IMPROVING WATER STORAGE OF RECLAMATION SOIL COVERS BY FRACTIONATION OF COARSE-TEXTURED SOIL

A Thesis Submitted to the College of Graduate Studies and Research

In Partial Fulfillment of the Requirements for the Degree of

Masters in Environment and Sustainability

In the School of Environment and Sustainability

University of Saskatchewan

Saskatoon

By

Yekaterina V. Dobrovolskaya

PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a graduate degree from the University of Saskatchewan, I agree that the Libraries of this University may make it freely available for inspection. I further agree that permission for copying of this thesis in any manner, in whole or in part, for scholarly purposes may be granted by the professor who supervised my work (Dr. Bing C. Si) or, in his absence, by the Director of the School of Environment and Sustainability. It is understood that any copying, publication, or use of this thesis or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of Saskatchewan in any scholarly use which may be made of any material in my thesis.

DISCLAIMER

Reference in this thesis to any specific commercial products, processes, or services by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement, recommendation, or favouring by the University of Saskatchewan. The views and opinions of the author expressed herein do not state or reflect those of the University of Saskatchewan, and shall not be used for advertising or product endorsement purposes.

Requests for permission to copy or to make other use of material in this thesis in whole or in part should be addressed to:

Executive Director, School of Environment and Sustainability

University of Saskatchewan,

Saskatoon, Saskatchewan, Canada S7N 5C8

ABSTRACT

Mining operations lead to considerable land disturbance and accumulation of large amounts of waste rock that may contain elevated concentrations of hazardous substances. Without proper capping, they may have considerable negative environmental impact on different spheres of the Earth. Capping of waste rock with a soil cover re-creates the water and nutrient regimes required for the growth of native plants and returns biological productivity and biodiversity of the land to a condition similar to that existing before site disturbance.

In many cases the area of disturbance is composed of coarse-textured materials with low water retention properties, which are not desirable in semi-arid zones. This study was conducted to determine (1) whether a considerable increase of water storage is possible after separation of coarse-textured soil into size fractions and layering them in such a way that the finer fraction overlies the coarser fraction; and (2) whether such soil covers are susceptible to preferential flow under various initial and boundary conditions and what influence this type of flow has on residence time.

Four types of soil covers were constructed in chambers: homogeneous covers composed of natural sand, two-layered covers with abrupt and gradual interlayer transitions, and four layered soil covers with abrupt transitions. Soil water storage was measured at field capacity (FC). Soil covers were tested under two types of lower boundary conditions: gravel layer and -25-cm matric potential. Flow stability was assessed during intermittent and constant ponded infiltrations. Intermittent infiltration into initially air-dry soil was conducted under seepage face=0 lower boundary condition. Water storage capacities (WSCs) for soil covers with -25-cm matric potential at the bottom of a cover were additionally simulated in HYDRUS-1D.

Water storage capacities increased with the number of layers under both lower boundary conditions. Two-layered covers with a transition layer had slightly lower water storage than the same cover without the transition, due to a decreased hydraulic contrast at the layer interface. Simulated WSCs under -25-cm matric potential at the bottom were in satisfactory agreement with measured WSCs.

The wetting front was stable in the homogeneous cover under both initially dry and FC conditions and in the two-layered cover with a gradual transition under initially dry water content during intermittent ponded infiltration. Unstable flow was observed only in the two-layered soil cover under both initial water contents. Other covers were partially unstable under initially air-dry and FC conditions. Generally, the wetting front was more diffuse at FC. Flow in all covers was stable under constant ponded infiltration. The residence time of water increased with the increase in the number of layers under both types of infiltration.

Results of the study show that WSC and residence time do increase with increasing number of layers in soil covers, where layers are composed of different fractions of coarse-textured soil. In addition, tested soil covers have shown limited susceptibility to preferential flow even when layered into finer-over-coarser soil systems.

Keywords: soil cover, water storage, preferential flow, coarse-textured, residence time.

ACKNOWLEDGMENTS

First of all, I thank God for giving me the opportunity to do research and supporting me in this endeavour as well as sending me challenges, which taught me valuable lessons. I owe many thanks to my mother for supporting my intentions to advance the level of my education as well as providing financial and spiritual support for all these years I was doing my Master's degree. I extend my appreciation to my husband, Kirill Gudkov, who was also patient and supportive.

I give a special thank you to my academic supervisor, Dr. Bing Si, for his valuable guidance in this work. His generous allocation of time for thoughtful discussions and sharing of ideas is greatly appreciated. I am also grateful for extension of my scholarships to give me opportunity to finish my studies.

I also would like to express my appreciation and gratitude to my supervisory committee. I am thankful to Dr. Lee Barbour for showing great interest in my research, his constructive comments and thought provoking questions. My research would not be what it is now without the useful advice and valuable guidance of Dr. Amin Elshorbagy. Sincere thanks to Dr. Bram Noble for the work he has done as a Chair of the committee and for his attention and support.

Big support has been received from our soil physics crew. I wanted to specifically acknowledge Henry Chau and Dr. Asim Biswas, who were always ready to teach and to discuss whatever issues I had with my research. I am very thankful to our graduate students Min Li, Trent Pernitsky, and Lindsay Tallon as well as summer students, Tim Blum and Eric Neil, for their invaluable assistance and responsible approach to their work. Finally, thanks to all those not mentioned, who lent support at various times throughout my study.

DEDICATION

“Energy and persistence conquer all things”

Benjamin Franklin

I dedicate this thesis to my mother for her love and support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AEV	Air-entry value
FC	Field capacity
SC	Soil cover
SWRC	Soil water retention curve
WSC	Water storage capacity
α	Fitting parameter for van Genuchten’s function
θ_s/θ_r	Saturated/residual water content
h	Matric potential
h_{we}	Matric potential at water-entry
K	Unsaturated hydraulic conductivity
K_s	Saturated hydraulic conductivity
m	Fitting parameter for van Genuchten’s function
n	Fitting parameter for van Genuchten’s function
V	Infiltration rate

1 INTRODUCTION

Mining operations lead to considerable land disturbance and the accumulation of large amounts of by-products such as waste rock and tailings. Examples of these disturbances range from oil sand mines in north-eastern Alberta (Canada) to Key Lake mine (Saskatchewan, Canada) situated in the Athabasca Sand Basin. In Alberta, 715 km^2 have been disturbed and this area is projected to increase to more than 1700 km^2 over the next 10-15 years (MacKenzie and Quideau, 2012). Oil sands are extracted by open pit mining, which involves stripping large areas of the land and digging as deep as 100 m to reach target resources (MacKenzie and Quideau, 2012). At Key Lake mine, over 1000 hectares of land has been disturbed during uranium mining operations (Johannesen et al., 1997). Extraction of uranium-rich rock is accompanied by the excavation of soil overlying these rocks (overburden) and soil that was in the nearest proximity to the ore body (waste rock). Both the overburden and waste rock are usually either stored on the ground or used to backfill a mine pit (Benes, 1999).

Open storage of waste rock on the ground surface is associated with a number of negative environmental impacts, because waste rock often contains contaminants such as radioactive material, heavy metals, etc. (Benes, 1999). The main impacts are physical and chemical weathering of contaminants from waste rock by wind and water, which eventually may lead to atmospheric, surface water, and groundwater contamination (Lottermoser and Ashley, 2006).

One of the methods of mitigating these impacts is to cap waste rock with a soil cover composed of uncontaminated material. The main functions of such a cover are to serve as a shield to wind and water erosion of waste rock, reduce water flux into waste rock to negligible amounts, and to accumulate water in the soil cover itself for plant growth. Some water is removed from such a cover by evapotranspiration to limit deep percolation, and this is why it is called an evapotranspirative soil cover (Tallon et al., 2011). Unlike resistive covers such as clay liners and geosynthetic materials, soil covers have better long-term stability and do not require an extensive maintenance (Albright et al., 2006). A soil cover is also usually more affordable than other types of covers (Johannesen et al., 1997). One of the main advantages of such a cover is that it allows use of soil natural to the site and, thus, is conducive to plants native to the area to grow. This is especially important, because the main purpose of any reclamation is to return the mining site and the waste rock storage area to a predevelopment state with a similar biological productivity and biodiversity of the land. However, soil covers are not devoid of limitations (Johannesen et al., 1997). These systems do not perform well under humid conditions with frequent and intense rainfalls (Morris and Stormont, 1997). Therefore, their application is limited to mainly arid and semi-arid regions (Khire et al, 2000).

For a soil cover to accumulate a sufficient amount of water for plant growth and to limit deep percolation of precipitating water into waste rock, it must have sufficient water storage capacity (WSC). Water storage capacity is the maximum amount of water a soil can hold after gravity drainage, i.e. at field capacity (FC) (Stormont and Morris, 1998). Depending on soil texture and organic matter content, soils can have higher (like clay) or lower (like sand) WSC (Stormont and Morris, 1998). Sand is a coarse-textured soil with poor water retention properties (Dingman, 2002). However, quite often the area of disturbance is composed of coarse-textured soil (Tallon et al., 2011). Despite its low water retention, sandy soil is able to support such forests as the jack pine, spruce and aspen forests of the Athabasca plain (Acton et al., 1998). These field soils most likely developed layers during soil formation that increased water storage and reduced flux through soil layers (Zettl et al., 2011). Similar to natural layered soil systems, reclamation soil cover with artificially created layers can have increased water storage allowing it to support vegetation.

The majority of past and current studies of soil covers or layered soil systems in general are focused on the investigation of water storage and performance of soil systems with layers of highly contrasting textures. In this thesis, the term “performance” refers to the response of soil cover to changing water content, boundary and/or initial conditions, and limitation of percolation to the underlying material by the soil cover. Similar studies involving layered soils from the same textural group (sands) are scarce, non-systematic, and fail to answer all the spectra of questions associated with the use of such soil systems as long-term reclamation cover. Moreover, at many mining sites, the available cover material is represented by a single soil texture, resulting from the homogenization of natural layered soils during excavation and stockpiling. In such a case, creating textural contrasts from a single cover material is required for successful reclamation. Studies on such soil systems have not been found. Theoretically, more water is stored in layered soil systems because of flow barriers forming at the layer interfaces due to the difference in the hydraulic properties of the layers. It is not evident whether coarse-textured soil that has been separated into finer and coarser fractions and laid down in layers will have significantly increased water storage compared to a soil cover of non-layered natural sand and whether or not this soil system will provide the required function of a soil cover.

Knowledge of preferential flow, a phenomenon that develops in both layered and non-layered soils that can considerably undermine functionality of soil cover, is also incomplete (Gerke et al., 2010). Finer-over-coarse layered soil systems are especially susceptible to preferential flow (Gerke, 2006). The wetting front becomes unstable mainly due to an abrupt change in the hydraulic conductivity of the layers. The most unfavourable feature of preferential flow in the environment is that preferential flow paths often occupy very small portions of the total soil volume, but may conduct a large quantity of water and consequently rapidly transport dissolved chemicals at velocities higher than those of uniform infiltration. In this case contaminants can be transported towards drinking water resources without a sufficient time for decomposition, and large volumes of soil are bypassed by flow, so that soil is not wetted uniformly (Gerke, 2006). Thus, even if more water can be stored in soil cover due to layering, preferential flow may increase water flux, reduce water storage and residence time of water in a soil system. The term residence time refers in this thesis to the average time water spends within a soil system before it reaches a designated point along its flow path (Kabeya et al., 2007) such as a specific soil depth. However, preferential flow develops only under certain initial and boundary conditions and in certain types of soil systems. Whether layered soil systems with a slight contrast in textures are susceptible to flow instability, and whether this phenomenon will have a drastic effect on the residence time is also unclear.

The other issue associated with the layering of soil is textural transitions between layers. They are often assumed to be abrupt in assessment of water storage and potential of preferential flow development, however, these transitions are almost always gradual in both field soils and constructed soil covers (Liu and Si, 2008). Ho and Webb (1998) noted that the assumption of abrupt textural transitions between layers may overpredict the water storage of soil systems. The influence of gradual textural transitions between layers on water storage has been scarcely investigated for soil systems with both low and high textural contrast between layers.

Based on the research that has been done by others and the remaining unstudied issues, it is hypothesized that:

1. Separation of finer and coarser fractions of natural sand and layering them in a soil cover considerably increases soil WSC relative to the profile of the non-segregated sand;

2. Preferential flow that may develop due to layering of the finer fraction over the coarser fraction can be mitigated by reducing the hydraulic contrast between the layers, by increasing the number of layers, and by extending interlayer transitions.

Objectives and thesis outline

As can be seen from the Introduction, there are certain research questions that still need to be resolved to create an optimal soil cover design. To address these questions, the research has been conducted with the following objectives:

1. To examine whether layering of sand fractions (finer-over-coarser) increases the WSC of soil covers;

2. To assess the susceptibility of layered and homogeneous (non-layered) soil covers to preferential flow under various initial and boundary conditions and to determine the influence this type of flow has on residence time.

In order to meet these objectives, intermittent and constant head ponded infiltration experiments were conducted under two different lower boundary conditions and under two initial water contents, initially air-dry and FC. Matric potential as well as wetting front properties (shape, propagation velocity) were monitored. After each infiltration experiment the soil cover was brought to FC from saturation to measure WSC.

This thesis is organized into 4 chapters. Chapter 1 provides an introduction, and the relevant scientific literature is reviewed in Chapter 2. Chapter 3 presents experimental methods used in this study and the results from laboratory infiltration experiments and sampling of soil covers for water content. Water storage capacities, wetting front characteristics of layered and non-layered soil covers are compared as well as residence time in these types of covers, and their differences are explained and discussed. Experimental results are summarised in Chapter 4, and the overall conclusions are provided along with implications for soil cover design and recommendations for future research.

2 LITERATURE REVIEW

2.1 Environmental impacts of open waste rock storage

The surface storage of waste rock without isolation from the external environment, or open waste rock storage poses a number of environmental risks due to elevated concentrations of toxic elements present in the waste rock. Open storage of waste rock mostly affects atmosphere and hydrosphere (Benes, 1999). The handling of uranium mining wastes serves as an illustration for the review of the environmental impact of waste rock storage practices below.

Wind erosion of wastes is the main vector for atmospheric contamination. Wind has a capacity to spread radioactive dust and alpha-bearing particles hundreds of metres away from openly stored uranium mining waste rock. In the prevailing direction of the wind, particulate matter can form a cover of dust up to tens of centimetres thick within 100 m of uncovered mill tailings repositories (Lottermoser and Ashley, 2006). In some cases, gamma radiation levels are several times greater than the background level in areas adjacent to a uranium mining site. In addition, radon gas (^{222}Rn) emitted from waste rock is the other main contributor to atmospheric contamination. Radon is an inert radioactive gas and a carcinogen that can migrate through the air and water filled pores of otherwise uncontaminated soil (Lottermoser and Ashley, 2006).

Hydrosphere contamination is another issue that must be addressed. Firstly, runoff water, flowing downslope of a waste rock pile, spreads contaminants, increasing contamination possibility of surface waters such as rivers, lakes, and ponds. The available evidence shows that intense rainfall can cause even the coarsely crushed waste rock to move up to hundreds of metres away (Lottermoser and Ashley, 2006). Moreover, contaminants from uranium-mining waste rock are known to reach groundwater. Meteoric water infiltrating through waste rock mobilizes radionuclides and toxic elements. Trace elements are liberated from their host minerals by oxidation and leaching of the uranium ore minerals (Lottermoser and Ashley, 2006). As noted by Porro (2001), contaminants are transported beyond their original burial boundary mainly by the movement of water through the wastes. Leaching of contaminants is accelerated by the acid generation in waste rock (Benes, 1999). As a consequence of the increased acidity, radionuclides and toxic metals become more mobile (Abdelouas, 2006).

The multiple potential impacts of open storage of uranium mining waste products on the environment are further exacerbated by uranium's (and it daughter products') slow radioactive decay time, as the contaminants remain active and thus, harmful to atmosphere and hydrosphere for an extremely long time.

2.2 Soil cover system as a mitigation measure of environmental impacts

Reclamation soil cover represents a capping material placed on top of waste rock. The compaction of waste rock and placement of natural soil covers seems to be an appropriate option for mitigating the wide spectra of environmental impacts associated with uncovered waste rock storage. The option has received increased attention as an alternative cover system for landfills, tailings, mining, and smelter waste (Morris and Stormont, 1997; Smesrud and Selker, 2001; Nyhan, 2005). For decades, clay-type soils have been the main material used to cover or line waste rock repositories and landfills (Cherrill and Phillips, 1997; Simms and Yanful, 1999; Yanful et al., 2003; Albright et al., 2006; Jutla, 2006). However, research has shown that such resistive covers and liners (made of clay and/or geosynthetic materials) are not stable over the long-term, since they rely solely on low hydraulic conductivity (Albright et al., 2006). Although clay has the lowest hydraulic conductivity among soil textures, it is also susceptible to cracking from subsidence, desiccation and freeze-thaw cycles, root and animal intrusion, which may substantially increase the hydraulic conductivity in a relatively short period of time (Simms and Yanful, 1999).

The amount of moisture that is released and stored in soil cover changes in response to climatic conditions and can be regulated by the number of layers along with their sequence and hydraulic properties. Natural processes, such as evapotranspiration which removes excessive water from the soil cover, play a major role in maintaining a water regime conducive to plant growth in a soil cover and in preventing seepage to groundwater (Morris and Stormont, 1997).

Since soil covers rely on natural processes to remove excessive water, they are more durable than resistive soil covers. This is very important in regard to longevity of reclamation covers (Morris and Stormont, 1999; Fayer and Gee, 2006), especially for soil covers placed on materials having some degree of radioactivity. Apart from long-term stability, soil covers are comparatively inexpensive, as there is neither a need for purchase and transportation of fine material, nor for expensive artificial materials (Morris and Stormont, 1997).

Water regimes and nutrient content are the most important requirements for native plant growth (Johannesen et al., 1997). The growth of native vegetation on the reclaimed site allows the land to return to a pre-disturbance biological productivity, which is one of the main requirements for land reclamation in Canada and the ultimate goal of any reclamation (Johannesen et al., 1997).

Soil cover design is inherently site-specific and largely depends on climatic conditions and the purposes of the cover (O'Kane, 1995; Johannesen et al., 1997). For this reason, it is difficult to develop common guidelines for the construction of soil covers. However, based on the previous discussion, it can be concluded that evapotranspirative soil cover should serve three main functions: 1) protect waste rock from water and wind erosion; 2) prevent the percolation of excessive amounts of water from the soil cover into the waste rock (i.e. prevent leaching of contaminants into groundwater and/or surface water); and 3) store an optimal amount of water for vegetation growth. Depending on the nature of the waste to be isolated, a soil cover can also serve as a gas barrier by preventing the emanation of radon gas. A soil cover can also limit the availability of oxygen, preventing the oxidation of waste rock and formation of acids (Benes, 1999). In order to create a soil cover that will satisfy these requirements, it is necessary to understand the main principles of water flow and distribution in layered and non-layered soil systems under unsaturated conditions.

