beginning to drain at an applied suction of approximately 0.8 kPa. The influence of the coarse drainage layer on the base boundary condition that existed in the column is difficult to define. The coarse drainage layer was uniform in nature with
respect to particle size and consisted of gravel that had been retained on the 3/8 inch sieve. It is reasonable to assume that this type of material drains under gravitational forces with virtually no measurable air entry value and the water phase rapidly becomes discontinuous at low values of suction in the range of 0.1 kPa. Three base boundary conditions were applied at the base of the coarse sand mesh in a sensitivity analysis designed to identify the boundary condition that existed in the laboratory study. In addition, the sensitivity analysis was intended to investigate the sensitivity of the modelling results to changes in the base boundary condition.

The first base boundary condition defined for the base of the coarse layer was a total head of -0.25 m (2.5 kPa suction) assuming a hydrostatic profile from the outlet tubes up to the coarse sand/drainage layer interface. The second defined boundary condition used a total head of -0.08 m (0.8 kPa suction), which assumed that the suction existing at the interface corresponded to a degree of saturation of 85%, which is approximately the maximum suction which could exist at the base of the coarse sand before the air phase would become continuous. The third boundary condition considered that the drainage layer was not water filled and that a capillary break existed at the interface between the coarse sand and the drainage layer. The maximum suction that the drainage layer could exert on the coarse sand would be equal to the residual suction of the drainage layer that was assumed to be approximately 0.1 kPa (total head of -0.01 m).

The results from the numerical modelling program showed that the effect of altering the base boundary condition was negligible on the flow partitioning results obtained for the first two cutoff heights of 590 mm and 390 mm (i.e., Test 1 and 2). It is
important to note that altering the base boundary condition in the coarse layer from −0.25 m to −0.01 m did not affect the calibration of the material properties. Figure 5.3 shows the pressure profiles that existed in the column for all three base boundary conditions for Test 2b. The pressure profiles in Fig. 5.3 for all three boundary conditions show that by the time the height of the cutoff is reached and the two layers are in direct contact, the influence of the base boundary condition does not affect the gradient which exists between the two materials.

The numerical modelling results presented in Table 5.1 for the simulations with lower cutoff heights (i.e., Test 3 and 4), show that changing the applied base boundary condition did influence the calculated partitioning of flow between the two materials. Figure 5.4 shows the pressure profiles with all three boundary conditions for Test 3b. The pressures in the coarse material for first two boundary conditions (i.e., −0.01 m and −0.08 m total head) increase near the bottom of the column to satisfy the imposed boundary condition. The pressures in the coarse material for the third boundary condition (−0.25 m total head) decrease near the bottom of the column to satisfy the imposed boundary condition. Regardless of the base boundary condition imposed on the coarse material, a gradient forms between the two vertical layers above the cutoff causing water from the coarse material to transfer laterally over to the fine sand. The fine sand is able to sustain a greater negative pressure at elevations greater than the height of the cutoff resulting in a total head gradient toward the fine vertical layer. The numerical modelling results that correlate the best with the laboratory column results are obtained with a base boundary condition of −0.01 m (0.1kPa suction).
Figure 5.3 Pressure profiles and velocity vectors for Test 2b for different boundary conditions along the base of the model:

A) -0.25 m (fine); -0.01 m (coarse)
B) -0.25 m (fine); -0.08 m (coarse)
C) -0.25 m (fine); -0.25 m (coarse)
Figure 5.4 Pressure profiles and velocity vectors for Test 3b for different boundary conditions along the base of the model:  
A) -0.25 m (fine); -0.01 m (coarse)  
B) -0.25 m (fine); -0.08 m (coarse)  
C) -0.25 m (fine); -0.25 m (coarse)
Some of the numerical modelling results obtained for the lowest cutoff height of 40 mm (i.e., Test 4) presented in Table 5.1 do not appear reasonable. The discrepancy between the calculated and laboratory results is related to how boundary conditions are defined in SEEP/W. Base boundaries can be defined as either constant heads or flux boundaries. It is not possible to define a boundary that is both a constant head and a zero flux boundary. By defining a constant head boundary, the model assumes that a water source is available at the base of the column and water is free to be drawn upward from this source. The velocity vectors presented in Fig. 5.5 show that for a differential base boundary condition between the two layers, water is drawn upward from the base of the coarse layer and is transferred over to the fine sand in response to the gradient that forms. As a result, the amount of water calculated to have exited the fine material is greater than 100% of the total applied flux. The numerical modelling results are not considered reliable for the lowest cutoff heights with a differential base boundary condition. The flux values determined using a base boundary condition of \(-0.25\) m for both the fine and coarse material did not result in excess water being included in the calculations, but the results do not correlate well with the laboratory measurements.

In summary, the base boundary condition that best correlated with the laboratory measurements for Tests 1, 2 and 3 and all applied surface fluxes was a total head base boundary condition of \(-0.01\) m applied to the coarse material and \(-0.25\) m applied to the fine material. The partitioning of flow results obtained using this boundary condition in addition to the laboratory results is what will be used to determine the effect of applied surface flux on preferential flow in vertically layered, unsaturated systems.
Figure 5.5 Pressure profiles and velocity vectors for Test 4b for different boundary conditions along the base of the model:
A) -0.25 m (fine); -0.01 m (coarse)
B) -0.25 m (fine); -0.08 m (coarse)
C) -0.25 m (fine); -0.25 m (coarse)
5.1.7 Effect of Applied Surface Flux

The actual surface fluxes that were applied to the column in the laboratory were used in the numerical modelling program and are presented in Table 5.1. It is apparent from comparing the laboratory results with the numerical modelling results presented in Table 5.1 that the base boundary condition had a significant effect on the results obtained in the numerical modelling program. It was determined through the sensitivity analysis that a total head base boundary condition of -0.25 m and -0.01 m applied at the base of the fine and coarse material respectively, provided the closest correlation with the laboratory results. It was also determined that the numerical modelling results obtained for the lowest cutoff height should not be considered accurate representations of the laboratory results. The effect of the rate of applied surface fluxes on the formation of preferential flow paths in vertically layered, unsaturated systems is best discussed using both the laboratory results and numerical modelling results for the first three cutoff heights of 590 mm, 390 mm and 140 mm (i.e., Test 1, Test 2 and Test 3).

In both the laboratory and numerical modelling programs an applied surface flux that was greater than the saturated hydraulic conductivity of the fine material (i.e., fluxes a and b) resulted in the majority of the water discharging from the base of the coarse sand for all cases but Test 3b (Fig. 5.6). When the applied surface fluxes were reduced to be less than the saturated hydraulic conductivity of the fine material (i.e., fluxes c and d), the preferential flow path shifted and the majority of water discharged from the base of the fine sand for all cases (Fig. 5.7).
Figure 5.6 Percentage of total effluent discharging from the base of the fine material for surface fluxes greater than the saturated hydraulic conductivity of the fine material.

Figure 5.7 Percentage of total effluent discharging from the base of the fine material for surface flux rates less than the saturated hydraulic conductivity of the fine material.
The numerical modelling profiles obtained during the calibration of Test 2 (a) and (b) are presented in Fig. 5.8. The profiles show the velocity vectors and the pressure head contours that formed within the column as well as the computed and laboratory measured flux values from both materials determined at the base of the column. Under flux (a), which was greater than the saturated hydraulic conductivity of the fine sand, the numerical modelling results show 36% of the flux that was initially applied to the surface of the fine sand transferred over to the coarse sand before the cutoff height of 390 mm was reached. The laboratory results show that 6% of the flux initially applied to the fine sand transferred over to the coarse sand before the top of the cutoff was reached.

Flux (b), which was also greater than the saturated hydraulic conductivity of the fine sand, resulted in 10% of the water that was initially applied to the fine sand transferring over to the coarse sand before the cutoff height of 390 mm was reached. The laboratory results show 12% of the flux initially applied to the fine sand transferred over to the coarse sand before the top of the cutoff was reached. The pressure head contours in Fig. 5.8 show that the horizontal transfer of water from the fine material over to the coarse material near the top of the column occurs in response to the total head gradient that forms under the applied flux rates. Total head is defined as the pressure head plus the elevation head, under both applied flux rates (a) and (b), a more negative pressure head forms at the top of the column in the coarse material than forms in the fine material at the same elevation resulting in a total head gradient toward the coarse material.
The pressure head contours in Fig. 5.8 show that while gradients develop at both the top and bottom of the column, an equilibrium suction forms in the middle of the column. Figures 5.9 and 5.10 show the pressure profiles that develop at the nodes in each vertical layer directly adjacent to the interface between the fine and coarse materials under applied surface fluxes (a) and (b) for Tests 1 and 2, respectively (i.e., cutoff heights of 590 mm and 390 mm).
Figure 5.9 Pressure versus elevation in the fine and coarse sand down the length of the column for Test 1a, and Test 1b.

Figure 5.10 Pressure versus elevation in the fine and coarse sand down the length of the column for Test 2a, and Test 2b.
The equilibrium suction that develops between the vertical layers for cutoff heights of 590 mm and 390 mm (i.e., Test 1 and Test 2), under applied flux (a) below the top of the cutoff is a little less than 1.50 kPa. Under applied flux (b), the equilibrium suction that develops as the two materials interact is 1.58 kPa.

Figure 5.11 shows a close-up of the hydraulic conductivity functions for both materials along with the applied flux rates (a) and (b) and the corresponding suctions that would develop if the column was filled with a homogenous mixture of either material. The flux rates intercept the hydraulic conductivity functions at suction values of approximately 1.50 kPa for flux (a) and 1.58 kPa for flux (b). It is the coarse material that is the more conductive of the materials at both of these suctions and which becomes the preferential flow path within the column.

The modelling results from Test 2 (c) and (d) (i.e., cutoff heights of 140 mm and 40 mm) are presented in Fig. 5.12. The profiles show the velocity vectors and the pressure head contours that form within the column as well as the computed and laboratory measured flux values from both materials determined at the base of the column. Under the third and fourth applied fluxes, (c) and (d), which were both less than the saturated hydraulic conductivity of the fine sand, water that was initially applied to the coarse sand transferred laterally over to the fine sand near the top of the column. The horizontal transfer of water from the coarse material over to the fine material occurs in response to the total head gradient that formed near the top of the column under the applied flux rates as shown by the pressure head contours in Fig. 5.12. A more negative pressure head develops at the top of the column in the fine material than in the coarse material at the same elevation resulting in a total head gradient toward the fine material.
Figure 5.11 Predicted unsaturated hydraulic conductivity functions and the equilibrium suction values that develop under applied fluxes (a) and (b).

The pressure head contours in Fig. 5.12 show that while gradients form at both the top and bottom of the column, an equilibrium suction forms in the middle section of the column. Figures 5.13 and 5.14 show the pressure profiles that establish at the interface between the vertical layers in both the fine and coarse materials under applied surface fluxes (c) and (d) for Tests 1 and 2, respectively.
The equilibrium suction that develops between the vertical layers for cutoff heights of 590 mm and 390 mm (i.e., Test 1 and Test 2) under applied flux (c) is greater than 2.1 kPa. Under applied flux (d), the equilibrium suction that develops between the two materials ranges between 2.6 and 2.8 kPa.
Figure 5.13  Pressures versus elevation forming in the fine and coarse sand down the length of the column for Test 1c, and Test 1d.

Figure 5.14  Pressures versus elevation forming in the fine and coarse sand down the length of the column for Test 2c, and Test 2d.
Figure 5.15 shows a close-up of the hydraulic conductivity functions for both materials and the corresponding suctions that develop under the applied flux rates (c) and (d). The flux rates intercept the hydraulic conductivity function for the fine sand at suction values of 3.90 kPa for flux (c) and 4.17 kPa for flux (d). The suctions corresponding to flux rates (c) and (d) for the coarse sand are 1.80 kPa and 1.87 kPa respectively. The equilibrium suctions that develop within the column as a result of the two materials interacting are indicated by small circles on Fig. 5.15. The equilibrium suction is greater than the suction that would form in a homogenous coarse sand but less than what would form in a homogenous fine sand. However, for both equilibrium suctions, it is the fine sand that is more conductive and forms the preferential flow path within the column.

Figure 5.15 Predicted unsaturated hydraulic conductivity functions and the equilibrium suction values that develop under applied fluxes (c) and (d).
The analysis of both the laboratory and numerical modelling data shows that when the applied flux is greater than the saturated hydraulic conductivity of the fine sand, the coarse sand is the preferential pathway through the column. This occurs because under the larger infiltration rate, the suctions that develop within the column are reduced. Even though the applied flux rate may result in unsaturated conditions within the coarse sand, the pores that remain fluid filled within the coarse sand ensure that the coarse material is able to conduct water more readily than the smaller, fluid filled pores of the fine sand.