2.3 Soil water balance and storage

Through the process of infiltration, a large fraction of precipitation moves into the soil once it reaches the land surface (Hillel, 1980). When infiltration capacity of soil is exceeded, some water may pond on top of soil or go into runoff (Dingman, 2002). A portion of infiltrated water returns to the atmosphere by evaporation from soil surface or transpiration by vegetation. Another portion of the water percolates below a certain depth of soil and the remainder is added to the soil water storage (Dingman, 2002). The water storage of a soil layer is the integration of the volumetric water content over the thickness of the layer (Stormont and Morris, 1998). It is well known that sand has a fairly low WSC (Dingman, 2002). Despite the low WSC of dominant soil (sand), the Athabasca sand basin, for example, is almost entirely covered by coniferous boreal forest (Acton et al., 1998). The ability of this area to support vegetation is due to the natural layering and segregation of sand into size fractions during the process of soil formation such as sedimentation, alluviation, illuviation, compaction, and particle orientation (Assoline and Or, 2006). It has already been concluded that layered soils have higher WSC than non-layered soils from theoretical analysis (Clothier et al., 1977; Stormont and Morris, 1998), laboratory experiments (Yang et al., 2004; Spies, 2010), simulations (Stormont and Morris, 1998; Morris and Stormont, 1999; Khire et al., 2000), and field observations (Clothier et al., 1977; Khire et al., 2000; Porro, 2001; Zettl et al., 2011). Laboratory experiments studying the layering of sequentially alternating medium-over-coarse sand in one metre high soil columns with 5-, 10-, and 25-cm layer depths showed that as the number of layers increases, drainage rates decrease and the amount of stored water increases (Spies, 2010). Therefore, since natural soils are mostly layered (Yang et al., 2006), natural sandy soils are able to store sufficient amount of water to support vegetation (Zettl et al., 2011).

Excavation during mining, stockpiling, and subsequent cover placement generally homogenize cover materials. Hence, layers need to be artificially re-created. The advantage of gaining additional water storage in layered soil systems can be realized by designing soil covers that mimic natural layering patterns. If the soil found on the site is predominantly from one texture class, the creation of layers requires separation of such soil into size fractions. As was mentioned earlier, the optimal number of layers and soil cover design are inherently site-specific. In most cases, the evapotranspirative soil cover has to be a multilayered system, since it is not possible for any single layer to meet all the design criteria such as long-term stability, sufficient WSC to support vegetation, and prevention of the percolation below the soil cover (O'Kane, 1995). Layering is especially important, when the only available reclamation material is coarse-textured soil, as it is often the case on mine sites (Tallon et al., 2011). For example, glacial deposits of the Athabasca plain, where most of Saskatchewan's uranium mining sites are located, occupy 7.4 million hectares or 11% of the province of Saskatchewan in Canada and are mainly composed of outwash sand and gravel with quartzite pebbles and cobbles (Lee, 1999).

Layered soil covers have higher WSC, compared to non-layered soil covers due to the presence of flow barriers (Khire et al., 2000). The mechanism of flow barriers is described in the next section. The position and texture of layers have a direct influence on water storage and percolation rate below the soil cover (Khire et al., 2000).

2.4 Role of flow barriers in increasing water storage and improving performance of soil covers

Many soils exhibit some degree of anisotropy of soil properties (Assoline and Or, 2006). Small differences in soil texture and/or density result in great differences in hydraulic conductivity, possibly resulting in anisotropy of the soil system (Ritsema and Dekker, 1994). Anisotropy in hydraulic conductivity that exists at the layer interface of texturally different layers leads to the creation of a flow barrier that can be divided into two categories, depending on a layering sequence: 1) capillary barrier (finer-over-coarser soil system) and 2) hydraulic barrier (coarser-over-finer soil system) as was classified by Alfnes et al. (2004). Under a certain degree of saturation these flow barriers contribute to an increased water storage (Zhu and Sun, 2010).

Capillary barrier

The layering of a finer layer over a coarser soil layer results in a formation of a capillary barrier at the interface of the layers (Morris and Stormont, 1999). Capillary barriers maximize water storage within unsaturated soil systems by reducing gravitational drainage (Khire et al., 2000). The principals of capillary barriers in unsaturated soil at initially low water content are explained as follows.

When water flows downward from the top of the soil in the finer-over-coarser soil system, if the bottom of the finer layer is at a low matric potential, a large amount of water does not enter the coarser layer right after the wetting front arrives at the interface of the layers (Morris and Stormont, 1999). According to a definition matric potential energy is “the amount of work that must be done per unit of a specified quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water, from a pool of soil solution at the elevation and the external gas pressure of the point under consideration, to the soil water at the point under consideration (above the water table)” (Scott, 2000). At a relatively low matric potential, the finer layer has a finite hydraulic conductivity but the coarser layer is relatively non-conductive (Morris and Stormont, 1999). Thus, the coarser layer is unable to transmit an appreciable flux from the finer layer at low matric potential, allowing the infiltrating water to increase the water content of the finer layer, especially in its lower portion (Yang et al., 2004). Water accumulating at the interface will gradually increase the water content of the coarser layer and thereby its conductivity. As saturation at the bottom of the finer layer increases, so does the matric potential in both layers. Eventually, the matric potential on top of the coarser layer reaches a water-entry value (h_{we}) into the coarser layer (Yang et al., 2004), which corresponds to the lower inflection point on the drying part of soil water retention curve (SWRC) (Baker and Hillel, 1990; Yang et al., 2004). Since at matric potentials above this point hydraulic conductivity of the coarser layer increases rapidly with a slight increase in matric potential, the coarser layer is able to conduct a considerable flux of water.

As the conductive coarser layer drains water, matric potential becomes lower at the bottom of the finer layer and, consequently, at the top of the coarser layer (Khire et al., 2000). Once matric potential falls to the lower inflection point at the SWRC for the coarser layer or close to the residual matric potential, the coarser layer becomes less conductive again. Low conductivity of the coarser layer at the residual matric potential prevents further loss of water from the finer layer, leading to the increased water content in the finer layer as compared to a non-layered profile (Khire et al., 2000).

If soil was initially relatively saturated in the finer-over-coarser profile, it starts to drain when an air-entry value (AEV) into the coarser layer has been reached (Nicholson et al., 1989). As more water is drained away from the soil system, the matric potential in the coarser layer becomes more negative. Hydraulic conductivity decreases very rapidly in the coarser layer as the matric potential decreases from the AEV to the residual matric potential, not allowing the finer layer to desaturate further and remain at relatively high water content. No matter for how long the drainage continues, matric potential in the coarser layer will not decrease much lower than the residual potential (Nicholson et al., 1989). Thus, water content in the coarser layer stays close to its residual value over time (Nicholson et al., 1989; Akindunni et al, 1991). As experimentally shown by Barbour (1994), during a prolonged drainage and in the absence of evaporation, matric potential profiles become static in the finer-over-coarser soil system. The minimum matric potential that develops in the coarser layer approximately corresponds to the residual water content. However, matric potential never reaches an equilibrium and the flow between layers continues, although at exceedingly slow rate (Barbour, 1994).

Hydraulic barrier

A hydraulic barrier forms when a coarser texture overlies a finer (Scott, 2000). When the wetting front reaches the interface of the layers, the low hydraulic conductivity of the finer soil limits the propagation of the wetting front and thus, over time water content in the coarse layer increases considerably. However, once the infiltration ceases, the coarser layer begins to desaturate (Scott, 2000). Therefore, a hydraulic barrier temporarily reduces water flow from the soil system and increases the residence time of water in soil.

Capillary and hydraulic barriers have been extensively employed in experimentation on evapotranspirative soil covers with the purpose of improving their performance and WSC. As predetermined by the mechanisms involved in functioning of flow barriers, the performance of capillary barriers depends on such factors as thickness of both the upper and the underlying layers, their hydraulic properties, rainfall frequency and intensity, coarseness of the underlying layer, vegetative cover, and the slope of a soil cover. Among these factors, the thickness and textural differences of layers in the capillary barrier are regarded by many researches as the most important factors. For example, Khire et al. (2000) showed that increasing the thickness of a coarser layer has a much smaller effect than increasing the thickness of a finer-grained layer in terms of reducing percolation from the bottom of the cover and increasing water storage. The thicker the finer layer, the higher the WSC of the soil cover, since more water accumulates in the finer than in the coarser layer. However, the thickness of the finer layer should not exceed the thickness of a rooting zone in order to remove excessive water through evapotranspiration (Khire et al., 2000). When the first layer is composed of coarse soil, there is little additional storage gained, since the greatest increase in storage is close to the layer interface (Khire et al., 2000).

Qian et al. (2010) stated that the thickness of the coarser sublayer has some influence on water storage and performance of the capillary barrier, but is not as influential as the coarseness of the sublayer. The coarser the sublayer material, the lower the unsaturated hydraulic conductivity until the h_{we} is reached. Therefore, gravel was found to stay non-conductive longer than concrete or medium sand (Stormont and Anderson, 1999; Yang et al., 2004). However, soils used in capillary barriers must be selected to attain an optimal combination of the h_{we}, which is directly related not only to the texture of layers but also to the pore size distribution (Boateng, 2007). Using a probabilistic approach, Boateng (2007) came to the conclusion that the optimal conditions for effective capillary barriers are more likely to be achieved when soils with the least uniform pore size distributions are used, such as clay-type soils. A clay loam-over-loamy sand capillary barrier was found to provide an optimal combination of the h_{we} difference of pore size distribution. This conclusion contradicts the conclusion of Yang et al. (2004) who stated that the more uniform and the coarser the texture of the lower layer, the more effective the capillary barrier is. This could be due to the fact that Yang et al. (2004) did not take into account the pore size distribution and their conclusion was based on the fact that the h_{we} of coarse soils (i.e. gravel) is much higher (more positive matric potential) than that of finer soils such as sand. Similar to Boateng (2007), Stormont and Morris (1999) stated that soils including loam in their classification tend to benefit the most from the capillary break. A soil system with a silt loam underlain by coarse sand with the AEV of -20 cm had a higher storage capacity than when clay was the finer layer. Clothier et al. (1977) concluded that there is little gain in soil water storage by layering clayey soil with a very small pore size distribution index and a very coarse-textured soil with the highest pore size distribution index. The largest increase is gained by sandy soils (Clothier et al., 1977).

The applied flux has a considerable influence in the performance of capillary barrier as well. When the flux on top of the cover is high, the capillary barrier effect is weakened and the amount of breakthrough water is increased (Qian et al., 2010). Therefore, capillary barriers can function only under unsaturated conditions, making capillary barrier design suitable for arid and semi-arid regions, as they do not perform well under humid conditions or in regions with frequent and intense rainfalls (Morris and Stormont, 1997).

2.5 Numerical studies of soil cover performance

Different factors that can influence the performance of soil covers have also been investigated through numerical studies. For instance, Khire et al. (2000) tested the influence of climate, vegetation, the thickness of finer and coarser layers, and the hydraulic properties of these layers on the water balance of the cover. A numerical study of the influence of different boundary conditions (such as different groundwater level positions), cover materials, and grain size contrasts on cover performance was performed by Yanful et al. (2006) for developing an optimal cover design. Although it is impossible to create a design of the cover that would be optimal for all climatic and site-, project-specific conditions, they proposed a conceptual flow-chart to help develop a cover design optimal for certain sites and objectives. Since performance of the cover is predicted as a function of the cost of implementation, it allows to develop the most economic cover design. Some numerical studies concentrate on determining the sensitivity of some components of the water balance (most often percolation) to the changes in parameters of soil covers such as rooting depth, cover thickness, and saturated hydraulic conductivity of capping materials (Zornberg et al., 2003).

Modeling of water balance constituents in soil covers has been conducted mainly to verify laboratory data and field observations as well as to confirm conclusions derived from the data (Woyshner and Yanful, 1995; Morris and Stormont, 1999; Khire et al., 2000; Scanlon et al., 2005). Modeling has also been employed to assess a long-term cover performance based on a short-term monitoring or other data (Woyshner and Yanful, 1995; Khire et al., 2000; Scanlon et al., 2005). Long-term predictions allow a reduction in the cost of the cover by eliminating long-term field monitoring where possible. This is very important, since the cost can be quite high, considering that soil covers should be monitored for at least 10-20 years after construction, because short-term monitoring may be dominated by construction effects and a climatic situation may deviate from the usual for the region (Scanlon et al., 2005).

Due to complexity of numerical models for water flow in layered soils, models incorporating layered soil systems remained to be very limited until the development of necessary theoretical basis, numerical schemes, and computer software at the beginning of the current century. One of the recent studies was implemented by Zettl et al. (2011), who proved through field studies and verified by modeling that natural sites composed of coarse-textured soil with higher textural heterogeneity have higher FC than the FC that would be estimated based on average soil textures alone using conventional methods.

Huang (2011) showed that HYDRUS-1D model can accurately predict soil water dynamics, when hysteresis was considered in the model during drainage. Use of optimized saturated hydraulic conductivity was also found to improve water content profiles and soil water storage simulation during an infiltration. It was also proved that Arya-Paris pedotransfer function can be used to estimate not only drying but also the wetting loop of a SWRC by incorporating a change in contact angle. Having compared results of double-ring infiltrometry for several natural ecosites with layered coarse-textured soil and the simulations of infiltration and drainage processes in same soils, they concluded that textural heterogeneity of natural soil profiles increases water storage relative to a similarly textured homogeneous soil profile.

Layered soil systems have been extensively studied recently, since they represent field soil better than non-layered; however, to date there are virtually no studies, including numerical, which investigate the effect of textural transitions between layers. Since soils are mostly heterogeneous in nature, abrupt transitions between layers rarely exist (Liu and Si, 2008), but very few studies address gradual rather than sharp interlayer transitions. Ho and Webb (1998) conducted numerical simulations on sloped capillary barriers with a gravel layer overlain by one of three types of a finer layer: homogeneous, layered heterogeneous (microlayers within the main layer), or random heterogeneous (the finer layer is graded from coarser at the top to finer at the bottom). The authors came to the conclusion that the assumption of uniform interfaces between layers may overpredict the diversion capacity of soil systems. Among three tested soil systems, layered heterogeneous systems were found to divert the largest amount of water and have the most delayed water breakthrough in the sublayer. On the other hand, random heterogeneous soil systems exhibited numerous breakthroughs along the interface of the layers due to highly variable permeability. The performance of these systems was poorer even when the finer layer in the capillary barrier was homogeneous. Water storage in the finer layer in layered heterogeneous systems was the highest due to additional capillary barriers forming within this layer. Ho and Webb (1998) indicated that during the construction of capillary barriers packing techniques that enhance layering in the finer layer should be used in order to create layered heterogeneous soil system with microlayers that will form additional capillary barriers. They also pointed out that it is possible to reasonably accurately predict the performance of layered heterogeneous systems, assuming homogeneity of the layers. However, their conclusions are based entirely on simulations and require practical verification.

2.6 Unstable flow phenomenon in layered soil covers

Layered soil provides greater WSC and better limits percolation of water below a soil system than a homogeneous (non-layered) soil, when flow in soil is stable. Although cases of unstable flow development in homogeneous soil profiles are known (Babel et al., 1995; Wang et al., 2003), layered soils are more susceptible to flow instabilities than non-layered soils under certain conditions (Onody et al., 1995; Sililo and Tellam, 2000). One of the main reasons for layered soils to be more susceptible to unstable flow is that layered profile may have a finer-over-coarser sequence of layers, which is the most critical combination for the instability (Hill and Parlange, 1972; Hillel, 1980, 1998).

Unstable flow is also called preferential flow and comprises all phenomena, where water and solutes move along certain pathways while bypassing other volume fractions (Gerke, 2006). Preferential flow paths often occupy very small portions of the total soil volume, but have the ability to conduct a majority of water with dissolved chemicals at velocities higher than those of uniform infiltration (Gerke et al., 2010). This phenomenon occurs on a wide range of spatial and temporal scales (Clothier et al., 2008; Gerke et al., 2010). In both industrial and agricultural contexts, preferential flow plays an important role, since it enhances the leaching of pollutants such as pesticides, heavy metals, radioactive waste from the surface to deeper layers and even into the groundwater zone (Coppola et al., 2009). Preferential flow also decreases the residence time of water in the profile, solute interaction with soil minerals, reduces effects of retardation, adsorption, and degradation (Tindall and Kunkel, 1999). When pollutants travel rapidly through a flow pathway, they do not have enough time to degrade to nontoxic chemicals, to be strongly adsorbed to soil particles, or be taken up by plants (Kung et al., 2000). Therefore, pollutants leach into the groundwater with almost the same toxicity level they had prior to entering the soil profile (Kung et al., 2000). Since preferential flow may lead to a considerable decrease in water storage, residence time, and an increase in drainage from soil (Gerke et al., 2010), it has been receiving increasing attention in studies of water flow in layered systems.

2.6.1 Mechanism and criteria for instability

The mechanism behind preferential flow phenomenon is not fully understood (Hillel and Baker, 1988; Yao and Hendrickx, 1996; Welter, 2009). In general, the mechanism of instability development in finer-over-coarser soil systems can be described as follows: under unsaturated conditions the wetting front moving in the finer layer will have too low of a matric potential to enter the coarser sublayer and will pause at the interface of the layers (Baker and Hillel, 1990). While the top layer continue to deliver water towards the interface, due to potential gradients above the layer interface, matric potential at the interface increases. Eventually, the matric potential at the interface reaches the h_{we} of the coarser layer and the flux into this layer starts to increase (Baker and Hillel, 1990). However, if the flux from the finer layer is insufficient to cover the flow for the entire interface area, water will tend to enter at a few locations, resulting in the instability of the wetting front and the concentration of the flow in finger-like or tongue-like protrusions as shown in Figure 2.1 (Hillel and Baker, 1988). That is why preferential flow caused by wetting front instability is called fingered flow and is most likely to be observed in layered non-structured soils (Jury and Fluhler, 1992). The described mechanism of preferential flow development is pertinent to gravity-driven flow and not applicable to very slow flows with a dominance of capillary forces, which smooth out instabilities.

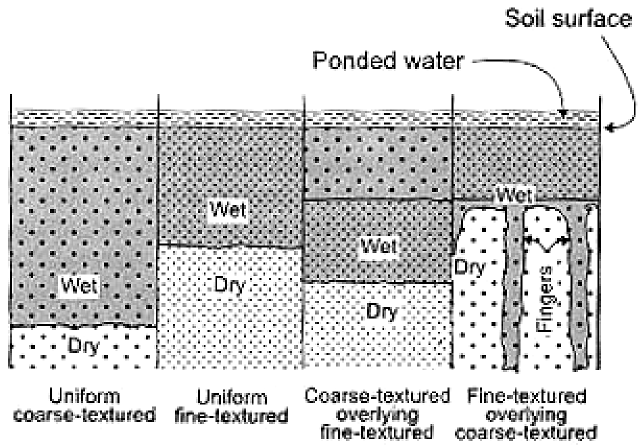


Figure 2.1 Stability of the wetting front traveling through different soil systems. After Hillel (1998).