When the applied flux is reduced to be less than the saturated hydraulic conductivity of the fine sand, the equilibrium suction that establishes within the column results in further drainage of the pores within the coarse sand. The drained pores act as barriers to the flow of liquid water and reduce the hydraulic conductivity of the coarse sand. At suctions greater than 1.6 kPa for the materials used in this study, the fine sand then becomes the more conductive material and the preferential pathway shifts to the fine sand. The single exception is the result obtained for Test 3b. The pressure head profile for Test 3b is shown in Fig. 5.16. The applied flux (b) was greater than the saturated hydraulic conductivity of the fine material, however both the laboratory and numerical modelling results showed that greater than 50% of the total applied flux discharged from the fine material.

The pressure head profiles in Fig. 5.16 show that a gradient developed between the two materials just above the height of the cutoff as a result of the base boundary condition. The pressures attempted to satisfy the imposed boundary condition at the
base of the column and the cutoff was not high enough to keep the layers from interacting.

Figure 5.16 Velocity vectors and pressure head contours for Test 3 for applied flux (b).

5.1.8 Effect of Contact Length

One of the objectives of the column study was to investigate the effect of increased contact length on the partitioning of flow between the two materials.

The laboratory results presented in Chapter 4 showed that when the applied surface flux was greater than the saturated hydraulic conductivity of the fine sand, lowering the cutoff resulted in an increasingly larger percentage of the total effluent being collected from the coarse-grained vertical layer. The exception to this trend was
Test 3b, which had greater than 50% of the applied flux exiting the fine sand. Numerical modelling revealed that a gradient developed over a distance greater than that of the cutoff height due to the differential base boundary condition (Fig. 5.10) providing an explanation for the contrary reading. The longer gradient/transition zone resulted in water transferring from the preferential coarse sand back over to the fine sand just above the height of the cutoff.

It was anticipated that the numerical modelling program would offer similar results to those measurements in the laboratory program. However, as illustrated in Fig. 5.17, increasing the contact length resulted in less water transferring over to the coarse layer.

![Figure 5.17](image)

**Figure 5.17** The effect of increased contact length on the percentage of total effluent collected from the coarse-grained material for flux (a).
Figure 5.18 shows a close agreement between the modelling and laboratory results. However, the laboratory and numerical modelling results obtained for fluxes greater than the saturated hydraulic conductivity of the fine material do not establish clear trends regarding the influence of contact length on the partitioning of flow in a vertically layered, unsaturated system. Some of the factors influencing the reliability of the numerical modelling program are discussed in the summary section of this chapter.

![Graph showing the effect of increased contact length on the percentage of total effluent collected from the coarse-grained material for flux (b).](image)

**Figure 5.18** The effect of increased contact length on the percentage of total effluent collected from the coarse-grained material for flux (b).

The results obtained for the two applied fluxes, which were less than the saturated hydraulic conductivity of the fine sand establish clearer trends regarding the influence of increased contact lengths on the partitioning of flow within the column. Figures 5.19
and 5.20 show the results from the laboratory and modelling program for fluxes (c) and (d) respectively.

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**Figure 5.19** The effect of increased contact length on the percentage of total effluent collected from the coarse-grained material for flux (c).

**Figure 5.20** The effect of increased contact length on the percentage of total effluent collected from the coarse-grained material for flux (d).
5.1.9 Effect of a Zero Suction Base Boundary Condition

The outlet tubes were located 250 mm below the base of the fine and coarse sand for most of the laboratory program. The location of the tubes resulted in a differential base boundary condition existing at the base of the vertically layered system. The sensitivity analysis conducted as part of the numerical modelling program showed that the best correlation between laboratory results and modelling results occurred with a suction of 2.5 kPa at the base of the fine sand and 0.1 kPa at the base of the coarse sand.

At the end of the laboratory study, after all sixteen experimental conditions had been completed, the cutoff was left undisturbed at a height of 40 mm and the outlet tubes were raised 250 mm to be flush with the base of the fine and coarse sand. The raising of the tubes established a constant suction at the base of both materials of 0 kPa. The last two applied surface fluxes (c) and (d), which were both less than the saturated hydraulic conductivity of the fine sand, were then reapplied to the surface of the column. Steady-state conditions were established and the resulting effluent was collected from each test. Virtually 100% of the applied flux discharged from the coarse sand and not from the fine sand for both applied fluxes.

The laboratory results recorded for the final two experimental conditions appear contrary to the results obtained from the other column tests. The trend established by the other results was when the applied surface flux was less than the saturated hydraulic conductivity of the fine sand, water which was initially applied to the coarse sand transferred laterally over to the fine sand layer, which became the preferential pathway. However, the findings are consistent with the results obtained by Horton and Hawkins (1965). Horton and Hawkins found that when the cutoff separating the fine soil from the
sand core was lowered so that it extended only 25.4 mm above the bottom, none of the applied fluxes that had previously resulted in the majority of effluent discharging from the fine soil provided similar results. The results showed that for all eleven simulated rainfall events, 97% to 100% of the effluent discharged from the coarse sand core. Horton and Hawkins (1965) concluded that the water must have flowed from the sand core into the fine soil near the top of the column as it had for all the previous experimental conditions. The water had then flowed back into the sand core near the base of the column in the region where the sand contained continuous water held by surface tension, which was pre-determined to be approximately 200 mm above the base of the column corresponding to an air entry value of approximately 2 kPa.

Based on a measured air entry value of 0.8 kPa, the capillary rise for the medium silica sand was expected to be approximately 80 mm, which was higher than the final cutoff height of 40 mm. Two simulations were completed for a cutoff height of 40 mm and surface fluxes (c) and (d) applied under steady-state conditions (i.e., Test 5c and Test 5d). The results from the numerical modelling program were not quite as extreme as the laboratory results with 89% and 87% of the total applied flux discharging from the coarse sand for fluxes (c) and (d), respectively.

The pressure contours and velocity vectors for Test 5c and 5d are presented in Fig. 5.21. The formation of a gradient at the top of the column is still responsible for the lateral transfer of water from the coarse sand over to the fine sand. The water remains in the fine sand down the length of the column and then flows back into the coarse layer near the base of the column where the majority of water then discharges from the base of the coarse sand.
Figure 5.21  Pressure head contours and velocity vectors for Test 5 (c) and (d) with a constant base boundary condition of 0 kPa.

The re-crossover of water corresponds to a pressure head contour of approximately -0.16 m in the coarse sand which converts to a suction 1.6 kPa. Figure 5.22 shows the two hydraulic conductivity functions for the two materials. At suctions greater than 1.6 kPa, the fine sand is more conductive. At suctions less than 1.6 kPa, the coarse sand is the more conductive of the two materials.
Chapter 5: Analysis and Discussion

5.2 SUMMARY

The numerical modelling program was conducted using the two-dimensional, saturated/unsaturated flow model SEEP/W. Calibration of the model was completed by adjusting the saturated hydraulic conductivity of the fine sand for Test 2(a), (b), (c) and (d) until the best correlation was achieved. Once the model was calibrated, the remaining column configurations were simulated.

A sensitivity analysis was conducted to identify the base boundary condition that existed in the laboratory column. No measurements for matric suction had been taken.

Figure 5.22 Hydraulic conductivity functions of fine and coarse sand showing the suction where the fine sand becomes more conductive than the coarse sand.
during the laboratory program and the location of the outlet tubes 250 mm below the base of the column resulted in a different boundary condition existing in the fine and coarse sand layers. The sensitivity analysis was conducted by maintaining the base boundary condition of the fine sand at total head of -0.25 m. The base boundary condition of the coarse sand was then defined as being either -0.01 m, -0.08 m or -0.25 m. The results obtained using a coarse base boundary condition of -0.01 m had the best agreement with the measured laboratory results and were used in the analysis of applied surface fluxes and contact lengths.

The analysis showed that applying a flux rate greater than the saturated hydraulic conductivity of the fine sand resulted in the coarse sand being the preferential flow path. The equilibrium suction that was established between the two vertical layers was approximately equal to the suction value that would develop in a homogenous column filled with coarse sand under the applied flux rate.

When the applied flux rate was reduced to be less than the saturated hydraulic conductivity of the fine sand, the fine sand vertical layer became the preferential flow path. The velocity vectors in Fig 5.12 show that water initially entering the coarse material was drawn over to the fine-grained material due to the formation of a total head gradient. If the column had been filled with a homogenous fine or coarse sand, the equilibrium suctions that would develop under the applied flux (c) would be 3.90 kPa and 1.80 kPa, respectively. Under the applied flux (d) the equilibrium suction that would develop for a homogenous column with fine or coarse sand would be 4.17 kPa and 1.87 kPa, respectively. Within a vertically layered system where the two materials are in direct contact, the equilibrium suction that actually develops under the applied
surface fluxes is equal to a value somewhere between these extreme values; 2.1 kPa for flux (c) and 2.6 to 2.8 kPa for flux (d). The equilibrium suction however, is still larger than the suction where the two functions cross at 1.6 kPa. The material that transports the majority of the water is the one that exhibits a greater hydraulic conductivity, which in this case is the fine sand.

Analysis of the effect of contact length between the two materials was not clear as the laboratory results and the numerical modelling results showed opposite trends when the applied flux was greater than the saturated hydraulic conductivity of the fine sand. When the applied flux was reduced, the results from the laboratory program correlated well with the numerical modelling results, but the influence of the differential base boundary condition became more significant.

In general the calibrated results from the numerical modelling program agreed with the laboratory results. There were some assumptions made as part of the modelling program that should be considered when comparing the laboratory results with the numerical modelling results.

The hydraulic conductivity functions used in the numerical modelling program were predicted from a single soil-water characteristic curve that was pre-determined with very little total stress applied. In fine-grained materials, consolidation of a soil reduces the void ratio and results in a modest increase in the air-entry value of a soil. In addition, the saturated hydraulic conductivity value is also sensitive to changes in void ratio, which is supported by the wide range of saturated hydraulic conductivities reported in the literature for Beaver Creek. The numerical model used a single hydraulic conductivity function and a single value of saturated hydraulic conductivity for each
material. It is possible that over the laboratory column height of 1140 mm, that the void ratio of the material located at the base of the column was slightly less than the void ratio at the top of the column and as a result, the saturated hydraulic conductivity of the Beaver Creek sand was not constant throughout. However, the generally positive correlation between the laboratory and numerical modelling results suggest that the predicted functions were close to being representative. It is more likely that significant variations between the laboratory program and the numerical modelling program are a result of the base boundary condition not being clearly identified.

The action of drawing down the cutoff within the laboratory column may have resulted in the formation of a gap between the two materials that may not have closed completely by inward sloughing of the coarse sand. A visible reduction in the height of the coarse vertical layer was noticed, but complete contact between the two materials located above the cutoff could not be confirmed. The numerical model did not take this possibility into account.
6.0 SUMMARY

The process of infiltration into a homogeneous soil has been extensively studied by both soil physicists and hydrologists. Research on preferential flow and on the flow of water through unsaturated soils has, in general, been completed by different disciplines of science and engineering resulting in a wide range of terminology and research objectives. Many of the research studies have been empirical and have applied only to the specific conditions analysed in the research. Rarely are material properties such as the soil-water characteristic curve or unsaturated hydraulic conductivity functions presented to help describe the processes governing flow through soils.

Excavation of a waste rock pile at the Golden Sunlight Mine (GSM) in Montana, revealed a highly stratified, steeply dipping, fine and coarse-layered environment. The field work conducted by Herasymuik (1996) at GSM showed that the fine-grained waste rock had elevated moisture contents while the adjacent coarse layers were dry and relatively unoxidized. These findings suggested the formation of preferential flow paths through the fine-grained material (Herasymuik, 1996).
In response to the findings by Herasymuik (1996), a thesis project involving column studies was developed to investigate the mechanisms for preferential flow through vertically stratified layers. Preliminary numerical modelling was conducted on both a vertically layered system and a steeply inclined system and showed the potential for preferential flow to develop in both environments. A vertically layered column was ultimately selected to remove the potential for lateral flow enhanced by gravity forces. The research into preferential flow conducted by Horton and Hawkins in 1965 provided an experimental basis for the column study described in this thesis. There are several significant differences between the two research programs. Horton and Hawkins were interested in relating the lateral transfer of water from a single type of coarse-grained material over to a single type of fine-grained material under specific rainfall rates and durations. For the project summarized in this thesis, the focus was to correlate steady-state surface fluxes to the hydraulic properties of two contrasting materials (i.e., fine versus coarse-grained materials). This approach ensured the findings of the research could then be applied to other materials and environments.