Once a finger forms, it is able to persist for a long time (Jury et al., 2003). Two criteria should be satisfied for fingers to persist: 1) there should not be lateral flow gradients between the core of the finger and the fringe area that forms around fingers' core; 2) matric potential at the interface of layers must be equal to the lateral h_{we} to ensure supply of water to the finger (Iwata et al., 1995).

Water from the finer layer and the matrix soil flows into the finger because once the depth of the wetting front penetration becomes greater at some point of the front than at others, matric potential distribution shifts towards this location (Jury et al., 2003). As a result, horizontal potential gradients start to enhance lateral flow, supplying water to the finger. Eventually, matric potential at the main wetting front decreases below the h_{we} of the coarser layer, preventing the main front from propagating downward and the flow continues only through fingers (Jury et al., 2003). Fingers may dissipate into the matrix, when after prolonged drainage the matric potential equilibrates between the finger and the matrix, but it requires much longer time than the propagation event (Jury et al., 2003).

Certain conditions must be present for flow to become unstable (Egorov et al., 2003): increase in the wetting front velocity or/and matric potential with depth, or when flux though the interface is less than the hydraulic conductivity at the water entry into the sublayer ($V<K_{we}$) of layered soil. Using an analysis of gravity-driven flow, Hill and Parlange (1972) developed a criterion for instability for soils at high water content: whenever infiltration rate (V) is less than saturated hydraulic conductivity ($V<K_s$) of the coarser layer in finer-over-coarser soil systems, preferential flow may occur. In gravity-driven flow, viscous forces will tend to stabilize flow, but gravitational forces may destabilize it. If the infiltrating flux is less than the unsaturated hydraulic conductivity of soil behind the front, the gravity will exceed the viscous force, and therefore instability may occur (DiCarlo, 2007). This inequality reduces to $V<K_{we}$ for unsaturated conditions, where K_{we} is the K at the water-entry value. In finer-over-coarser layered soil systems, when $V<K_{we}$ (either because flux is too low or K_{we} of the sublayer is too high), the sublayer will not receive a sufficient volume of water to conduct through the entire layer interface, and it will be forced to conduct water through fractions of the interface, causing fingered flow (Hillel and Baker, 1988). For very small surface flux, gravity driven fingering does not occur, since prevailing capillary forces have a stabilizing effect as was experimentally shown by Yao and Hendrickx (1996). Hendrickx and Yao (1996) proposed to use $V<K_s$ criterion for evaluation of wetting front stability in field soils at high infiltration rates (exceeding or equal to K_s). Although this criterion is largely empirical, it satisfactorily predicted the occurrence of unstable flow in field soil (Hendrickx and Yao, 1996). Wang et al. (1998) used the same $V<K_s$ instability criterion for laboratory studies of preferential flow in initially air-dry homogeneous and layered soil. In most of the cases this criterion accurately predicted stability of the front. However, they concluded that this criterion is not applicable, when flow is dominated by capillary forces.

In the early stages of stability analysis of infiltration, Raats (1973) proposed the criterion for instability: if velocity of the wetting front increases with depth, the front will be unstable. This criterion was derived from the Green-Ampt model and, therefore, is applicable only to sharp wetting fronts, coarse-textured soil, and when there is no air entrapment ahead of the wetting front (Raats, 1973). Since Raats proposed his criterion without a supporting analysis, Philip (1975) later conducted a rigorous hydrodynamic stability analysis of the Green-Ampt model used by Raats (1973). From the hydrodynamic stability analysis, Philip (1975) concluded that unlike Raats (1973) initially predicted, the main criterion for instability was an increase of the matric potential ahead of the wetting front or, when the capillary pressure gradient opposes flow. Thus, the following instability criterion was developed:

$$G=h_f+h_a-h_0>0 \qquad [2.1]$$

where G is matric potential gradient, h_f is the matric potential at or immediately behind the wetting front, h_a is the air pressure in soil, and h_0 is the matric potential certain distance behind the wetting front (could be at the soil surface).

The Green-Ampt model used by both Philip (1975) and Raats (1973) is based on the step-function that represents a simplified solution for the infiltration problem. The abovementioned instability criteria are mostly applicable to gravity-driven flows (Philip, 1975). The Richards' equation is non-linear and more generally applicable because of the possibility to apply it to unsaturated flows and non-sharp fronts. However, it is impossible to represent flow instability with the classical Richards' equation, because it was derived by upscaling of microscopic equations, which do not account for pore scale processes (Egorov et al., 2003). As Egorov et al. (2003) noted modification is needed to the macroscopic flow equations to incorporate microscopic flow phenomena.

The classical Richards' equation also does not take the h_{we} and a hysteresis into account to be able to model instability (Jury et al., 2003). However, the Richards' equation is a well-accepted description of flow in unsaturated media, and therefore many attempts have been made to apply some modifications to this equation to enable it to predict instability (Dimentet al., 1982; Kapoor, 1996; Ursino, 2000; Egorov et al., 2003, etc.). For example, Egorov et al. (2003) proposed a model based on Darcian flow with nonequilibrium capillary pressure-saturation relation. Their travelling wave solution for this model turned out to be conditionally stable and, therefore, applicable to describe preferential flow. Through linear stability analysis they concluded that the original Richards' equation is unconditionally stable to infinitesimal perturbations. However, not all attempts to analyse stability of Richards' equation were successful. Kapoor (1996), for example, came to an incorrect conclusion that the Richards' equation is conditionally stable because of a simplifying assumption he made that planar perturbations are small compared to perturbations in the direction of flow.

The most thorough stability analysis of the Richards' equation was performed by Diment et al. (1982) and Diment and Watson (1983). They derived the differential equation that describes the perturbation problem for a non-sharp wetting front. Results of analysis by Diment et al. (1982) were found to have similar trends with Philip's analysis for soil type and initial water content, although Diment's results always showed higher levels of stability.

2.6.2 Main conditions favouring instability

There are numerous causes of preferential flow such as air entrapment (de Rooij, 2000); capillary hysteresis (Lee, 2007); perturbation of pressure potential (Philip, 1975; Hillel and Baker, 1988); fluid instability (Butts and Jensen, 1996); variation in local soil properties (Coppola et al., 2009), including textural heterogeneities (Wang et al., 2003) and an increase of the soil hydraulic conductivity with depth (de Rooij, 2000); soil water repellency (Bauters et al., 1998; Carrillo et al., 2000); and presence of macropores (Gerke, 2006). However, initial water content plays one of the most important roles (Flury et al., 1994; Bauters et al., 2000). Non-uniform water content may form under reoccurring rainfall events. Relatively wet soil zones are more easily accessible to infiltrating water than drier regions. This can be the cause of more intensive flow through certain regions of soil (Ritsema and Dekker, 1994).

Some researchers state that unstable flow is more evident in drier soils, rather than in soils with high water content (Diment and Watson, 1985; Bauters et al., 2000; Wang et al., 2003). Soil water content influences the shape of the wetting front and fingers. Usually, the fingers are wider in soil with higher water content (Bauters et al., 2000). A small increase in water content (up to 0.01 cm^3/cm^3 saturation) was found to cause an increase in the width of fingers in coarse sand with time (Diment and Watson, 1985). Bauters et al. (2000), on the other hand, observed a slight decrease in the width of fingers in 0.60-0.84 mm sand at the same 0.01 cm^3/cm^3 water content compared to dry conditions. However, an increase of water content to 0.02 cm^3/cm^3 and higher resulted in enhanced widening of fingers (Bauters et al., 2000). Babel et al. (1995) experimentally showed that saturation of a coarse sand to FC causes fingering suppression. The same conclusion was reached by Bauters et al. (2000) from the experiments with sands. Although it became generally accepted that the wetting front tends towards stability with increasing wetness, “conflicting evidence exists as to whether fingers widen in wetter soil or dissipate altogether” (de Rooij, 2000).

Fingered flow was found to occur under many different upper boundary conditions. Most of the cases of preferential flow were reported to occur under continuous ponded infiltration (Hill and Parlange, 1972; Diment and Watson, 1985; Baker and Hillel, 1990), probably because most of the laboratory experiments were conducted under this condition. Such a condition is easier to maintain and it ensures more uniform distribution of water over the soil surface. Preferential flow was also observed under continuous nonponded infiltration at the intermediate and high application rate in homogeneous (Selker, 1992) and layered soil (Flury et al., 1994; Hendrickx and Yao, 1996; McLeod et al., 1998; Wang et al., 1998; Welter, 2009). Definitions of application rates are provided as proposed by Hendrickx and Yao (1996): high rate (exceeding or equal to K_s), intermediate (between K_s and gentle rainfall), and low rates are approximately <0.2 cm/h for sandy soil. The diameter of fingers was found to increase with a decrease in infiltration rate, and at a low rate (<1 cm/h) the wetting front tended to stabilize (Yao and Hendrickx, 1996). From their laboratory experiments on sands, Yao and Hendrickx (1996) came to the important conclusion that at the low infiltration rates that are common for many precipitation events, capillary forces play a big role in sandy soil because gravity forces are weak.

Cases of preferential flow under conditions of commonly occurring nonponded rainfall even in homogeneous coarse soil are also known and quite wide-spread (White, 1976; Selker et al., 1992; Babel et al., 1995). Fingered flow was observed by Yao and Hendrickx (1996) in homogeneous perlite and quartz sands at an intermediate infiltration rate. Babel et al. (1995)

observed preferential flow in coarse and very coarse sand homogeneous columns under 0.58-0.85 cm/h rainfall intensity. Having conducted laboratory infiltration experiments on homogeneous coarse sand columns and having compared them with field experiments on non-layered sandy soils, they hypothesized that fingering may be more common in natural sandy soils than is generally recognized, even under nonponded rainfall.

Water flow can be unstable during not only infiltration, but also redistribution. However, this matters mainly for coarse soils, because fingers can travel comparatively long distances during redistribution only in coarse-textured soil. Fingers in finer soil are wider, contain more water, and occupy more cross-sectional area (Jury et al., 2003). Therefore, they differ from these in coarse soil because the equilibrium between the finger and wetted area above it will be reached during redistribution without much downward movement of fingers in the finer soil (Wang et al., 2004). Transition from infiltration to redistribution makes the matric potential gradient change from negative to positive. Combined with hysteresis and a threshold water-entry value, change in sign of a hydraulic gradient creates favourable conditions for development of preferential flow during redistribution. Generally, fingering during the redistribution process remains poorly understood compared to that during infiltration (Wang et al., 2004).

2.6.3 Preferential flow in layered soil covers

Studies of unstable flow in layered soil systems are mostly limited to two-layered soil systems. Influence of increasing the number of layers on flow stability has not been thoroughly studied. Wang et al. (1998) conducted nonponded infiltration experiments under air-confined conditions and observed that in a four-layered loam-over-sand system, flow was preferential in sand layers, but stabilized in finer layers. Similar situations were observed in sand-over-loam covers. Sililo and Tellam (2000), on the other hand, concluded that stratification enhances fingering. This could be because finer silica sand layers overlying coarser sand layers in initially air-dry two-layered and four-layered soil systems were several times thinner than coarser ones. Although there were quite a few fingers, when the wetting front reached the bottom of the soil system, there was no fingering in finer layers and the number of fingers was reduced after passing the second finer layer. Therefore, finer layers still had some stabilizing effects. In three-layered soil system with coarse sand on top of layers of very fine and coarse sands, the wetting front propagated uniformly in the first two layers, but broke into fingers slightly below the interface of very fine and coarse layers (Hill and Parlange, 1972).

The textural contrast between layers also plays an important role in preferential flow development. Instabilities in two-layered columns with a slight textural contrast were studied by Onody et al. (1995). Under constant 1.5-cm water head, when medium sand underlay very fine sand, the fraction of wetted area was 53% compared to 15%, when coarse sand was used as a sublayer. As the textural contrast increased, the wetting front became more and more unstable. Baker and Hillel (1990) traced the wetting front under ponded infiltration and found that wetting front was uniform, when silt to very fine sand were on top of fine sand. When the bottom layer was comprised of medium sand, some fingers started forming. When coarse sand was used as a sublayer, wetting front became unstable immediately after crossing the interface between the layers and separated into narrow, persisting fingers.

In all recent studies on preferential flow on layered soils, including theoretical, experimental, and numerical, the interface between layers is almost always considered as a very sharp transition from one layer to another in terms of texture and hydraulic properties. The necessity of studying textural interfaces between layers was mentioned by Glass et al. (1989), because it allows for better understanding of finger formation, since preferential flow usually develops in this zone. Baker and Hillel (1990) studied fingering in soil systems, consisting of very fine sand (0.045-0.106 mm) layered over a sublayer of matrix sand (0.5 to 0.71 mm) with different percentages of very fine sand added to the matrix (3.8, 7.6, and 13.8%). They noticed that when more of the surface texture was mixed into the sublayer, fingering became less pronounced, and the less the sublayer can be described by Green-Ampt model. When 7.6% of fine sand was added to the matrix sand, fingers were much wider than in experiments with pure 0.5-0.71 mm sand. Wetting fronts were found to be more diffuse in soil systems with a wide range of particle sizes.

2.7 Research gaps

The literature synthesis shows that while considerable knowledge has been accumulated in the area of the water flow in homogeneous soil matrices, studies of water flow and storage in layered profiles are insufficient. Particularly, trials with coarse-textured soils are quite rare. Reported cases of reclamation with the use of coarse materials are scarce, since even now, clay is considered the most suitable soil for this purpose in many regions of the world. However, clays are highly susceptible to swelling and cracking during wetting/drying cycles and may develop large macropores and cracks, enhancing preferential flow. Moreover, the Land Capability Classification System for Forest Ecosystems requires more research on coarse-grained capping soils in order to develop appropriate guidelines for reclamation prescriptions (Zettl et al., 2011).

Some theoretical and experimental knowledge has been accumulated on conventional capillary barriers, consisting of two layers of finer-over-coarser material; however, often different initial and boundary conditions are used, which produces “mixed results” (Morris and Stormont, 1999). Many studies investigate flow barriers incorporating artificial materials (geosynthetics), which also obscures the influence of hydraulic properties of soil on the cover’s performance. Most of the studies have been conducted on soil of highly contrasting textures with unequal proportions of finer and coarser material in soil covers, making comparisons difficult. From a limited number of existing experiments on layered soil systems with slightly contrasting textures of the layers, it is difficult to draw quantitatively-based conclusions on how much water storage can be increased and performance improved through layering of such soils. However, findings of Clothier et al. (1977), Morris and Stormont (1999), and Boateng (2007) show that a combination of fine sand fraction overlying coarse sand sieved from natural sand has the potential to have considerably higher water storage compared to a uniform profile of natural sand. To the best of the author’s knowledge, studies on soil covers composed of sieved fractions of coarse-textured soil natural to the reclamation site are almost non-existent.

Very few studies report the performance of soil systems consisting of more than two layers. Although studies of heterogeneous (layered) soils have gained more attention in recent decades, they were conducted mainly on initially air-dry, artificial soils like construction quartz and often without taking into account heterogeneity of soil hydraulic properties. Moreover, many scientists compare their research results with results of other studies, omitting the differences in methodologies of tracer applications and initial/boundary conditions that lead to the misinterpretation of findings. Finer and coarser layers of soil systems in most cases have different depths, which makes statistical comparison difficult.

It has been proven that preferential flow is more evident in layered soil systems (especially finer-over-coarser) than in non-layered soil. However, it is not known whether soil covers with a slight textural contrast will be as susceptible to preferential flow as soil systems with layers of different texture classes. And if they are, to what degree the residence time of water in them will be affected. Studies on polydisperse and random heterogeneous soil systems such as soil covers with a gradual textural transition zone at the interface of the layers are anecdotal from both flow barrier and preferential flow points of view. It remains unclear whether layering has a stabilizing effect on unstable flow. There is also a need to provide further insight into the degree of fingering under different levels of initial saturation. Since there is not enough knowledge on behaviour of the front during redistribution; more data, including empirical, is needed to have a better understanding of water flow in soil systems.

The causes and governing mechanisms of unstable flow are still not fully understood. A better understanding of the mechanisms responsible for preferential flow would help to manage such environmental problems as groundwater recharge, leaching of contaminants in waste rock, and transport of industrial chemicals below the root zone.

3 WATER STORAGE CAPACITY, RESIDENCE TIME, AND FLOW STABILITY OF LAYERED VS. NON-LAYERED SOIL COVERS

3.1 Introduction

Soil covers are becoming an increasingly popular method of capping waste rock (Lee, 1999). Previous experience has shown that the utilization of a restrictive soil cover composed of fine soils and/or artificial impermeable materials is often not a reliable long-term option (Albright et al., 2006). Soil natural to the site is always a better capping material because of its ability to re-create similar water regimes to those existing before site disturbance (Johannesen et al., 1997). When the natural soil is coarse-textured it has to be properly layered to be able to support vegetation and limit deep percolation.

In many cases only one cover material with a narrow particle size distribution is available for reclamation. Even materials that are naturally different in soil texture can be unintentionally homogenized due to excavation, stockpiling, and placement. Without additional treatment, the homogenized coarse-textured material would not be able to sustain water regimes conducive to vegetation establishment. Among currently available studies on water retention and flow stability in finer-over-coarser soil systems, there are almost no studies on soil systems with layers represented by sieved fractions of coarse-textured soil. It is unknown whether these soil systems will be able to store sufficient water for prolonged periods of time, will not be susceptible to preferential flow, and will form flow barriers that are able to limit water flux from the cover, to be acceptable for reclamation projects. Such soil systems will have a slight textural contrast between layers. However, current studies concentrate mainly on soil system with a high textural contrast. Some degree of a contrast between layers may be important in order to improve reclamation practices.

Another issue with layered soil covers that remains almost unstudied, but may have a considerable impact on water storage and water flow in layered soil covers, is the interface between layers. The latter is almost always assumed to be sharp in experimental studies as well as in models, but such type of interface between layers is hard to encounter in nature and is never possible to reach during a soil cover construction *in situ* (Ho and Webb, 1998).

Layered soil systems are also more susceptible to preferential flow than non-layered (Onody et al., 1995; Sililo and Tellam, 2000). Preferential flow decreases water storage and considerably compromises the ability of the soil cover to limit water percolation through it. However, it is again unclear how preferential flow, if any, will develop in soil with a slight textural contrast. The layering and stability of the wetting front are also closely related to the residence time of water in soil covers: the more of fast-moving fingers develop, the less time it will take for the wetting front to travel through the cover.

The following sections are devoted to a description of methods applied in this research, the results of experiments and their explanation is provided in the Discussion section. Overall conclusions are provided in Chapter 4 along with recommendations for the industry and possible directions for future research.

3.2 Materials and Methods

3.2.1 Soil source site description

Soil for experiments has been sourced from the Key Lake Operation (Cameco Corporation, Ltd.) located in north-central Saskatchewan (57^{0}11'N and 105^{0}34'W), which is 560 km North of Saskatoon (Lee, 1999). Key Lake lies on the south side of the Athabasca sand basin. Natural soils of the Pleistocene age are represented mainly by organically poor white sandstone, outwash sand, and sandy tills containing pebbles. Till deposits accumulate in ground moraines and drumlins and consist of unsorted and unstratified sandy materials with angular and sub-rounded grey sandstone fragments (Lee, 1999).