The column was designed to create an environment where the amount of lateral flow between two vertical layers could be quantified and related to the applied surface flux under steady-state conditions. In addition, an adjustable, thin metal sheet was incorporated into the column design to determine the significance of increased contact length between the vertical layers on the partitioning of flow within the column.

The experimental procedure for the laboratory column study consisted of sixteen different applied flux/cutoff height configurations. Four steady-state fluxes were applied to the surface for four different cutoff heights. Of the four applied fluxes, two were
greater than the saturated hydraulic conductivity of the fine sand and two were less than the saturated hydraulic conductivity of the fine sand. The outlet tubes for both layers were located 250 mm below the base of the sand. The results obtained from the initial sixteen experiments led to the extension of the laboratory program by two additional tests by changing the base boundary. For these two conditions, the outlet hoses were raised 250 mm and placed at the elevation of the bottom of the layered materials to ensure that the suction at the base of both materials was 0 kPa.

6.1 CONCLUSIONS

- The unsaturated hydraulic conductivity functions for both the fine and coarse materials showed that at very low suctions, (i.e., less than 1.6 kPa), the coarse material was more conductive. However, the two curves intersected at approximately 1.6 kPa and at suctions greater than 1.6 kPa, the fine sand was the most conductive material.

- Both the laboratory and numerical modelling results showed that when the applied surface flux was greater than the saturated hydraulic conductivity of the finer sand, the total head gradient that formed near the top of the column resulted in an initial transfer of water from the fine sand over to the coarse sand. The equilibrium suction that developed within the middle of the column was less than 1.6 kPa resulting in the more conductive coarse layer becoming the preferential flow path. Reducing the infiltration rate below the saturated hydraulic conductivity of the fine sand resulted in a total head gradient toward the fine sand near the top of the column. The equilibrium suction that developed within the column was greater than that which
would have formed in a homogenous coarse sand and less than what would have formed in a homogenous fine sand. However, the suction was still greater than that corresponding to the intersection of the two hydraulic conductivity functions, (i.e., 1.6 kPa), resulting in the fine sand becoming the preferential flow path within the column. One of the laboratory and numerical modelling tests did not follow this trend. It was determined that the cutoff was not of sufficient height to eliminate the effect of the imposed base boundary conditions. In general the results from the numerical modelling program correlated well with the measured laboratory results for this analysis in identifying preferential flow paths under applied surface flux rates.

- Lowering the cutoff in the laboratory under applied surface flux rates greater than the saturated hydraulic conductivity of the fine sand generally resulted in a greater lateral transfer of water from the fine sand over to the more conductive coarse sand layer. The results from the numerical modelling program did not correlate well with the laboratory results. The discrepancy in results between the two programs may be attributed to changes in void ratio resulting in saturated hydraulic conductivities that were not constant values down the length of the column. The numerical modelling program considered a single value and did not account for subtle changes in the structure of the materials over depth and time. In addition, the lowering of the cutoff within the laboratory column may have resulted in the formation of a gap between the two materials that may not have closed completely by inward sloughing of the coarse sand. A visible reduction in the height of the coarse vertical layer was noticed, but complete contact between the two materials located above the cutoff.
could not be confirmed. The numerical model did not take this possibility into account.

- The last two experiments that were conducted in the laboratory consisted of creating a 0 kPa base boundary condition across both materials at the bottom of the column under the last two applied surface fluxes (i.e., c and d). Although the applied fluxes were less than the saturated hydraulic conductivity of the fine sand, and the other experimental conditions had shown that, for that low a flux, the fine sand should be the preferential flow path, virtually all of the discharging water was collected from the coarse sand layer. The modelling confirmed this trend but showed less extreme results. The effect of reducing the base boundary condition to 0 kPa resulted in water that was flowing preferentially through the fine sand, then transferring laterally back over to the coarse sand. The re-cross-over occurred because the suctions reduced in both materials to satisfy the base boundary condition. As the suctions reduced below 1.6 kPa, the coarse sand became the more conductive material and the formation of a total head gradient towards the coarse layer resulted in the lateral transfer of water from the fine layer over to the coarse sand.

- The results of the research conducted for this thesis show that water prefers to flow where water exists. A fine-grained soil has smaller interstitial pores and is able to maintain fluid-filled pores at suctions greater than that of a coarse-grained material. Once suctions exceed the air entry value of the material, air enters the system which increases the tortuosity of the liquid water flow path, resulting in a reduction in the materials ability to conduct water. The decrease in hydraulic conductivity with
increased suctions for each material is dependant on the distribution of pore sizes. A well-graded material will not experience as great a reduction in hydraulic conductivity with increased suctions as a uniform material. In an unsaturated system it is this mechanism of decreasing hydraulic conductivity with increasing suctions that can result in a fine-grained material becoming more conductive than a coarse-grained material.

- Under a steady-state surface flux, an equilibrium suction develops within the column. Near the top of the vertically layered system, a transition zone develops as the suctions in either material adjust from the independent suctions at the surface of the system to the equilibrium suction that develops further down. As a result of the suction profiles in both materials at the top of the system, a total head gradient forms toward the material which is more conductive at the equilibrium suction. The base boundary condition that exists at the bottom of the layered system influences the suctions that develop near the bottom of the system and results in the formation of another transition zone that depending on the base boundary condition and the materials involved, may result in a re-transfer of the water near the bottom of the column.

6.2 APPLICATION OF RESEARCH

It is critical to understand the hydraulic properties of the materials within a system to be able to predict the behaviour of the system. There are many applications where fine and coarse materials are in direct contact and the potential development of preferential flow paths needs to be considered. One application is the design of sand
drains used to remove excess pore-water pressure from a surrounding fine-grained soil. Based on the results of this research, the sand drains will function when the suctions between the two materials reduce low enough so that the coarser sand becomes more conductive than the surrounding fine material. If the suctions are not low enough to achieve this, the sand drains will not function as intended.

Another application that relates to the research conducted in this study is the use of chimney drains as a central core to reduce down-stream seepage in earth dams. Depending on the suctions that develop, a syphon effect could occur up and over the top of the chimney drain, resulting in downstream seepage.

### 6.3 FURTHER RESEARCH

The research conducted as part of this study was not able to identify a critical depth of infiltration based on the applied surface flux. While the results of the research indicate that the lateral transfer of water occurs over a very shallow depth, the initial cutoff height was too low and the influence of the base boundary condition did not help determine the effect of cutoff heights on the lateral transfer of water. Additional column studies that lower the cutoff in smaller increments and include a vented coarse drainage layer should be carried out to determine the critical depth of infiltration. Alternatively, additional numerical modelling could be conducted on a taller column, which would reduce the impact of the base boundary condition on the partitioning of flow further up in the column and would aid in the determination of a critical depth of infiltration.
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APPENDIX A

Waste Rock Column Study

A1 INTRODUCTION

In the main body of this thesis, a laboratory column study and numerical modelling program was described that investigated a mechanism for preferential flow in vertically layered, unsaturated systems. The materials used in the column study were Beaver Creek sand and medium silica sand, which were easily characterized and had been used by many other researchers in controlled experimental conditions. The results from the primary column study showed that the development of preferential flow paths was governed by the interaction of the unsaturated hydraulic characteristics of both materials under various applied surface flux rates.

Following the completion of the initial eighteen experimental conditions, the column was dismantled and reassembled with a fine and coarse-grained waste rock. The results from this second column configuration are presented in the following sections.
A2 MINING IN CANADA

In Canada, mining is an essential component of our economy and is crucial to the economic well-being of all Canadian provinces. The ability of the industry to remain competitive and sustain mining development is largely dependent on the mining industry’s ability to balance the economics of ore recovery with the environmental costs associated with mining.

Generally there are two streams of waste material that are generated during the life of the mine, tailings and waste rock. Waste rock piles are commonly constructed in mining operations during the removal of overburden and low-grade rock. Historically the waste rock piles are not progressively remediated, but remain uncovered and free to interact with the atmosphere.

Water that is applied to the surface of the waste rock in the form of precipitation and snowmelt, enters the waste rock pile and may appear as a discharge at the base of the pile. Of critical concern to the Canadian mining industry is the potential for waste rock piles to generate an acidic effluent called acid rock drainage, (ARD). Acid rock drainage occurs when the sulphide-bearing minerals that may be present in the waste rock react with oxygen and infiltrating water to form sulphuric acid. At various stages within the acid forming process, both chemical and biological oxidation occurs. The acid mixes with the pore fluid of the waste material and the resulting effluent creates a hazardous environment due to its acidic nature. The effluent also facilitates the transport of residual metals from the waste material to surface waters, threatening natural aquatic life in streams and lakes surrounding the mine site. Serious environmental damage as a result of acid rock drainage has, and continues to occur at many mine sites. Predictions
of when a pile may start to generate acid and how long a pile may release the associated contaminants to the environment, are related on a fundamental level to understanding the principals of liquid water flow within a waste rock pile (Smith et al, 1995). The level of uncertainty which currently exists regarding the dominant liquid water transport mechanisms in a waste rock pile, can be a serious impediment to predicting the behavior of new waste rock piles in addition to the successful decommissioning of existing sites.

A2.1 Hydrogeologic Characterization of Waste Rock Piles

There is limited information available regarding the internal structure of waste rock piles. There are several papers that discuss the heterogeneity of waste rock materials and the presence of preferential flow paths, but there is little quantifying documentation regarding these discussions. In recent years there have been a couple research programs that have been conducted at various mine sites in an attempt to provide information regarding waste rock material classification (Herasymuik, 1996, Dawson and Morganstern, 1995) and waste rock hydrogeology (Smith et al, 1995, Morin et al, 1994, Eriksson and Destouni, 1994; Day and Harpley, 1993).

There are many different views expressed in the available literature regarding the transport of liquid water through waste rock. Some researchers have suggested that liquid water flow in waste rock can be treated as flow through a porous medium, for example at Rum Jungle in Australia (Pantelis and Ritchie, 1991). Other researchers have found that water flow in waste rock dumps occurs preferentially through discrete channels (Harries and Ritchie, 1983). It is generally recognized that in order to accurately predict the quality and quantity of leachate flowing from a waste rock dump,
both porous medium flow through fine material, and discrete, channelized flow through coarse material must be considered (Pedersen et al., 1980; Whiting, 1985; Day and Harpley, 1993; Eriksson and Destouni, 1994; Smith et al., 1995).

Robertson and Barton-Bridges (1990) interpreted highly oxidized, fine-grained material surrounded by fresh grey waste rock as evidence of preferential oxidation within the fine layers. The development of seepage channels is discussed, but the material characteristics of the materials forming the preferential pathways are not documented.

Kent and Johnson (1993) and Dawson et al. (1995) cited reduced pore-water pressures in fine-grained layers of mine waste as a potential source of slope instability. Many existing models attempt to predict the onset of acidic drainage and the resulting quality of leachate from waste rock piles.

In 1995, Smith et al. released a report regarding the hydrogeology of waste rock piles. The focus of the report was on the physical properties of the dump materials and the hydrostratigraphy of waste rock dumps. The researchers used water content measurements, temperature distributions and outflow hydrograph data to indicate the hydrostratigraphy and distribution of flow paths within the pile. Smith et al. (1995) proposed four models to characterize the hydrostratigraphy of waste rock piles depending on the construction methods used. Both porous flow and channel flow were described as flow mechanisms that can occur in waste rock piles.

In 1996, Herasymuik released the results of a field and laboratory project for the waste rock pile at Golden Sunlight Mine in Montana. The laboratory results and field observations made at Golden Sunlight Mine led to the extension of the primary column
study in determining a mechanism for preferential flow in vertically layered unsaturated systems to waste rock systems.

A3 THE GOLDEN SUNLIGHT MINE RESEARCH PROJECT

In 1994, Placer Dome Canada Inc. and the Unsaturated Soils Group (USG) at the University of Saskatchewan initiated a multi-phase research program to investigate the hydraulic properties and moisture migration pathways found in the east waste rock pile at Golden Sunlight Mine (GSM). Phase I consisted of an extensive field investigation that consisted of logging and sampling structures within the waste rock pile. Phase II involved data reduction and laboratory analysis of the sampled waste rock.