Drumlins were chosen for soil sourcing because sandy till covers this area almost entirely and contains 86-90% sand (Lee, 1999). This till has almost equal proportion of fine, very fine and medium, and coarse and very coarse sand fractions, allowing separation into relatively finer and coarser fractions. Moreover, a trial soil cover composed of a layer of sandy till with pebbles is currently placed over compacted waste rock from uranium mining at Key Lake. The purpose of this study is to investigate whether such a soil cover is suitable for reclamation of the Deilmann North waste rock pile, covering an area of 50 Ha (Johannesen et al., 1997).

Climatologically, the region is characterized by short cool summers and long cold winters (Lee, 1999). The mean number of frost days is 222 days per year. Key Lake is located in the continental subarctic region. The precipitation typically occurs as snow from October to April, and as rain from May to September. Potential evapotranspiration is 260 mm. The mean annual total precipitation is 458 mm with 35% falling as snow, and 65% as rain based on monthly precipitation statistics from 1977 to 1997 for the Key Lake weather station (Lee, 1999).

3.2.2 Soil packing

Particle size distribution of the sand and its fractions was measured by Laser Scattering Particle Size Analyzer (HORIBA LA950, HORIBA Ltd., USA). The coarser fraction is represented by particles retained between #10 and #60 U.S. standard sieves with apertures of 2 and 0.25 mm, respectively. The finer fraction contained all particles that passed through a #60 sieve.

Four types of experimental soil covers were tested: a non-layered or homogeneous cover (further referred as 1L), a two-layered cover (2L), a two-layered cover with a gradual interlayer transition (2LT), and a four-layered soil cover (4L). The 1L soil cover was composed of natural sand from Key Lake. Layered soil covers represent layering of the finer fraction of natural sand over the coarser fraction. The amount of finer and coarser soil in every test soil cover was kept equal for statistical comparison. Each layer was 50-cm deep in the 2L and 25-cm deep in the 4L soil cover. Total depth of each cover was 100 cm. The 2LT represents a cover with a 10 cm zone in the middle of the profile (45-55 cm), where the amount of the finer fraction gradually decreases, when transitioning from the finer to the coarser layer (Table 3.1).

Table 3.1 Composition of a transition zone in two-layered cover with a gradual transition

Depth of the layer, cm	**Bulk density, g/cm^3**	**Coarser fraction, %**
45-46	1.5	5
46-47	1.6	15
47-48	1.6	25
48-49	1.6	35
49-50	1.6	45
50-51	1.7	55
51-52	1.7	65
52-53	1.7	75
53-54	1.7	85
54-55	1.7	95

Air-dry soil was packed into a thin slab chamber with internal dimensions 1.17×0.4×0.02 m, using a funnel-extension randomizer technique (Glass et al., 1989): sand was poured into a funnel that was manually moved from one end to another at the top of the chamber with an approximately consistent speed. Falling sand was randomized by a mesh screen with the orifice size bigger than the size of the biggest particles of the soil to be packed: #8 sieve (2.38 mm opening) for the natural sand and the coarser fraction, and #30 (0.59 mm) for the finer fraction. The mesh was held approximately 20 cm above the level of soil at the time of packing to produce uniform packing. Walls inside the chamber were sprayed with teflon dry film lubricant before each packing. The same procedure was used by Carrillo et al. (2000) to prevent preferential flow of water down the walls of a chamber. Air-dry natural sand and its coarser fraction were packed to the density of 1.7 g/cm^3, and the finer fraction was packed to the density of 1.5 g/cm^3. These densities were easily achieved and repeatable without a need for additional compaction, when the method of Glass et al. (1989) was used. The finer fraction was packed to the lower density, because 1.7 g/cm^3 density of the finer layer made the interface of the layers to curve towards the centre due to the higher weight of the finer layer. Although the attempts were made to pack soil as uniformly as possible, slight microlayering still occurred. The transition zone in the 2LT cover was divided into 10 layers from 45-cm to

55-cm depth and packed with gradually increasing density from 1.5 g/cm^3 at the top of the transition to 1.7 g/cm^3 at the bottom of the transition (Table 3.1).

3.2.3 Slab chamber infiltration experiments

Two types of infiltration experiments were conducted in the slab chamber: (1) constant head ponded infiltration, and (2) intermittent ponded infiltration. Infiltration experiments conducted under favourable for preferential flow development ponding conditions allowed assessment of the stability of the wetting front and performance of soil covers under different initial and boundary conditions.

Initial and boundary conditions of infiltration experiments are described below and summarized in the Table 3.2. Intermittent ponded infiltration was conducted on initially air-dry soil covers first, and then on the same soil covers at FC without repacking, except for the 4L cover. Only the 4L cover had to be repacked to the density of 1.7 g/cm^3 of both finer and coarser layers due to the formation of voids between layers after intermittent infiltration into initially air-dry cover, when finer layers were packed to the lower density. The further details are provided in the section 3.3.2. Separate covers were packed for the constant and intermittent ponded infiltration due to different lower boundary conditions.

Table 3.2 Summary of infiltration experiments conducted and conditions applied

	Intermittent ponded infiltration	**Constant ponded infiltration**
Types of soil covers tested	Homogeneous, two-layered, two-layered with a gradual transition, four-layered	Homogeneous, two-layered, two-layered with a gradual transition (3 replicates of each)
Initial conditions	Air-dry, field capacity	Air-dry
Upper boundary conditions	1.5 cm applied every 2 days	$H†_{const}$=4 cm
Lower boundary conditions	Air-dry water content of a cover: seepage face=0 (partially restricted flow at the bottom, atmospheric pressure) Field capacity water content of a cover: h‡=-25 cm at the bottom	Seepage face=0 (gravel layer)

† Water head

‡ Matric potential

Constant head ponded infiltration

Constant head infiltration experiments were conducted on 1L, 2L, and 2LT soil covers under initially air-dry conditions only, because maintaining water content of the cover at FC would mean intermittent water application, which was done in the next set of experiments. This type of experiment was done in triplicate. Constant ponded infiltration was conducted using an air humidifier, which maintained constant 4-cm water head on the soil surface. The bottom of the chamber contained multiple holes (0.5 cm diameter) to create air draining conditions. A 3-cm thick gravel layer, sieved from the natural sand, was placed on the bottom of the chamber, creating saturated conditions at the bottom of a cover, once water reached the gravel layer. The gravel simulated the presence of compacted waste rock below the soil cover.

Intermittent ponded infiltration

Intermittent infiltration experiments were conducted under air-dry and FC initial water contents on all four types of soil covers. This type of experiment was conducted without replication because of prohibitive duration of the experiment (approximately two months under both initial water contents). Two initial water contents, initially air-dry and FC were chosen, since the two conditions represent two extreme water contents, very low and high. Although these water contents do not cover all water contents possible in field and field soil is never at air-dry water content, except for very close to the surface, they give a general understanding of the degree of stability of covers between these two extreme conditions.

The experiment started from initially air-dry water content of soil covers. Intermittent vertical infiltration allowed the simulation of a heavy and frequently occurring rainfall event under laboratory conditions. Distilled de-aired water was applied to each type of soil cover at air-dry water content every other day as a pulse of 1.5 cm. One and a half centimetre of water a day corresponds to the return period of 5.5 years at Key Lake, based on precipitation data of 1990-2009 (Dr. L. Barbour, personal communication, University of Saskatchewan, Saskatoon, SK).

Water was almost instantaneously ponded on top of the soil to avoid non-uniform water distribution on the surface. After water application, two days were allowed for movement of water under gravity to cease before a new water application. The total amount of liquid (16.5 cm) was applied to each soil cover at each initial water content over 11 water applications. The amount of liquid applied in total was based on the amount required for a wetting front to reach the end of the profile in the cover with a maximum number of layers (4L) determined experimentally in this study. The wetting front was well visible on the light colour of initially air-dry soil. The bottom of a soil cover was open to the atmosphere under initially air-dry water content; however, free drainage was semi-restricted at the bottom by a matric potential regulation tube, which was empty under initially air-dry conditions, but filled with water when a soil cover was at FC to maintain -25-cm matric potential at the bottom. At the end of the intermittent infiltration experiment under initially air-dry conditions, the soil cover was saturated and allowed to drain for 3-4 days to reach FC that represented initial water content for the next experiment. The chamber had three rows of tiny holes for air to escape at 14, 52, and 112.5 cm from the top of 117-cm high chamber.

The soil covers were saturated with de-aired water. Level of saturation was monitored through inflow-outflow data and/or matric potential data. Attempts were made to saturate the entire column from the bottom, since this type of saturation is known to provide a higher degree of saturation, compared to a water application from the top of the column (Dane and Topp, 2002). However, the rising water (even to half of the height of the soil cover) resulted in water leakage through tensiometer ports and air holes washing out soil particles and, eventually, forming voids in soil. Therefore, part of the soil cover was saturated from the bottom and part from the top. When saturating from the top, 4.5-5 cm of water head was maintained for 12 to about 24 h at the soil surface. After saturation, soil was allowed to desaturate for at least three days. According to the definition, FC is reached when all gravitational water has drained away and the outflow rate has become negligible, which usually takes place within 2-3 days after rainfall or irrigation in coarse-textured soil (Veihmeyer and Hendrickson, 1950).

When the soil was at FC, the same amount of liquid was applied with the same periodicity as under initially air-dry conditions, but brilliant blue dye FC&D#1 was added into deaired water (C=2 kg/m^3) to ensure good visibility of the wetting front. The concentration of dye was lower than usually used because of a light colour of soil. Brilliant blue dye has a pH of 4.6 in water (Nemez, 2013). Chen (1993) reported that the dye has no effect on surface tension of water at pH of 3 and 5 at concentrations up to 0.003 M. Since the concentration of the solution used in my study was 0.0025 M, it can be concluded that the blue dye had no influence on surface tension of water and could not artificially provoke preferential flow.

Matric potential of -25-cm was maintained at the bottom of the profile using a plexiglass tube covered with a nylon membrane with an AEV of -30 cm (Figure 3.1). The tube was perforated on the upper side and kept filled with water all the time to maintain a hydraulic contact with soil. Two smaller diameter tubings were attached to the tube from both ends; one end of the tubing was plugged and another one lowered to 25 cm so that excess water could flow out of the soil as effluent through the needle inserted into a rubber plug.

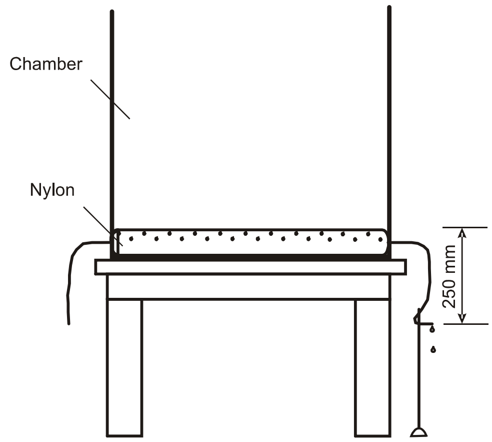


Figure 3.1 Schematic bottom matric potential regulation setup

The top of the chamber was covered to avoid evaporation for both types of infiltration experiments. Hydraulic properties like infiltration rate and wetting front velocity were measured in both types of experiments (the intermittent and constant head infiltration). Wetting patterns were tracked under intermittent ponded infiltration as well as under constant ponded conditions. Information on the wetting front propagation velocity was used to determine residence time of water. Photographs of the wetting front taken with a digital camera Canon Power Shot A530 (5 MPixels) helped to track the wetting front velocity and shape, and to analyse area covered by the wetting front.

3.2.4 Instrumentation of soil covers

Soil covers tested under intermittent infiltration were equipped with tensiometers. Mini tensiometers with 31.03 kPa pressure transducers (Soil Measurement Systems, Arizona, USA) were used to measure a matric potential in cm of water. A tensiometer consists of three basic interconnected elements: a porous ceramic cup, which is attached to a transparent tensiometer body or water reservoir, and a pressure transducer (Figure 3.2). When placed in soil, water from the tensiometer will flow either in or out of the soil, depending on the matric potential of the soil. Movement of water continues until static equilibrium between soil and a ceramic cup is reached (Dane and Topp, 2002).

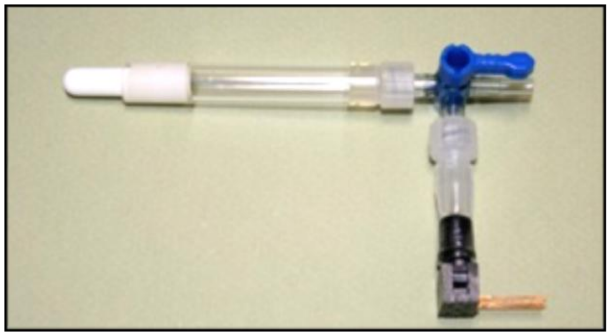


Figure 3.2 Column tensiometer with 3-way valve and pressure transducer, 06/2012, http://www.soilmeasurement.com

To avoid air bubbles in the ceramic cup, deaerated water was pumped through the ceramic cup with a syringe while the cup was held under water until no bubbles appeared in the water. Each pressure transducer was calibrated at several matric potentials, h, for example, 0, 20, 50, 80 cm, using the hanging water column method for calibration. One end of the transparent tubing, which was filled with water, was connected to the transducer and levelled at a reference point (h=0). The other end of the tube, which had a needle inserted into it, was set to a desired matric potential (cm below the reference point). Millivoltage measured by transducer was plotted versus its corresponded known matric potential to get a conversion equation. The relationships were linear with R^2 very close to 1.

Tensiometers were installed in such a way in order to obtain measurements from 1 cm above and below layer interfaces at 24-, 25-, 49-, 51-, 74-, and 76-cm depths in all covers. At some depths, two tensiometers were used to check data and to obtain matric potential at different points in horizontal direction. Two additional tensiometers were installed at the very top of the soil cover (2.5 cm from top) and at 90-cm depth each in the 2LT and 4L soil covers. In the 2LT, additional tensiometers were installed also at 44-, 54-, and 63.5-cm depths to check the influence of the transition zone on the stability and performance of the cover. Tensiometers were not installed at all abovementioned depths in all covers, since not all tensiometers were available for certain experiments.

Tensiometers provide precise data, when there is a good contact with soil and no air bubbles in the tensiometer body or the ceramic cup (Dane and Topp, 2002). Tensiometers were inserted only into relatively wet soil (after the wetting front passed the tensiometer's port) to avoid desiccation of the tensiometer's cup before the wetting front reached it. When bubbles appeared in the tensiometer's body, the three-way valve was opened and water was flushed through a syringe with help of a long needle. Data from pressure transducers was collected on an hourly basis through CR10X dataloggers (Campbell Scientific Inc., Utah, USA), which were connected to a regulated power supply source (Circuit-test, PS-5030). Data exchange between the datalogger and laptop computer was through a SC32A adapter, cable, and LoggerNet v. 3.4.1 Datalogger Support Software (Campbell Scientific Inc., Utah, USA).

3.2.5 Determination of WSC of soil covers

To determine WSC of non-layered soil cover prototypes and to evaluate change with increasing number of layers, soil covers from both types of infiltration experiments were sampled for water content at the end of the experiments after saturation and drainage to FC. The sampling scheme applied to each soil cover was the same: every 10 cm in both vertical and horizontal directions (in layered covers additional samples were taken at layer interface). This was the optimal frequency of sampling to sample each layer in every cover. Samples were analysed by gravimetric method (Dane and Topp, 2002): each moist sample of about 25 g was weighed, dried in the oven for 24 h at 105°C, and reweighed. Gravimetric water content (θ_w) was calculated from the following formula:

$$\theta_w=\frac{(\text{mass of moist soil}+\text{tin})-(\text{mass of dry soil}+\text{tin})}{\text{mass of dry soil}} \qquad [3.1]$$

Gravimetric water content (M/M) was related to volumetric water content θ_v (L^3/L^3) through the bulk density of dry soil, ρ_b (M/L^3) and the density of water ρ_w, (M/L^3), according to the formula (Dane and Topp, 2002):

$$\theta_v=(\rho_b/\rho_w)\theta_w \qquad [3.2]$$

Sometimes samples were taken for verification of packing density after infiltration experiment. However, often some part of the cover was stuck to one of the walls of the chamber and the full sample could not be taken.

3.2.6 Determination of hydraulic parameters of soil and water retention curves

Water retention curves were measured in tempe cells using the hanging column apparatus (Dane and Topp, 2002) for the natural sand and the finer and coarser fractions with replication. Soil was packed in 3-cm high metal cores to the same density as used in infiltration experiments. Soil samples were saturated under vacuum for 3 days to ensure maximum achievable degree of saturation (Dane and Topp, 2002). To do this, samples were placed in a desiccator, which was evacuated for several minutes, filled with CO_2, and allowed to stay for 10 min. After that deaerated water was slowly added to cover 1/4 of the sample and left under vacuum. More water was added under vacuum over another two days before almost entire sample was wetted. After saturation, samples were placed in hydraulic contact with a saturated ceramic disk and saturated again. For h=0, the end of the water-filled tubing was set to coincide with the middle of the core. The basic principal of the tempe cell is to apply certain matric potential to a sample by lowering the water column and waiting for soil to equilibrate hydraulically at the specific matric potential. The weight loss of the sample is then measured. Knowledge of the weight of sample at different matric potentials, its oven-dry water content, and bulk density allowed a calculation of the volumetric water content at each matric potential (Dane and Topp, 2002). Matric potential was measured in 10-cm increments.

At pressures higher than 100 cm, SWRCs (soil water retention curve) were measured using the pressure plate extractor (Dane and Topp, 2002). Pressure applied from the top to soil during the experiment was 14, 34, 48, 69, and 90 kPa. This method was used for natural sand and its finer fraction with triple replication. The coarser fraction had lost almost all water during measurement of SWRC by hanging column apparatus. Only the drying part of the SWRC was measured for all soil types.

Saturated hydraulic conductivity (K_s) was measured using the constant head soil core method (Dane and Topp, 2002) for the natural sand and fractions with triple replication. When the water level stabilized at the surface of saturated samples, effluent samples were collected for 30, 60, 90 s for the coarser fraction, and for 600, 900, 1500 s for natural sand and the finer fraction. Darcy's Law was used to calculate K_s (L/T):

$$K_s=(4QL)/(\pi d_c^2 \Delta t \Delta H) \quad [3.3]$$

where Q (L^3) is the volume of effluent collected during time interval Δt [T], L (L) is the height of the soil sample, ΔH (L) is the level of water head on top of soil, and d_c (L) is the inner diameter of the core (Dane and Topp, 2002).

Van Genuchten's (1980) equation was used to describe the relationship between matric potential (h) and volumetric water content (θ_v):

$$\theta_v = \theta_r + \frac{(\theta_s - \theta_r)}{[1+(\alpha h)^n]^m} \quad [3.4]$$

where θ_s and θ_r are the saturated and residual values of the water content, respectively; α, m, and n (1/cm) are the fitting parameters and m=1−1/n. Unsaturated hydraulic conductivity (K) was calculated also based on van Genuchten's function (1980):

$$K = K_s \frac{(1-(\alpha h)^{mn}(1+(\alpha h)^n)^{-m})^2}{(1+(\alpha h)^n)^{m/2}} \quad [3.5]$$

Complete water retention curves were estimated from particle-size analysis data based on the Arya-Paris model, using the method of similarity (Arya et al., 1999; Dane and Topp, 2002). This method has shown to give satisfactory fit of available data compared to the method of logistic growth. The Arya-Paris pedotransfer function was used, because it allows the estimation of water retention at very high pressures that are not always feasible to measure.

Hydraulic parameters for layers in the transition zone of the 2LT cover were calculated through linear interpolation between the values of these parameters for the finer and coarser fractions:

$$P(x) = y_0 + \frac{(y_1 - y_0)}{n}(x - x_0) \qquad [3.6]$$

where y_0 is the value of the variable for a finer layer, y_1 is the value of the variable for the coarser layer, n is the total number of layers, and $(x - x_0)$ specifies the consecutive number of the layer.

The parameters shown in Table 3.3 are those of the layers in the middle and at the bottom of the transition zone, where matric potential was measured in tested covers. θ_s is lower in the middle layer than in the lower layer, because the finer fraction tended to shrink unlike the coarser fraction.

Table 3.3 Hydraulic parameters of soil in the textural transition zone of two-layered cover with a gradual transition

	α (1/cm)	**n**	**θ_r**	**θ_s**	**K_s (cm/h)**
Middle layer (48-49 cm)	0.04	2.9	0.01	0.33	86.9
Lower layer (54-55 cm)	0.05	4.8	0.01	0.34	194.2

The water retention curve for the middle layer looks more like the curve for the finer fraction, because it contains 65% of finer fraction, while the lower layer has parameters similar to the coarser fraction (Figure 3.3), since it contains only 15% of the finer fraction (Table 3.1).

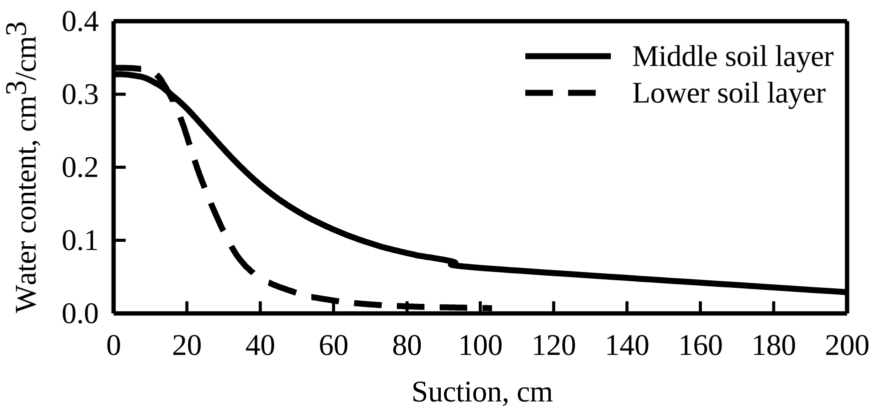


Figure 3.3 Fitted water retention curves for middle and lower layers in the transition zone of two-layered cover with a gradual transition

Unsaturated hydraulic conductivity of the finer fraction was equal to that of the layer in the middle of the transition zone at 121-cm suction (Figure 3.4). At less than 50-cm suction the difference in *K* between these soils became more than an order of magnitude.

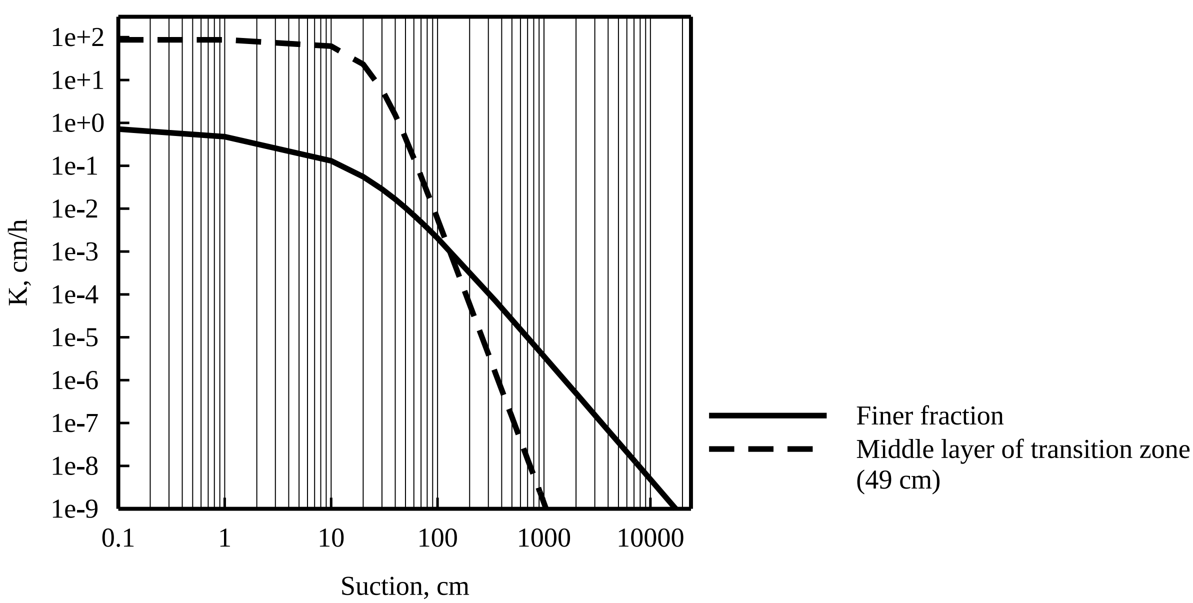


Figure 3.4 Estimated unsaturated hydraulic conductivity (*K*) as a function of suction for finer fraction and the layer in the middle of the transition zone of two-layered cover with a gradual transition

3.2.7 Statistical analysis

The statistical analysis was performed in SPSS (PASW Statistics 18, SPSS Inc.). A single factor Analysis of Variance was performed on water storage data of soil covers under shallow water table conditions. The null hypothesis (H_0) for this analysis was that the "layering does not have an effect on water storage", whereas the alternative hypothesis (H_1) was that the "layering does have an effect on water storage".

3.2.8 Simulation of laboratory infiltration experiments

Modeling was performed to verify results of experiments done without replication. Modeling also allowed to obtain the outflow rate from soil covers, which was a variable missing from the experiments due to leakage of the matric potential regulation tube at the bottom of some covers.

Governing equation

Water storage capacity as well as intermittent ponded infiltration for each experimental cover were simulated in the HYDRUS-1D numerical modeling code. The governing equation used in the software was the modified Richards' equation for one-dimensional Darcian flow in a partially saturated, rigid porous medium:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}(K\left(\frac{\partial h}{\partial z} + cos\alpha\right)) \qquad [3.7]$$

where h is the matric potential [L], θ is the volumetric water content [L^3/L^3], t is time [T], z is the spatial coordinate [L] (positive upward), α is the angle between the flow direction and the vertical axis, i.e., $\alpha = 0$ for vertical flow (Šimůnek et al., 2009). K is given by the following function:

$$K(h,z) = \mathrm{K_s}(z)K_r(h,z) \qquad [3.8]$$

where K_r is the relative hydraulic conductivity [-] described by Vogel and Císlerová (1988), K_s the saturated hydraulic conductivity [L/T] (Šimůnek et al., 2009).

Hydraulic parameters used in simulations were estimated from van Genuchten's functions [3.4] and [3.5]. HYDRUS-1D does not allow the specification of more than 10 different layers for mass balance. Since the transition zone in the 2LT cover consisted of 10, 1-cm deep layers, the layers had to be combined into 5, 2-cm deep layers due to limitations of the modeling tool (Table 3.4).

Minimum, maximum, and initial time steps varied depending on conditions modeled. The more layers the cover had, and the more complex the boundary conditions that were imposed, the finer was the time step that was specified. Sometimes a fairly small difference between minimum and maximum time steps was required for the solution to converge. One-cm space discretization in the vertical direction was used for the 100-cm profile for all covers.

Table 3.4 Hydraulic parameters for soil layers in two-layered cover with a gradual transition

Layer	**θ_r**	**θ_s**	**α (1/cm)**	**n**	**K_s (cm/h)**
Finer (1)	0.01	0.32	0.03	1.4	1
2	0.01	0.32	0.03	2.0	40.3
3	0.01	0.33	0.04	2.7	79.7
4	0.01	0.33	0.04	3.4	119.1
5	0.01	0.33	0.04	4.1	158.5
6	0.01	0.34	0.05	4.8	197.8
Coarser (7)	0.01	0.34	0.05	5.5	237.2

Initial and boundary conditions

Infiltration

In order to predict water storage of soil covers, water infiltration to saturation followed by drainage was simulated. Variable pressure head was chosen in HYDRUS as the upper boundary condition: 4.5 cm of water head was specified for 47.9 hours and 0-cm head for 0.1 h. Seepage face (h=0) was used as a lower boundary condition, which means that when the wetting front reaches the bottom of the soil column, zero matric potential condition is automatically applied. This system-dependant condition is often used in simulation of column experiments (Šimůnek et al., 2009). Minutes were used as the time unit for all soil covers, except for the 1L covers, where such a fine time step was not required for a solution to converge and hours were used as the time unit. The initial matric potential of -100000 cm was used for natural sand and the finer size fraction, and -3000 cm for the coarser size fraction, since soil covers were initially at air-dry water content. The matric potential was specified as -3000 cm for the coarser fraction, since even if -100000 cm were specified as initial matric potential, HYDRUS changed the matric potential to -3000 cm at the very beginning of simulation automatically. Such matric potential was considered acceptable to represent air-dry conditions in soil, since water content is residual at this matric potential as modeling results showed.

Drainage

Matric potential profiles at the end of the infiltration were used as initial matric potential profiles for the simulation of drainage. Hours were used as the time unit for all covers, except for the 2LT, where convergence could not be obtained on the order of hours and the finer time step was required. Constant flux equal to zero was set as the upper boundary condition and seepage face (h=-25 cm) as the lower boundary condition. Drainage was simulated for 96 h, after which water storage was calculated for each cover. This drainage duration was chosen, because sometimes laboratory tested columns were allowed to drain for 4 days.

Intermittent ponded infiltration into initially air-dry soil cover

The initial matric potential in the air-dry soil was set to -100000 cm for the natural sand and the finer fraction, -3000 cm for the coarser fraction. Atmospheric boundary condition with surface layer was used as the upper boundary condition, since it allows for ponding on the soil surface, instead of immediately considering this as runoff (Šimůnek et al., 2009). The applied pulse was specified as a precipitation rate (18.75 cm/min). This rate is based on the amount of liquid applied (1.5 cm) and average time required for its application (4.8 s). This amount of time on average was required for 1.5 cm of water to be distributed over the soil surface or at least water head on the soil surface did not change considerably over this time. Since water was applied 11 times as a pulse every two days, 11 pulses were simulated. The lower boundary condition was specified as seepage face (h=0 cm). Attempts to use other models in HYDRUS such as variable head/flux model with stepwise head specification resulted in a considerable overestimation of cumulative infiltration. Evaporation was set to zero, since the column was kept covered on top between water applications. The minimum matric potential at the top of the soil was set to -100000 cm.

3.3 Results

3.3.1 Soil characterization

Following the Canadian System of soil classification (Haynes, 1998) the natural sand used in the experimental covers is classified as a sand texture (Table 3.5). Natural sand, which contains 40% of finer and 60% of coarser fraction, was separated into two fractions. The finer sand fraction was classified as loamy sand. The coarser fraction contains a small percentage of very fine particles (<0.001 mm), and therefore overlaps with the natural sand on the top and bottom of the particle size curve (Figure 3.5).

Table 3.5 Textures of tested soils

Texture	Natural sand	Finer fraction	Coarser fraction
		%	
Gravel-sand	1	0	2
Sand	88	81	93
Silt	7	12	3
Clay	4	7	2

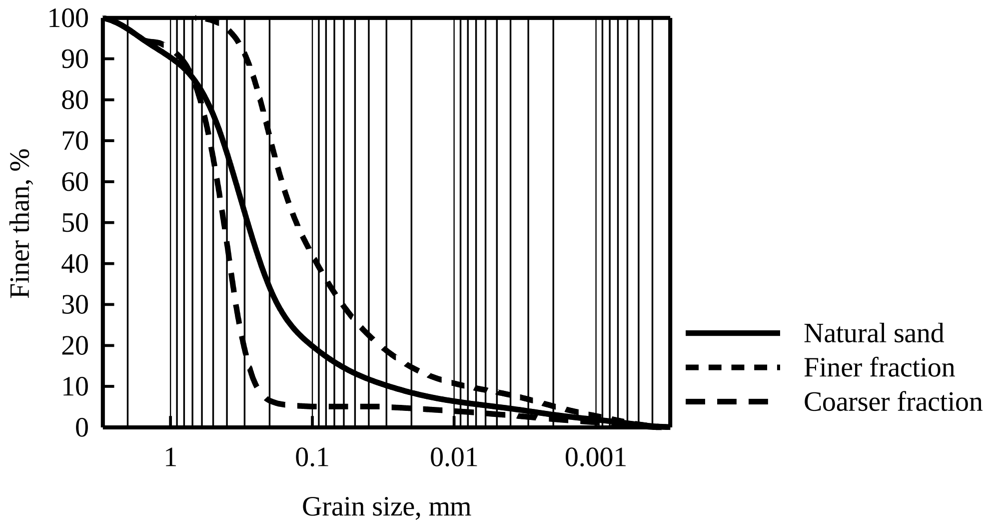


Figure 3.5 Particle size distribution of natural soil and sieved fractions

The particle size distribution and bulk density of the soil largely determine the hydraulic properties of sand and its fractions. Due to some post wetting shrinkage of natural sand and the finer fraction, volumetric water content was calculated based on measured volume (which was smaller than the volume of the ring that contained the soil sample). Measured SWRCs are plotted in Figure 3.6 - Figure 3.8, taking into account the change in soil volume. Since sieved coarser fraction was missing certain sized particles, the water retention curve for the coarser fraction, estimated from the particle size distribution (based on the Arya-Paris model), differed considerably from the experimental curve and is not shown here. Hydraulic parameters of sand and the fractions, determined from fitting van Genuchten’s function to the measured SWRC, are shown in Table 3.6.

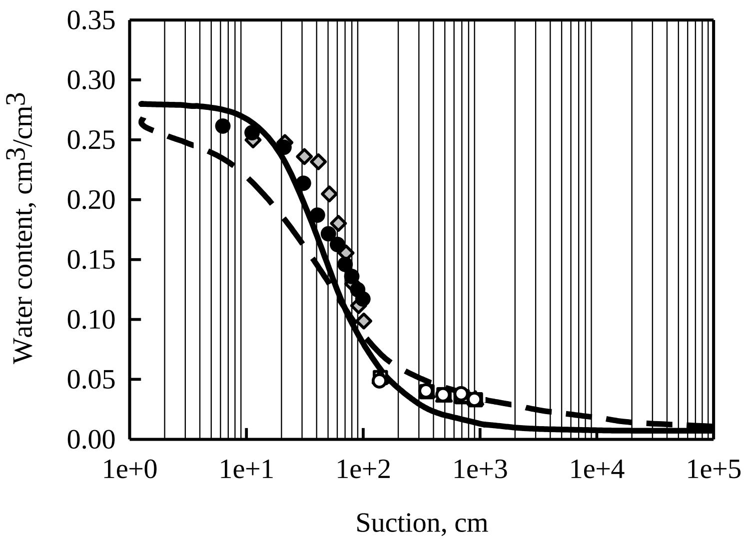


Figure 3.6 Soil water retention curves of natural sand. Shapes represent measured replicates, solid line is fitted van Genuchten's function, dashed line is estimated function from particle size analysis (method of similarity).

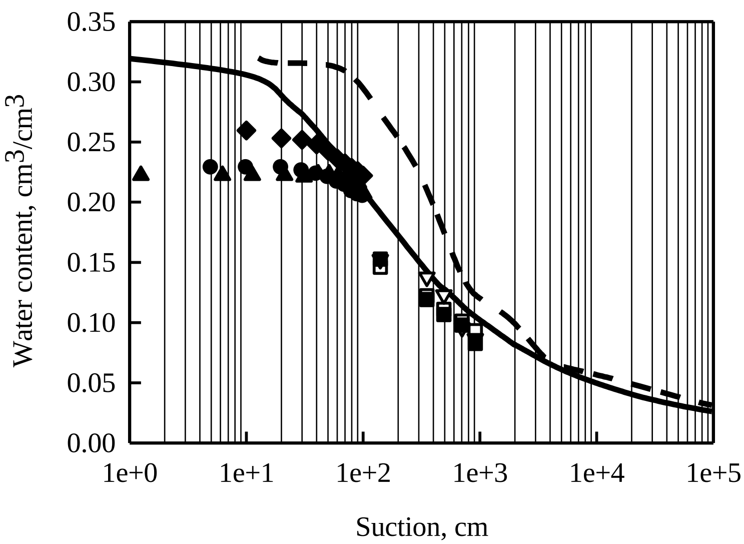


Figure 3.7 Soil water retention curves of finer fraction. Shapes represent measured replicates, solid line is fitted van Genuchten's function, dashed line is estimated function from particle size analysis (method of similarity).

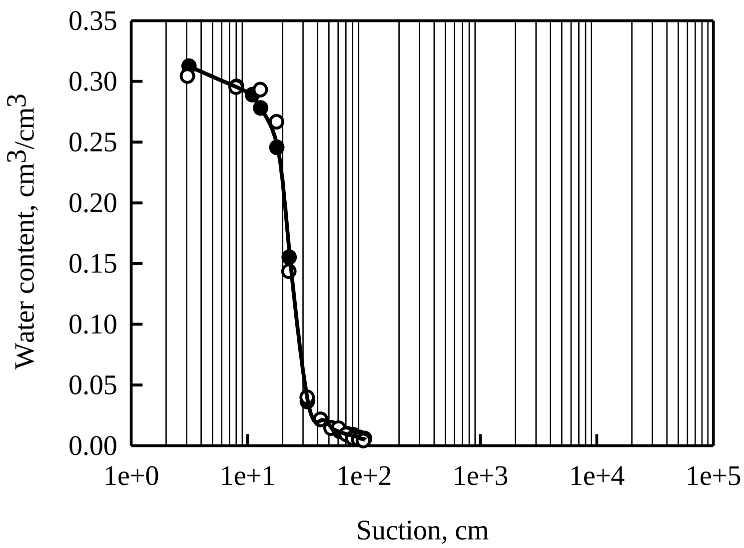


Figure 3.8 Soil water retention curves of coarser fraction. Circles represent measured replicates, solid line is a fitted van Genuchten's function.