The research project was conducted on a large waste rock dump at Golden Sunlight Mine, a large, open pit gold mine in southwestern Montana. The project was initiated as a result of a unique opportunity presented as a result of a massive earth movement deep beneath the waste rock pile. The earth movement necessitated the partial excavation of the existing 100 million ton waste rock pile. To stabilize the pile, approximately 15 million tons of waste rock were excavated in a series of 20 m lifts. Test pits were excavated along pre-determined transect lines during the excavation and material samples as well as insitu measurements were taken (Herasymuik, 1996).

The waste rock pile at Golden Sunlight was constructed by end-dumping waste rock from several platform elevations. Herasymuik (1996) observed that this method of construction strongly controlled the structural orientation within the pile.

The structure of the dipping layers was defined by colour and/or grainsize differences. Figure A1 shows an example of the dipping, layered structure which was
visible on an excavated section of the waste rock dump. The layer thickness within the pile varied considerably ranging from thin lenses of 100-200 mm in width to layers in excess of several meters.

![Photograph showing a highly defined, layered structure within the waste rock pile (Herasymuik, 1996).](image)

**Figure A1.** Photograph showing a highly defined, layered structure within the waste rock pile (Herasymuik, 1996).

The potential variation in grain sizes between adjacent layers was found to be extreme, with coarse rubble layers exhibiting large open interparticle voids in sharp contact with fine layers containing significant percentages of silt and sand which infilled the interparticle voids. These layers also dipped at an angle consistent with the overall structure of the pile. The presence of a basal coarse layer was confirmed to exist at the base of the pile as a result of material segregation during the end-dumping procedure.
The waste rock pile at Golden Sunlight was also found to contain a wetting front. The moisture existed within the highly oxidized fine-grained layers while the coarse waste rock remained dry and unoxidized, suggesting the formation of preferential flow paths within the pile.

A3.1 Material Characterization

The laboratory program conducted by Herasymuik (1996) involved classifying the sampled waste rock and determining basic hydrogeologic properties including; grain-size distributions, soil-water characteristic curves, and saturated hydraulic conductivity.

The determination of soil-water characteristic curves revealed two general types of waste rock material. The first type of waste rock was considered to be fine waste rock, capable of retaining water under unsaturated conditions. The second type was considered to be coarse waste rock that would desaturate with the application of small suctions. Herasymuik (1996) used the #4 sieve (i.e., mesh size of 4.75 mm) to differentiate between the fine and coarse waste rock. To be considered fine waste rock at least 40% of the total mass needed to pass the #4 sieve (i.e., particle sizes less than 4.75 mm). Coarse waste rock could still consist of a wide range of particle sizes but contained less than 40% of the total mass passing the #4 sieve (i.e., less than 40% of the material had a particle size smaller than 4.75 mm). Herasymuik determined that if a sample contained greater than 40% fine material (i.e., smaller than 4.75 mm), the quantity of fine material would be sufficient to fill the interparticle voids and the sample would behave “soil-like” with the hydraulic properties being governed by the fine
material. If a sample contained less than 40% fine material, there would be an insufficient quantity of fine material to fill the interparticle voids and the sample would behave “rock-like” with the large open pores governing the hydraulic characteristics of the sample.

Figure A2 shows two soil-water characteristic curves that were obtained for a fine and a coarse waste rock. The percentage value appearing in legend for each curve presented in Fig. A2 indicates the percentage of material that was smaller than 4.75 mm.

The soil-water characteristic curves presented in Fig. A2 together with saturated hydraulic conductivity values of $3.4 \times 10^{-5}$ m/s for the fine waste rock and $1.0 \times 10^{-3}$ m/s for the coarse waste rock were used to generate unsaturated hydraulic conductivity functions that are presented in Fig. A3 (Fredlund et al., 1994).

![Figure A2: Soil-water characteristic curves for a fine waste rock (TP5GS1) and a coarse waste rock (TP6GS5) (after Herasymuik, 1996).](image-url)
The soil-water characteristic curve and hydraulic conductivity functions presented in Figs. A2 and A3 show that the fine waste rock was capable of retaining waster under unsaturated conditions as indicated by the presence of an air-entry value or 3 – 4 kPa. The coarse waste rock exhibits little capacity to retain water under negative pore pressures as there is insufficient fine material to fill the interparticle voids. The coarse waste rock had virtually no air entry value with the largest pores starting to drain as soon as suctions were applied. Although the coarse waste rock initially had a greater saturated hydraulic conductivity than the fine waste rock, the drainage of the large pores resulted in a rapid decrease in unsaturated hydraulic conductivity with applied matric suction. The fine waste rock maintains fluid-filled pores and at suctions exceeding
approximately 0.1 kPa, has a greater unsaturated hydraulic conductivity than the coarse waste rock.

A4 COLUMN STUDY USING WASTE ROCK

Field observations made by Herasymuik (1996) indicated that the waste rock pile at Golden Sunlight Mine was highly structured with steeply-dipping layers. Fine and coarse layers were found to be in sharp contact with each other and the presence of a wetting front within the fine waste rock suggested the formation of a preferential pathway through the waste rock pile.

The same column that had been used during the primary laboratory program was reassembled with fine and coarse waste rock placed adjacent to each other in two vertical columns. The gradations of waste rock used in the column were created using barren, unoxidized waste rock from Equity Silver Mine in B.C. The Equity Silver waste rock had been previous sieved and sorted and was used to create a fine waste rock (i.e., TP5GS1) and a modified coarse waste rock (TP6GS5, modified) using the grain-size distribution curves measured by Herasymuik (1996). There was a modification made to the coarse waste rock sample as Herasymuik (1996) had determined that the coarse waste rock gradation did not contain enough fine material to fill the inter-particle voids. As a result, large voids remained in the waste rock and the transport of liquid water was dominated by the coarse fraction. To avoid settlement of the fines and the development of a non-uniform gradation within the column, the coarse waste rock was modified to remove the material that passed the #70 (0.21 mm) sieve. The total height of the material within the column for the waste rock study was 1360 mm and a single cutoff
height of 360 mm was used. Figure A4 shows a schematic of the column containing waste rock.

Figure A4: Schematic drawing showing the overall design of the laboratory apparatus for the fine and coarse waste rock configuration.
A4.1 Column Assembly and Procedure

To assemble the column, a single acrylic section was placed on top of the base plate with the metal cutoff already in position up to an elevation of 360 mm. A layer of coarse gravel, 30 mm in depth was placed at the bottom of the column to avoid clogging of the drainage system by the fine material. A wire screen was placed on top of the gravel to inhibit the migration of fine particles into the coarse gravel. The fine and coarse materials were wet to an unspecified water content and were placed in 200 mm lifts. The waste rock was lightly tamped into place in each lift to approximately simulate the loose manner in which waste rock is placed.