Table 3.6 Hydraulic parameters of soils used in tested soil covers

	α (1/cm)	**n**	**θ_r**	**θ_s**	**K_s (cm/h)**
Natural sand	0.03	2.1	0.01	0.28	6.9
Finer soil	0.03	1.4	0.01	0.32	1.0
Coarser soil	0.05	5.5	0.01	0.34	237.2

With only a slight change in soil texture, saturated hydraulic conductivity varied considerably (Table 3.6). Estimated unsaturated hydraulic conductivity curves based on [3.4-3.5] are shown in Figure 3.9 and Figure 3.10. The curves for the *K* of the finer and coarser fractions intersect at 40-cm of suction. Above this suction, *K* of the coarser sand increases more rapidly than *K* of the finer sand with a decreasing suction.

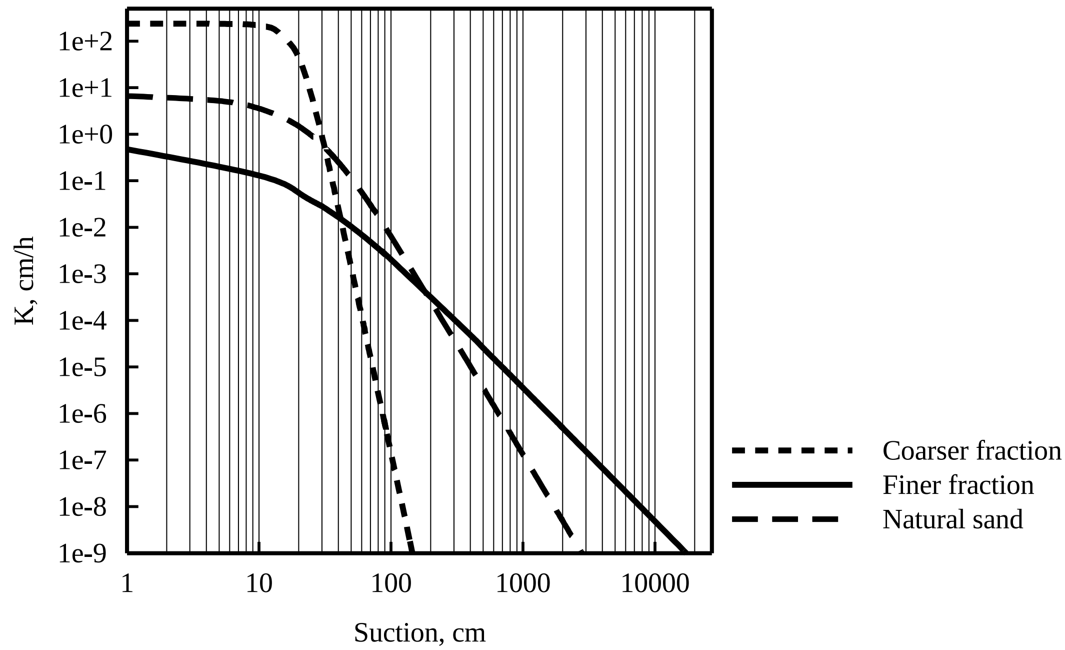


Figure 3.9 Estimated unsaturated hydraulic conductivity (*K*) as a function of suction for three tested soils

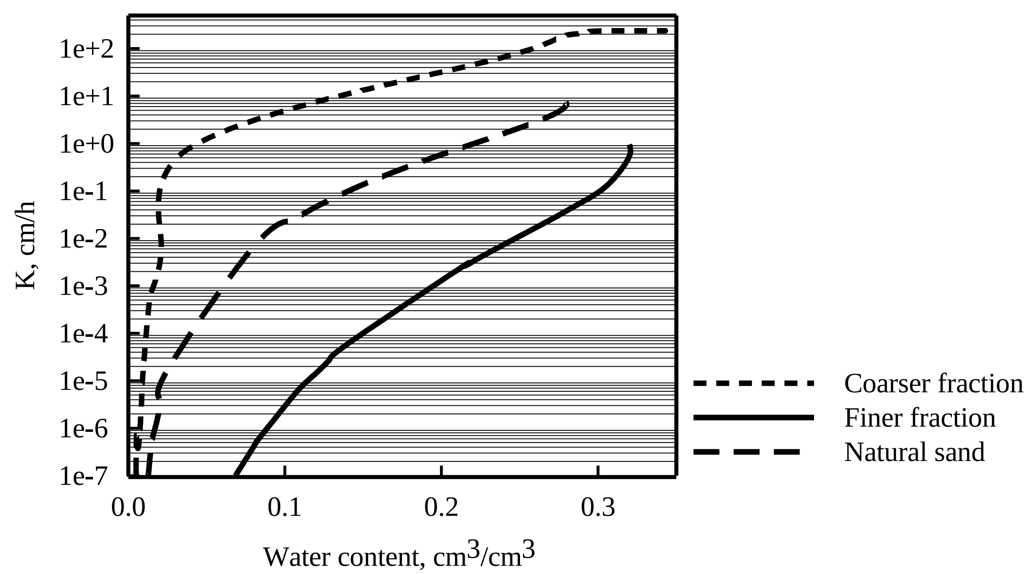


Figure 3.10 Estimated unsaturated hydraulic conductivity (*K*) as a function of volumetric water content for three tested soils

3.3.2 Water storage capacity of soil covers

The results of the water storage measurements at FC of the entire cover and simulations are presented below under two types of lower boundary conditions: (1) bottom of the cover contains a 3-cm gravel layer, to simulate a situation with compacted waste rock below a soil cover; and (2) bottom of the cover is at -25-cm matric potential, to simulate a shallow water table condition.

Compacted waste rock lower boundary condition (1)

Under the first type of lower boundary condition, the gravel layer acts as a seepage face=0, which means that when infiltrating water reaches the gravel layer, a thin zone of saturation starts to form at the interface of the cover and gravel. Water storage capacity and soil water content distribution in the profile were greatly affected by soil layering (Table 3.7, Figure 3.11). Soil covers composed of the finer fraction layered over the coarser fraction of the natural sand stored more water than those composed of uniform natural sand. The 2L covers stored 16.8 cm/m on average, which is 4.5 cm more than the water storage of the 1L covers. Water was stored mostly in finer layers and the water content was the highest just above the layer interface (Figure 3.11). Nevertheless, the 2LT covers stored 1.6 cm more than the 1L soil covers, they stored 2.9 cm less water on average than the 2L covers.

Table 3.7 Water storage capacities of soil covers tested under two types of lower boundary conditions

	Homogeneous soil cover	Two-layered soil cover	Two-layered soil cover with a gradual transition	Four-layered soil cover
	Water storage capacity under type 1 condition (cm)			
Top soil (50 cm)	4.1±0.02†	11.2±0.63	8.6±0.11	N/A
Lower 50 cm	8.2±0.12	5.6±0.37	5.4±0.36	N/A
Total	**12.3±0.10**	**16.8±0.85**	**13.9±0.44**	N/A
	Water storage capacity under type 2 condition (cm)			
Top soil (50 cm)	4.0	10.3	9.3	6.0
Lower 50 cm	8.8	3.5	3.5	9.4
Total	**12.8**	**13.8**	**12.8**	**15.4**

† Standard deviations

The soil water content distribution in the 1L cover monotonically increased with the increase in soil depth due to the lower boundary condition. Water storage capacity was lower in the upper part of the 1L cover than in layered covers, since there was no capillary barrier effect to increase the WSC in the first half of the 1L cover. In the 2L covers the water content increased with depth to about 50 cm, then started to decrease sharply up to approximately 65-cm depth, and continued to increase again below this depth (Figure 3.11). The gradual transition zone affected only water content of the finer layers, whereas water content profiles of the coarser layers of the 2L and 2LT soil covers were almost identical.

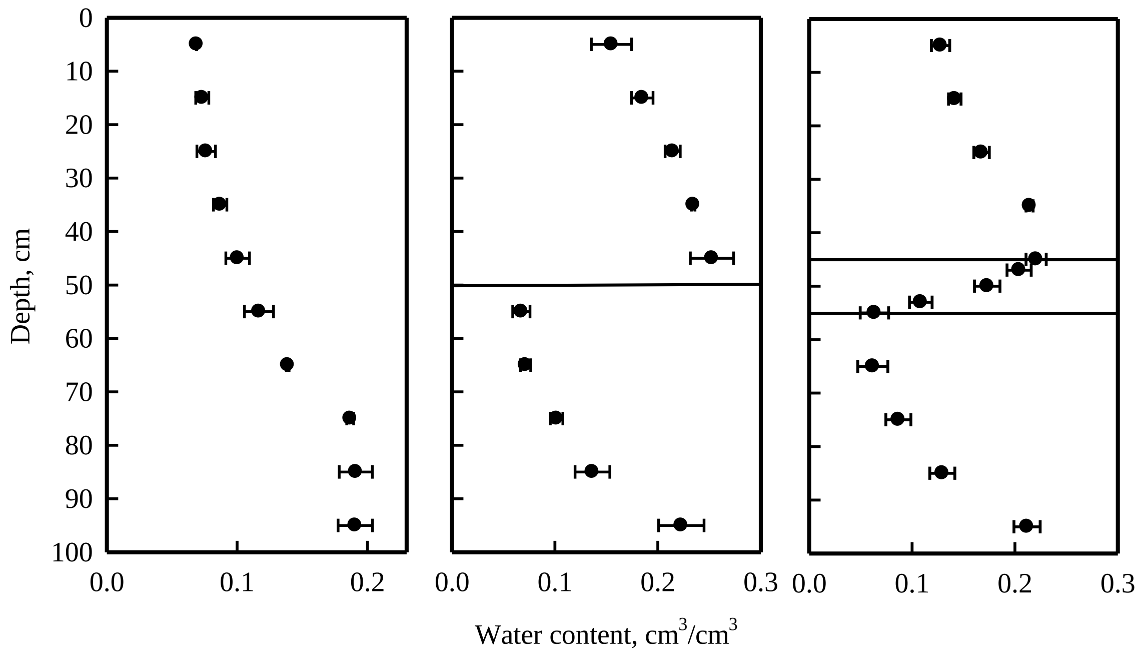


Figure 3.11 Measured water contents (circles) at FC in homogeneous (left), two-layered (middle), and two-layered with a gradual transition (right) soil covers under gravel layer lower boundary condition. Solid lines represent layers interface. Bars indicate standard deviations.

The total water storage even in the 2LT covers under the gravel layer lower boundary condition was significantly higher (P=0.0011) than that of the 1L covers. It can be concluded that layering did increase water storage and the null hypothesis (H_0) that the "layers do not have an effect on water storage when they are texturally similar", was rejected.

Shallow water table lower boundary condition (2)

Similar to the type 1 condition, WSC increased with layering of covers under the type 2 lower boundary condition (Table 3.7). In the 1L cover, WSC was higher under the type 2 condition than under the type 1 condition. Water storage capacity of the 1L cover was expected to be slightly lower under the type 2 condition (h=-25 cm) than under the type 1 condition, where a layer of gravel created saturated conditions at the bottom, when the cover was at FC. The reason for this discrepancy is the unintentional increase of matric potential under the type 2 condition, due to flushing of air bubbles out of the matric potential regulation tube. Caused by the microholes in the membrane made by the soil particles during packing or moving of the column, air bubbles periodically formed in the tube.

Water content increased from 0.07 cm^3/cm^3, at the top 5 cm of the profile to 0.23 cm^3/cm^3 at 95-cm depth of the 1L cover (Figure 3.12). The 2L soil had a 13.8 cm WSC with most of the water stored in the first half of the profile (10.3 cm). The 2LT stored 1 cm less water in the first 50 cm than the 2L. The total water storage of the 2LT was exactly the same as that of the 1L cover. Probably WSC of the 2LT would be higher than that of the 1L cover, if there was no unintentional increase of water content at the bottom of the 1L cover. Shapes of the water content profiles of both two-layered soil covers were very similar (Figure 3.12), except for water content at the bottom of the finer layer being lower in the 2LT. A decrease in water content from 45 to 55 cm was more gradual in the 2LT cover. Water content at 55-cm depth was slightly higher in the 2LT cover than in the 2L.

The 4L soil system had the highest WSC (15.4 cm/m), which was 2.6 cm greater than that of the 1L soil cover and 1.6 cm greater than that of the 2L soil cover (Table 3.7). Similarly to other covers, most of the water was stored in the finer-textured layers of the 4L soil cover: first finer-textured layer (0 to 25 cm) stored 5.1 cm of water and the second finer layer (50 to 75 cm) stored 6.6 cm. Water storage in the first finer layer (0-25 cm) was 1.5 cm less than that of the second finer layer (50-75 cm), which was due to the effect of the lower boundary condition at the bottom of the cover during drainage. The water storage in the first half of the 4L profile was 4.3 cm less than that of the 2L soil cover. Therefore, there is a considerable decrease in plant available water in the top 50 cm of the 4L cover compared to two-layered soil covers. However, beneficial for deep-rooted plants, water storage was higher in the lower 50 cm of the 4L soil cover than in all other covers. Since samples for water content were taken exactly from the interface of the layers (25, 50, 75 cm) only in this 4L soil cover with a 1.5 g/cm^3 density of the finer layers, water storage could be slightly underestimated. Therefore, the water content profile is shown for another 4L cover, where samples were taken 1 cm above and below the interfaces (Figure 3.12). Both the finer and coarser layers were packed to a density of 1.7 g/cm^3 in this cover, as when the finer layers were packed to 1.5 g/cm^3, they shrank during redistribution cycles and formed void spaces between the coarser layers. Therefore, in order to conduct a representative infiltration experiment at FC, the cover had to be packed to the 1.7 g/cm^3 density in all layers.

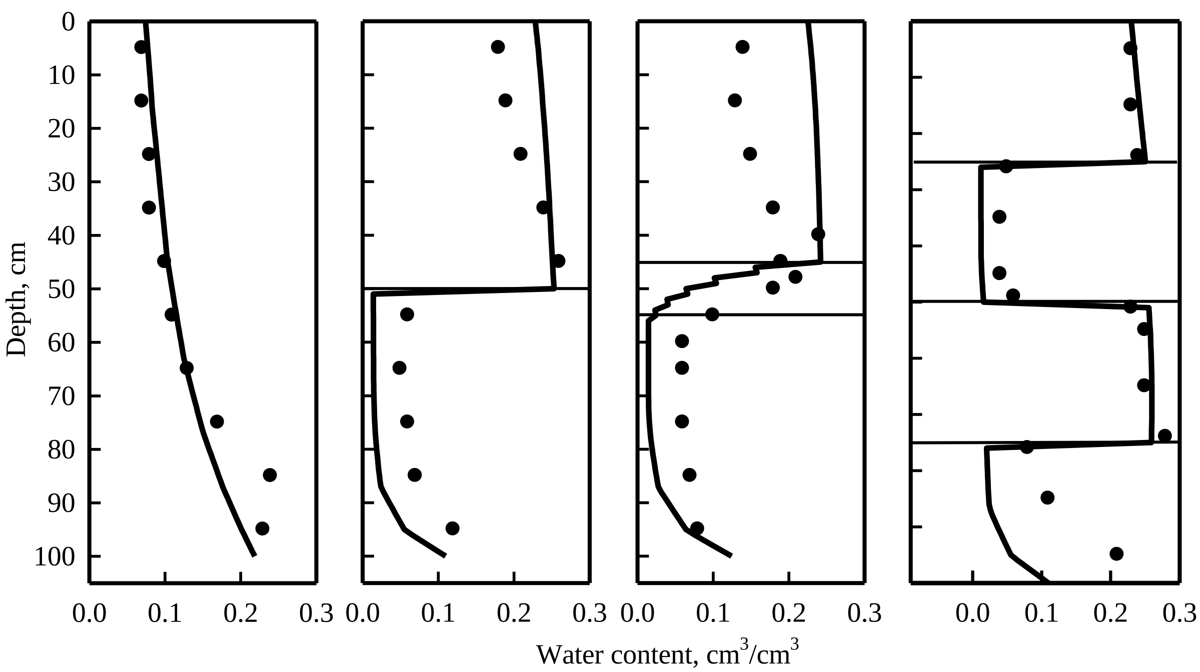


Figure 3.12 Water content profiles in soil covers at FC with -25-cm matric potential at the bottom: homogeneous, two-layered, two-layered with a gradual transition, four-layered (from left to right). Density of finer layers in four-layered cover is 1.7 g/cm^3. Solid line represents layer interface. Circles represent measured data and curves are simulated profiles.

The difference in matric potentials at the bottom of covers under two lower boundary conditions affected the water content in the lower part of the covers. Under the type 1 condition (h=0 cm), the considerable increase in water content started to be observed below 65-cm, and 85-cm under the type 2 condition (h=-25 cm).

Under shallow water table conditions (h=-25 cm), the WSC of layered soil covers increased with the number of layers, although the absence of replicates made statistical significance impossible to determine. However, there was a common trend among experiments conducted under different boundary conditions. Water storage increased after separation of the natural sand into the finer and coarser size fractions and the creation of a simple soil system with the finer fraction on top of the coarser one.

Total simulated WSC correlated better with the measured WSC than simulated and measured water content distribution within soil covers (Figure 3.12). The simulated water storage in the 1L soil cover was 12.3 cm/m, 13.7 cm/m in the 2L, 13.1 cm/m in the 2LT, and 14.1 cm/m in the 4L soil cover. There was a slight overestimation of water storage in the 2LT; this may be a result of linear interpolation of hydraulic properties in the transition zone. Water storage in the 4L soil cover was underestimated by 1.3 cm in the model. The higher level of error for this soil system than for other soil covers could be associated with the greater complexity of the problem due to multiple layers.

Water contents in the model coincided well with measured water contents for the 1L soil cover. In the 2L cover, agreement between measured (0.26 cm^3/cm^3) and simulated water content at the bottom of the finer layer (0.25 cm^3/cm^3) was also fairly good. However, in the upper part of the finer layer the measured water content was less than the simulated water content. In the 4L soil cover, the simulated water storage was slightly higher in the second finer layer (6.5 cm), than that in the first finer layer (5.7 cm) similar to measured results. Generally, measured and simulated water content profiles agreed well in the 4L soil cover. The simulated water content was underestimated for coarser layers in all layered soil covers and in the transition zone, compared to the measured values.

The simulated data showed the same trends as the measured data: WSC increased with the increasing number of layers in the cover, but the addition of an interlayer transition led to a decrease in the WSC. This suggests that the model based on the measured soil hydraulic parameters was able to catch the salient feature of water flow, proving the obtained simulations are reliable.

Water storage capacity could also be expressed as net storage capacity or available water holding capacity, which is the difference between FC and permanent wilting point, multiplied by depth of a layer (Stormont and Morris, 1998). However, this definition is mainly based on availability of water for plants. The purpose of this study, however, was to determine the maximum possible WSC a SC may have in field, when vegetation is dormant and evaporation is low, such as most of the year in cold regions. The knowledge of water storage in soil covers at FC will allow to find an optimal cover design that can accommodate abrupt and high increases in water content as during partial or final snowmelt in such regions. Therefore, WSC was not estimated as a net storage capacity.

Even though WSC of soil covers proved to increase with layering of sand fractions, the finer-over-coarser soil systems are susceptible to preferential flow, which may diminish the water storage of layered covers, as was described earlier in Chapter 2. Therefore, water flow stability was evaluated in each cover and is presented in the section below.

3.3.3 Wetting front stability

In order to quantify if tested soil covers are susceptible to preferential flow, the stability of the wetting front during infiltration experiments was assessed based on three instability criteria (described in more details in Chapter 2): 1) $V<K_{we}$ the velocity criterion proposed by Hill and Parlange (1972), where V is the infiltration rate, and K_{we} is the hydraulic conductivity at the water-entry value into the sublayer of a finer-over-coarser soil system; 2) increase of the wetting front velocity with the depth criterion proposed by Raats (1973); 3) the G criterion: $G=h_f+h_a-h_0>0$, where G is the matric potential gradient, h_f is the matric potential at or immediately behind the wetting front, h_a is the air pressure in soil, and h_0 is the matric potential behind the wetting front. The wetting front is unstable when the matric potential gradient opposes the flow or when matric potential at the wetting front is much higher than behind the front (Philip 1975).

All these criteria predict only a potential for instability and accuracy of their predictions should always be verified by visual observations of the wetting front during the experiment. Satisfaction of 1st or 3rd criterion is sufficient to predict a potential for instability of the wetting front. Since the 2nd criterion is not the main criterion as was mentioned in Chapter 2, it serves as a complimentary criterion. The difference between the two main criteria is that the $V<K_{we}$ criterion can only be applied in layered soil systems; whereas, the G criterion is mainly applicable to non-layered soils, but under certain conditions can be applied to layered soils

too. Infiltration and wetting front propagation velocity profiles are provided in Appendices A and B.

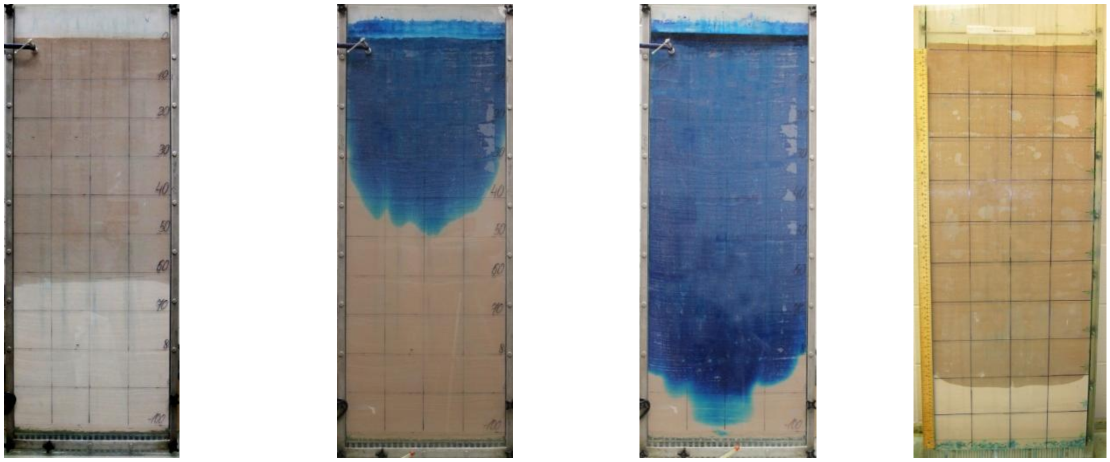
Homogeneous soil covers

The wetting front was uniform in the 1L cover during intermittent infiltration under both initial water contents as seen from Figure 3.13 (a, b). Velocity of the wetting front gradually changed from 54 to 0.29 cm/h at the end of the experiment. Thus, there was no increase of the velocity with depth as could be observed if flow was preferential.

When the wetting front traveled 59 cm, the matric potential at 51-cm depth was -70.3 cm and the matric potential on top of the profile was -61 cm. According to [2.1], $G=h_f+h_a-h_0=$ -70.3+0+61=-9.3 cm. Stability was assessed, when the wetting front passed half of the profile, because matric potential data were not available for the time when the wetting front just passed 76 cm. Since the soil was usually not saturated at the front, the wetting front was not very sharp. This prevented compression of air ahead of the wetting front, and therefore $h_a=0$ was assumed. Since the matric potential was higher at the top of the layer and decreased downward, $G>0$ inequality for unstable flow was not satisfied. According to two instability criteria the wetting front was stable in the initially air-dry 1L soil cover.

Under constant head ponded infiltration into the initially air-dry 1L soil cover, the wetting front propagated much faster but still remained very uniform (Figure 3.13c). Since the matric potential was not measured under constant infiltration experiments, conclusions can only be made from visual observations and the wetting front velocity data. The velocity gradually decreased from 150 to 43.8 cm/h with increasing depth during the experiment and the wetting front remained uniform. Therefore, the wetting front was stable in the 1L soil covers.

Under FC water content, the velocity of the wetting front gradually decreased from 19.92 to 0.31 cm/h during the experiment. At all depths the wetting front was somewhat wavy, but no sign of fingers formation was observed (Figure 3.13 b).



(a) (b) (c)

Figure 3.13 Shape of the wetting front in homogeneous soil cover (a) under intermittent ponded infiltration into initially air-dry soil with a seepage face=0 at the bottom; (b) under intermittent ponded infiltration at FC with h=-25 cm at the bottom; (c) under constant infiltration into initially air-dry soil with a gravel layer at the bottom.

Two-layered soil covers

Flow stability under initially air-dry water content

Under intermittent infiltration, the wetting front was very uniform in the finer layer of the 2L cover under initially air-dry conditions and it remained stable before reaching 64-cm, but started to become more wavy below this depth. In the coarser layer, wetting front velocity increased from 0.16 cm/h at 64 cm to 0.21 cm/h at 100-cm depth.

When the wetting front traveled 70 cm, the matric potential started to be higher at the wetting front than behind the front. As the wetting front traveled 77.5 cm, the matric potential was equal to -22.4 cm at 51-cm depth and -13.1 cm at 74-cm depth. Generally, there was no evidence of very high unexpected increases in matric potential in the coarser layer and no sudden decreases at the bottom of the finer layer (Figure 3.14) as would occur in the case of pronounced instability development. Thus, although no distinct, fast-moving fingers formed (Figure 3.15a), there was some increase in the wetting front velocity and some perturbation of the matric potential was observed at the wetting front. Therefore, flow in this cover can be characterised as having some potential for instability.

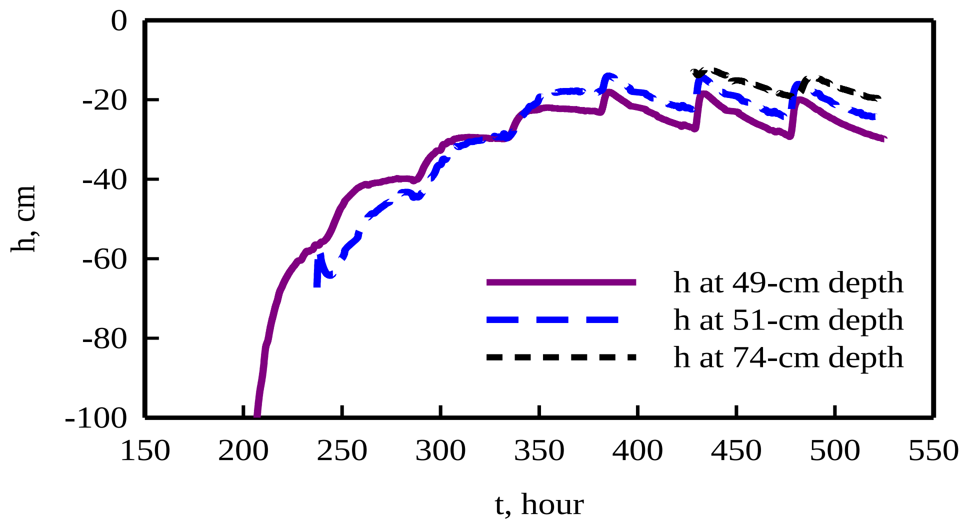
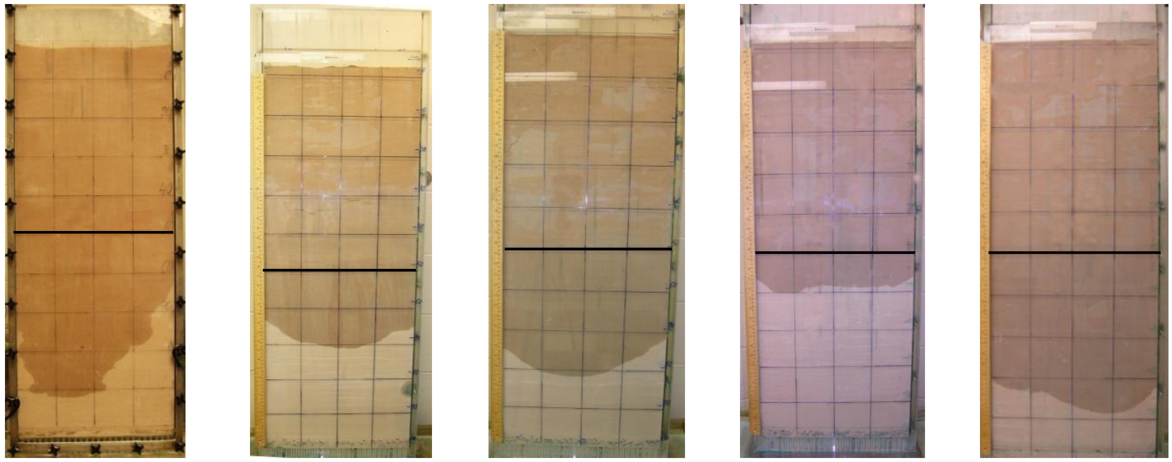


Figure 3.14 Change of measured matric potential (h) over time (t) above and below the layer interface in two-layered soil cover during intermittent infiltration under initially air-dry conditions and a seepage face=0 at the bottom

At the same time, under constant head conditions the wetting front was less wavy and more stable as could be concluded from visual observations of the four 2L columns (Figure 3.15b). Infiltration rate changed from 4.85±1.24 cm/h at the beginning of the experiment to 1.40±0.24 cm/h at the end. Since the infiltration rate *(V)* was higher than hydraulic conductivity of the coarser layer at the water-entry value ($K(h_{we})$=0.65 cm/h, h_{we}=-30 cm), $V<K_{we}$ instability criterion was not satisfied for all replicates. Thus, presumably, flux at the bottom of the finer layer was sufficient to cover the interface between layers.

Wetting front velocity mostly gradually decreased from 60 to 7.12±0.82 cm/h from the beginning until the end of the experiment. Although matric potential data were not available, it can be concluded that unlike under intermittent infiltration, the wetting front was stable under constant head ponding.

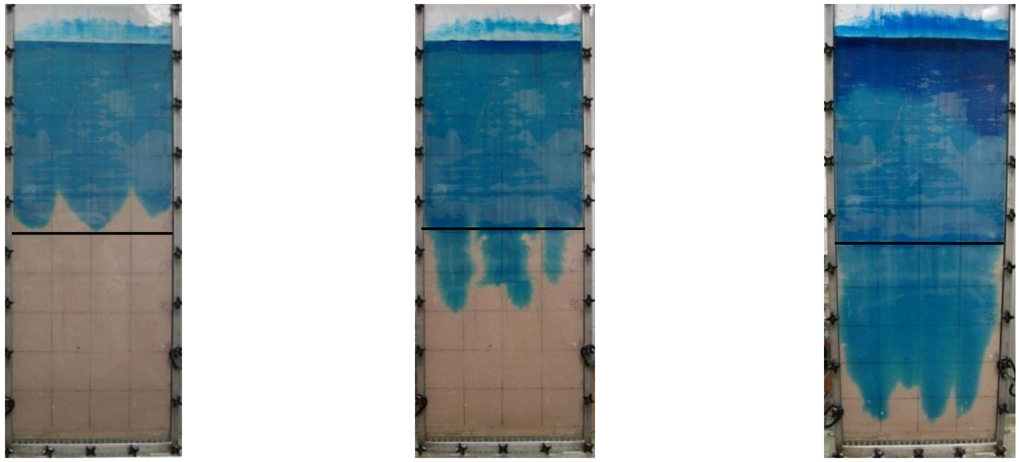


(a) (b)

Figure 3.15 Shape of the wetting front in initially air-dry two-layered soil covers (a) under intermittent infiltration and a seepage face=0 at the bottom; (b) under constant infiltration with a gravel layer at the bottom (4 replicates). Solid line represents interface between layers.

Flow stability under field capacity

The wetting front velocity slowly decreased from 3.58 to 0.16 cm/h in the finer layer under intermittent infiltration. Velocity started to increase from 0.15 cm/h after passing 50-cm depth and rose to 0.20 cm/h by the time the wetting front reached the bottom of the cover. The wetting front entered the coarser layer not as a uniform wetting front, since waves formed in the finer layer were not smoothed out at the interface (Figure 3.16a), where the wetting front was stagnant for 11.8 h. Due to the coarser texture, narrower fingers developed in the coarser layer from these waves (Figure 3.16b). The formed fingers had 10-cm diameter and were 20-cm long, and the one on the most right-hand side had half the diameter and was 12-cm long, when fingers were at 70-cm depth. Cores of the fingers did not coincide with the positions of tensiometers, therefore it was not possible to determine whether finger tips were saturated and whether there was a perturbation of a matric potential. Fingers that formed after crossing the interface were very close to each other and became wider as the experiment progressed. As the wetting front traveled below 75 cm, they almost merged into one wetting front. By the time the wetting front reached the bottom of the cover no fingers could be distinguished (Figure 3.16c).



(a) (b) (c)

Figure 3.16 Wetting front in two-layered cover at FC under intermittent infiltration, -25-cm matric potential at the bottom (a) staying at the interface of finer and coarser layers of two-layered soil cover; (b) at 70 cm in two-layered soil cover; (c) merging of fingers in the lower part of the cover. Solid line represents interface between layers.

The infiltration rate at the soil surface of the 2L soil cover decreased from 1.41 to 0.27 cm/h, when the wetting front traveled 50 cm, and changed from 0.27 cm/h at 50-cm depth to 0.36 cm/h by the time it reached the depth of 100 cm. The $V<K_{we}$ criterion for instability was satisfied for the coarser layer; therefore, there was not enough flux to cover the entire interface of the layers.

Measured matric potential profiles for finer and coarser layers did not show any sudden decrease in matric potential behind the wetting front in the finer layer and increase at the front (Figure 3.17). Though, based on visual observations and the instability criteria the wetting front was unstable at FC.

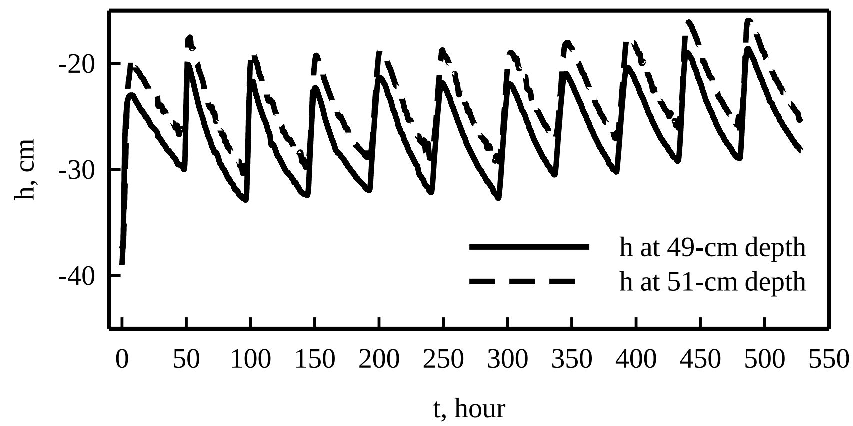


Figure 3.17 Change of measured matric potential (h) over time (t) right above and below layer interface in two-layered soil cover at FC during intermittent infiltration and -25-cm matric potential.

Two-layered soil covers with a gradual transition

Flow stability under initially air-dry water content

The wetting front moved very uniformly in the finer layer under intermittent infiltration into the initially air-dry 2LT. It was not wavy in the transition zone and quite stable below it in the upper part of the coarser layer. Shape of the wetting front became more round below 70-cm depth (Figure 3.18a) but fingers never developed. When the wetting front entered the transition zone (45 cm), it had a velocity of 0.27 cm/h, which decreased to 0.25 cm/h at the end of the transition zone (55 cm). The velocity decreased further to 0.20 cm/h, but increased by 0.02 cm/h from 76-cm to 100-cm depth, which was a smaller increase than in the 2L cover. Although some increase in the wetting front velocity was observed, it was not substantial and the wetting front remained comparatively uniform.

The infiltration rate (19.3 – 1.7 cm/h) was always higher than K_{we}=0.30 cm/h into the middle layer of the transition zone (48-49 cm) with h_{we}=-50 cm. The V<K_{we} criterion for instability was not satisfied. Any perturbations of matric potential at the wetting front were not observed. Since the wetting front velocity did not increase much in the coarser layer and the other instability criteria were not satisfied, the wetting front was stable in this cover. In addition, the wetting front was less wavy in the 2LT cover (Figure 3.18) than in the 2L cover (Figure 3.15a).

There was not much difference between the shapes of the wetting fronts of one column under intermittent and the three 2LT covers under constant head ponded conditions (Figure 3.18a, b). On average, velocity of the wetting front changed from 38±1.16 to 7.05±1.57 cm/h under constant head ponding. No fingers were observed (Figure 3.18b). The infiltration rate changed from 5.86±0.24 to 1.62±0.34 cm/h. Since infiltration rate stayed higher than K_{we} of the middle layer, the wetting front was stable. Generally, the wetting front was stable in the given cover under constant head, although velocity of the wetting front started to increase slightly after 57.5-cm depth in the second replicate.

(a) (b)

Figure 3.18 Shape of the wetting front in initially air-dry two-layered soil cover with a gradual transition (a) under intermittent infiltration and a seepage face=0 at the bottom; (b) under constant infiltration, a gravel layer at the bottom. Solid line represents interface between layers.

Flow stability under field capacity

The wetting front was wavy in the finer layer of the 2LT under intermittent infiltration (Figure 3.19a). The wetting front started propagation with 10 cm/h velocity and then gradually decreased until it reached 0.19-0.18 cm/h in the transition zone. The wetting front did not enter the transition zone as a uniform front and its right-hand side traveled faster than the left one

(Figure 3.19b). When the wetting front had traveled 58 cm on the right-hand side, it was still at 48-cm depth on the left side (Figure 3.19b). In the coarser layer, fingers gradually grew horizontally until they eventually merged together (Figure 3.19c). When the wetting front reached 100-cm depth, the dye covered less area in the coarser layer, compared to the 2L cover (Figure 3.19d). The wetting front velocity increased from 0.20 cm/h at 63-cm depth to 0.23 cm/h at the end of the cover.