Once the first acrylic section was filled to capacity, the next section was lowered into place and fastened to the lower section using screws and butterfly nuts. Subsequent sections were filled using the same procedure as the first. A water tight seal was achieved between each section by the use of greased o-rings, which fit into machined grooves that outlined the base of each section (Fig. 3.2 – Block A: Plan View). As the waste rock layered extended above the height of the cutoff, a 200 mm piece of sheet metal was used to help place the material. Before each additional section was placed, the temporary cutoff was removed and the both sides were tamped to ensure that the gap left by the removal of the cutoff was infilled. The total finished height of the column was 1360 mm. The surface flux application system consisting of a perestaultic pump and two constant head tanks connected a surface flux distribution system was placed over the top of the column.

The outlet tubes were placed at the elevation of the base of the column resulting in a base boundary condition of 0 kPa in both materials.
A4.2 Surface Flux Application Rates

The results from the first laboratory column study had showed that when the steady-state surface flux was greater than the saturated hydraulic conductivity of the fine material, the coarse material became the preferential flow path within the vertically layered system. Once the surface flux was reduced to be less than the saturated hydraulic conductivity of the fine material, the fine vertical column became the preferential flow path. Herasymuik (1996) had measured the saturated hydraulic conductivity of the fine waste rock sample TP5GS1 to be $3.4 \times 10^{-5}$ m/s.

An initial flux rate of $1 \times 10^{-4}$ m/s produced a significant free water surface on the top of the fine waste rock layer. The surface flux was reduced until a film of water was visible on the surface of the fine waste rock and then the flux rate was further reduced two more times. In total, three surface flux application rates were evenly applied over the surface of the waste rock for a single cutoff height of 360 mm. The first applied surface flux was $5.15 \times 10^{-6}$ m/s, the second was $1.41 \times 10^{-7}$ m/s and the third was $5.56 \times 10^{-8}$ m/s. Following the application of each surface flux, steady-state conditions were established and the amount of water discharging from each side of the column was collected and recorded.

A5 WASTE ROCK COLUMN RESULTS AND DISCUSSION

The percentage of water collected from both the fine and coarse waste rock for each applied surface flux is presented in Table A1.
Table A1: Column results

<table>
<thead>
<tr>
<th>Cutoff Height (Contact Length) (mm)</th>
<th>Applied Flux Rate (m/s)</th>
<th>Percentage of Total Effluent Discharging from each Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>% Fine</td>
</tr>
<tr>
<td><strong>Test 1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>360 (1000)</td>
<td>a) $5.15 \times 10^{-6}$</td>
<td>18%</td>
</tr>
<tr>
<td><strong>Test 2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>360 (1000)</td>
<td>b) $1.41 \times 10^{-7}$</td>
<td>48%</td>
</tr>
<tr>
<td><strong>Test 3</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>360 (1000)</td>
<td>c) $5.56 \times 10^{-8}$</td>
<td>65%</td>
</tr>
</tbody>
</table>

For an applied surface flux of $5.15 \times 10^{-6}$ m/s, 18% of the total flux was collected from the bottom of the fine waste rock layer. Reducing the surface flux to $1.41 \times 10^{-7}$ m/s resulted in increasing the amount of water being transported through the fine waste rock from 18% to 48%. Further reducing the applied flux to $5.56 \times 10^{-8}$ m/s resulted in the fine waste rock layer becoming the preferential flow path with 65% of the applied surface flux being collected from the bottom of the fine waste rock.

Although the measured saturated hydraulic conductivity of the fine waste rock was reported by Herasymuik to be $3.4 \times 10^{-5}$ m/s, the flux rate required to make the fine waste rock the preferential flow path needed to be less than approximately $1 \times 10^{-7}$ m/s. Based on the results of the primary column conducted with Beaver Creek sand and medium silica sand, the saturated hydraulic conductivity of the fine waste rock within
the column must have been less than the value measured by Herasymuik (1996). There was no numerical modelling conducted at the end of the laboratory program, so calibration of the material properties within the column was not done.

A6 CONCLUSIONS

The results from the waste rock column study show that in a vertically layered unsaturated waste rock system, conditions can exist where the fine waste rock layer will be the preferential flow path within the system. Water initially entering the coarse waste rock is transferred laterally over to the fine waste rock before a depth of 1000 mm.

The applied surface flux required in the laboratory experiment that resulted in the fine waste rock layer serving as the preferential flow path was $5.56 \times 10^{-8}$ m/s. In 1995, Swanson determined the net infiltration rate into the waste rock pile at Golden Sunlight Mine to be $6.35 \text{ mm/year}$ or $2.01 \times 10^{-10}$ m/s. This value is still significantly less than the flux value needed to produce preferential flow through the fine waste rock at Golden Sunlight Mine within the column study.

The implications of the fine waste rock layer becoming a preferential flow within a waste rock pile can be significant. Both Kent and Johnson (1993) and Dawson et al (1995) cited reduced pore-water pressures in fine-grained layers of mine waste as a potential source of slope instability. In an unsaturated system, both water and oxygen are present which can lead to oxidation of the sulphide bearing waste rock. Oxidation and weathering of the fine waste rock results in an increased potential for the storage of acid rock drainage within the fine waste rock layers and causes a further decrease in the
grain-size distribution of the fine waste rock, which can lead to potential layers of instability.

The concept of water flowing through the large open channels in waste rock piles is a common perception. Certainly macropore flow does occur within waste rock piles. However, a redistribution of water between fine and coarse waste rock layers can occur based on the hydraulic properties of the waste rock and the infiltrating flux rate. The typically remediation of waste rock piles in Canada is the construction of a soil cover on the surface of the pile. The soil cover would further increase the potential for fine waste rock preferential flow paths as the net infiltrating flux would buffered by the storage potential within the cover system.

Further research needs to be conducted on the hydrogeology of fine and coarse layered waste rock systems. In the future waste rock piles may be constructed to maximize oxidation in order to remove long-term liability from the mining company. Alternatively, if fine barren material was placed adjacent to coarse acid-producing material, perhaps the decommissioning strategy could be designed to focus on encouraging flow through the fine layered system reducing the acid producing potential of the waste rock pile.