(a) (b) (c) (d)

Figure 3.19 Shape of the wetting front in two-layered soil cover with a gradual transition at FC under intermittent infiltration and -25-cm matric potential at the bottom: (a) in the finer layer; (b) entering the coarser layer; (c) at 90-cm depth when two flow paths already merged; (d) at 100-cm depth in the coarser layer. Solid line represents interface between layers.

The infiltration rate decreased from 1 to 0.86 cm/h after the second water application, when the wetting front traveled only 17 cm, and then gradually increased until it reached 1.8 cm/h during the last water application. The infiltration rate was higher than K_{we} into the middle of the transition zone (0.30 cm/h). As compared to the 2L, flow paths in the 2LT had less well-defined shape and did not resemble fingers as much.

Matric potentials at the bottom of the finer layer and at different depths in the transition zone did not exhibit any unexpected changes that would suggest presence of preferential flow (Figure 3.20) such as an abrupt increase of matric potential at the wetting front, and subsequent decrease behind the front at the bottom of the finer layer. Overall, flow in the second half of the profile can be defined as partially unstable, since the wetting front velocity slightly increased in the coarser layer and the shape of the wetting front was not uniform.

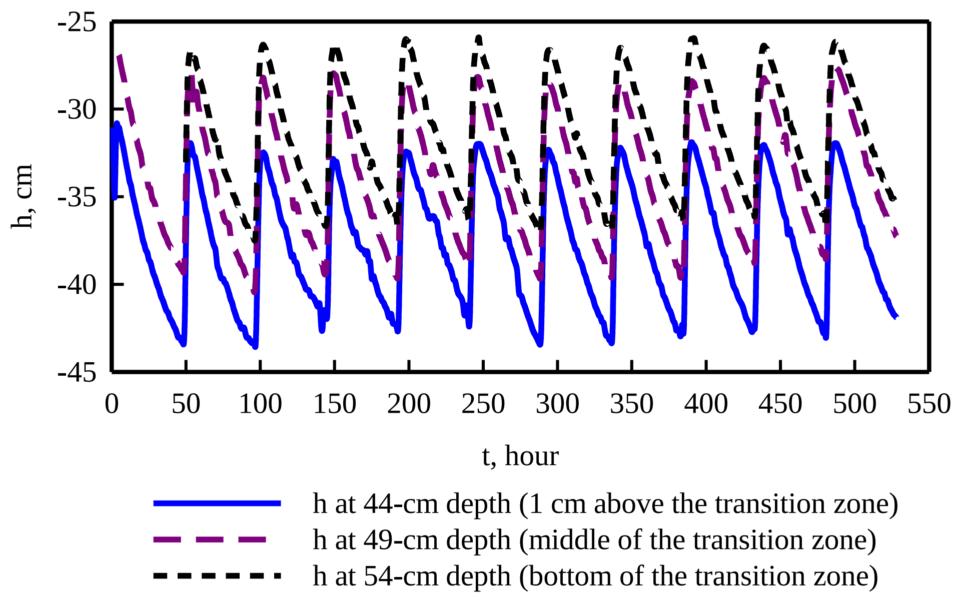


Figure 3.20 Change of measured matric potential (h) over time (t) in two-layered soil cover with a gradual transition at FC during intermittent infiltration and -25-cm matric potential lower boundary condition.

Four-layered soil cover

Flow stability under initially air-dry water content

In the initially air-dry 4L soil system, the wetting front was uniform as it entered the first coarser layer; however, at 36.6-cm depth it became somewhat wavy under the intermittent infiltration (Figure 3.21a). The wetting front did not cover the whole interface area as it was entering the second finer layer (Figure 3.21b). It stabilized more after crossing the interface between the first coarser and the second finer layers (Figure 3.21c). The wetting front became less uniform again in the second coarser layer (Figure 3.21d), but by the time it reached the bottom of the cover, it covered most of the layer.

(a) (b) (c) (d)

Figure 3.21 Wetting front in initially air-dry four-layered soil cover under intermittent infiltration and a seepage face=0 at the bottom: (a) entering first coarser layer; (b) entering second finer layer; (c) at the entry to the second coarser layer; (d) in the second coarser layer. Solid line represents interface between layers.

The wetting front velocity gradually decreased from 180 to 0.35 cm/h as the wetting front reached 25-cm depth. It continued to decrease in the first coarser layer to 0.17 cm/h but started to increase at 32.5-cm depth and continued increasing until it reached 0.25 cm/h at 72-cm depth. After this the velocity decreased to 0.19 cm/h at 81.4-cm depth and started to increase again from this depth, reaching 0.20 cm/h at 100 cm. Thus, the instability criterion based on the wetting front velocity increase was satisfied for the second finer layer and only partially for coarser layers.

Infiltration rate in the first coarser layer was between 4.09 and 1.45 cm/h and between 1.13 and 1.20 cm/h in the second coarser layer. Infiltration rate was higher than K_{we} into the coarser layer (0.65 cm/h).

The matric potential data did not show the presence of preferential flow (Figure 3.22). When the wetting front reached the bottom of the first finer layer, matric potential was lower at the bottom of the layer (-202.2 cm) than at the top of the layer (-93 cm). It was not possible to determine the matric potential, when the wetting front just reached the bottom of the first coarser layer, which would allow to determine whether preferential flow had a place in this part of the cover. This was because by the time the tensiometer reached the equilibrium with soil, the matric potential at 49 cm was already at -14.1 cm. When the wetting front was moving through the third layer (315 h), matric potentials were -61.6 cm at 50-cm depth and -67.2 cm at 74-cm depth. Thus, the matric potential decreased with depth. Considering that the wetting front velocity increased within certain depth increments and a slightly wavy shape of the wetting front in the coarser layers was evened out by the finer layers, water flow in the 4L soil cover can be called partially unstable.

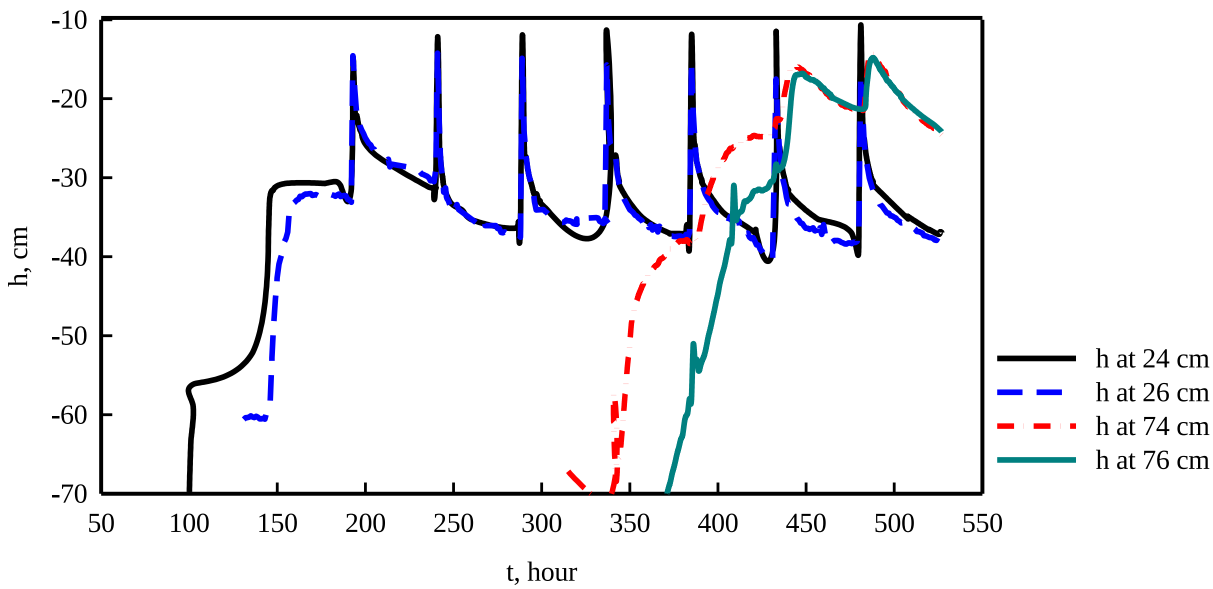
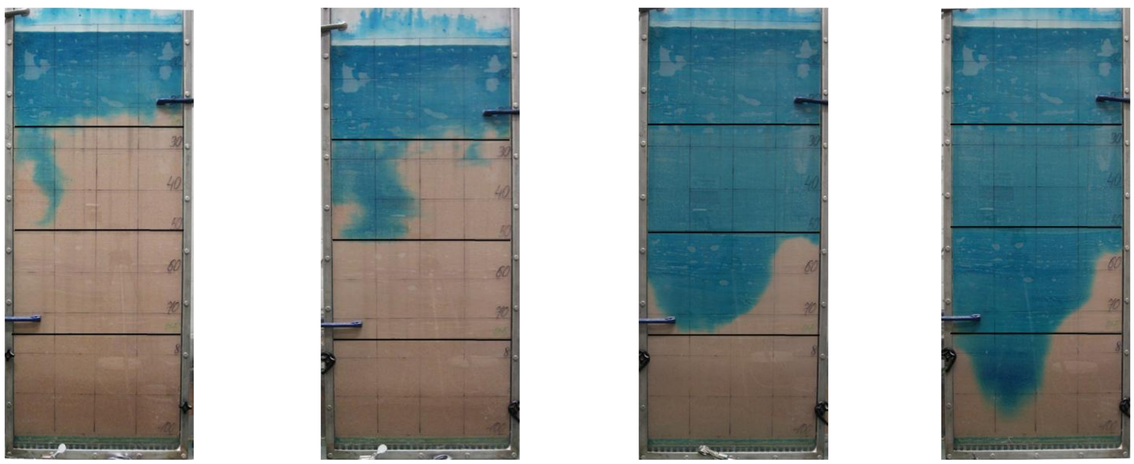


Figure 3.22 Measured matric potential profiles (h) over time (t) during intermittent infiltration into initially air-dry four-layered cover with a seepage face=0 at the bottom. Profiles for 49- and 51-cm depths are not shown.

Flow stability under field capacity

Under intermittent infiltration, the velocity of the wetting front steadily increased from 0.19 cm/h at 28-cm depth to 0.25 cm/h at 48.5 cm in the first coarser layer of the 4L cover. A preferential flow path 25-cm long propagated faster than the rest of the wetting front. The path became stagnant for 25.3 h at 50-cm depth (Figure 3.23a), growing more laterally than vertically. This path occupied only about 1/3 of the interface before it entered the second finer layer (Figure 3.23b). In the second finer layer the wetting front grew laterally, but by the time it reached 75 cm, the right-hand side of the front was still almost 25 cm behind (Figure 3.23c). The advancement of the wetting front was limited by the second finer layer, which was indicated by the decrease in the velocity of the wetting front from 0.27 to 0.18 cm/h in the second finer layer. The velocity increased again in the second coarser layer from 0.18 to 0.20 cm/h. In addition, the wetting front was narrower in coarser layers than in finer layers (Figure 3.23b, d).



(a) (b) (c) (d)

Figure 3.23 Wetting front position in four-layered soil cover at FC under intermittent infiltration and -25-cm matric potential at the bottom: (a) just reached the middle of the profile; (b) at the entry to the second finer layer; (c) at 75-cm depth; (d) at 97-cm depth. Solid line represents interface between layers.

The infiltration rate decreased from 1.02 cm/h at the beginning of the experiment to 0.65 cm/h after the last water application. Therefore, the V<K_{we} criterion for instability was not satisfied.

Thus, only one instability criterion was satisfied for coarser layers: increase in the wetting front velocity. Since the velocity of the wetting front increased in both coarser layers and the wetting front divided into narrower paths, the wetting front was less stable in the coarser than in finer layers, which is similar to the initially air-dry conditions. Velocity of the wetting front decreased in the finer layers and flow paths became wider during the experiment, which means that finer layers weakened instabilities. Therefore, water flow in the entire cover was partially unstable.

As experimental results showed, flow was stable in both layered and non-layered initially air-dry covers under constant ponded infiltration. Degree of the wetting front stability is summarized for each soil cover type under conditions of intermittent infiltration in Table 3.8. Under intermittent infiltration, the wetting front was stable in non-layered and partially unstable or unstable in layered covers. Flow in soil covers had similar level of stability under both initially air-dry and FC water contents. The 2LT was the only exception from these general trends, since flow in it was partially unstable under FC conditions and stable under initially air-dry conditions.

Table 3.8 Stability of the wetting front in tested soil covers during intermittent infiltration

	Homogeneous soil cover		Two-layered soil cover		Two-layered soil cover with a gradual transition		Four-layered soil cover	
	Initially air-dry	FC	Initially air-dry	FC	Initially air-dry	FC	Initially air-dry	FC
Stability of the wetting front	Stable	Stable	Unstable	Unstable	Stable	Partially unstable	Partially unstable	Partially unstable

3.3.4 Residence time of water in soil covers

The residence time or amount of time required for a droplet of water to travel from the top to the bottom of the cover was obtained during the infiltration experiments. Residence time provides valuable information on the performance of soil covers and complements data on WSC of covers measured only under static conditions. Total WSC does not provide much information on how long water will stay in the cover. Usually it takes longer for a wetting front to travel through layered soil systems than through non-layered, provided that flow is stable. If preferential flow develops, residence time of water can be very short even in the layered soil system. For this reason information on residence time allows verification of wetting front stability of soil covers.

Similar to the water storage, residence time increased in tested soil covers with an increasing number of layers (Table 3.9). Gradual textural transition between layers had an effect of decreasing residence time, but the latter was still higher in the 2LT than in the 1L cover.

Table 3.9 Residence time of water in soil covers under intermittent ponded infiltration

	Homogeneous soil cover		**Two-layered soil cover**		**Two-layered soil cover with a gradual transition**		**Four-layered soil cover**	
Residence time	Initially air-dry	FC	Initially air-dry	FC	Initially air-dry	FC	Initially air-dry	FC
	h							
0-50 cm depth	142.0	95.0	189.3	318.3	185.5	267.0	241.3	193.0
0-100 cm depth	343.0	323.3	470.1	503.8	458.7	431.0	504.7	506.9

Residence time in the non-layered soil cover was much lower under constant head ponded conditions than in layered soil covers (Table 3.10). As can be seen, natural sand conducts water very rapidly under constant head ponding. The residence time of water in the 2L and 2LT covers was approximately 6 times longer than in non-layered covers under constant head infiltration. This is a greater difference in residence time between layered and non-layered soil covers, since the residence time in layered soil covers under the intermittent infiltration was approximately 1.5 times longer than that in the non-layered soil cover. The difference in residence time between the 2L and the 2LT was on the order of 1.6% under constant head infiltration, which is similar to 2.4% under intermittent infiltration and initially air-dry conditions.

Table 3.10 Residence time of soil water in initially dry soil covers under constant head ponded infiltration

Residence time	**Homogeneous soil cover**	**Two-layered soil cover**	**Two-layered soil cover with a gradual transition**
		h	
0-50-cm depth	0.73	6.4±0.2	6.1±0.9
0-100-cm depth	2.28	14.1±1.7	14.6±3.0

3.4 Discussion

3.4.1 Hydraulic properties of soil used in tested soil covers

As shown in Table 3.6, the saturated water content (θ_s) of natural sand and the finer fraction of the sand was lower than that of the coarser one, although the finer sand was packed to a lower density (1.5 g/cm^3). This occurred due to the decrease in porosity (φ) in the natural sand and the finer fraction after application of some matric potential to saturated samples. The rearrangement and reorientation of soil particles after wetting is the reason for the considerable decrease in porosity of the natural sand and of the finer fraction. The samples of the natural sand and the finer fraction had higher porosity at saturation (Table 3.6); however, after applying some matric potential, the volume of the finer sand samples reduced by 19-25% and of the natural sand samples by 8-12% (Table 3.11). The sample volume did not reduce further at lower matric potentials.

Table 3.11 Porosity of dry soil used in experiments and conducting porosity after wetting

Soil	φ_{dry}†	φ_{wet}
Natural sand	0.35±0.01‡	0.29±0.02
Finer	0.43±0.00	0.29±0.01
Coarser	0.35±0.01	0.35±0.01

†$\varphi_{dry/wet}$ is porosity of dry soil and conducting porosity after wetting

‡ Standard deviation

The obtained φ and θ_s were comparable to those reported in the literature. For example, Onody et al. (1995) packed sand into a slab chamber with particles sizes of 0.5-2 mm and a bulk density of 2.18 g/cm^3 and 2.24 g/cm^3. Their resulting porosity ranged from 18.2±4% to 16±3%. Similarly, for a fine sand, Yang et al. (2006) reported θ_s of repacked medium sand to be 0.21 cm^3/cm^3 and 0.26 cm^3/cm^3.

The rapid shrinkage of the natural sand and the finer fraction had a direct influence on the shape of SWRCs. The natural sand and the finer fraction lost more water at high matric potentials than was estimated according to SWRCs from particle size analysis at the same matric potentials (Figure 3.6-Figure 3.7). Since neither van Genuchten's power function, nor Arya-Paris model take shrinkage of soil into account, there was less agreement between fitted and measured curves at high matric potentials than at lower ones (Stange and Horn, 2005). The pedotransfer functions were used because of their ubiquity and suitability of fit for the experimental data for non-shrinking soil (Arya et al., 1999; Dane and Topp, 2002). Functions accounting for shrinkage, to the best of the author's knowledge, are not available. The only one model for fitting of hydraulic parameters was developed by Stange and Horn (2005) and takes into account a changing void ratio of soil during SWRC determination. However, their model is for a soil with a slowly changing porosity during application of various matric potentials and requires determination of many additional empirical parameters, which is beyond the scope of this thesis.

The fitted α and n (parameters that determine the slope of the SWRC) decrease with increasing silt and clay contents in the sample (Table 3.5). The values of α and n are the lowest for the finer fraction and the highest for the coarser fraction, which is consistent with assumptions of van Genuchten's function (Dane and Topp, 2002). All measured SWRCs have an "S-shape" (Figure 3.6-Figure 3.8). Van Genuchten's function fits S-shaped curves better than other widely used SWRC functions, such as the Brooks and Corey equation (Dane and Topp, 2002). Deviation from the S-shape at high matric potentials could be caused by preferential loss of the largest pores during shrinking. Not all pores are reduced in size in the same way: the largest pores are usually lost or reduced in size first (Dexter, 2004). At high matric potentials, when most of large pores are being lost, the curves showed a greater deviation from fitted SWRCs, particularly in the finer fraction and in the natural sand (Figure 3.6-Figure 3.7). At low matric potentials, the slope change was more gradual.

To conclude, the finer and coarser fractions of natural sand have substantially different hydraulic properties. The finer fraction is similar to loamy soil (it is classified as loamy sand based on the texture) and the coarser fraction has properties of typical sand, although these fractions are separates of the same soil. This difference is especially pronounced in hydraulic conductivities (Figure 3.9, Figure 3.10). Differences in hydraulic properties of sieved fractions had considerable positive influence on water storage and performance of soil covers as shown in the next section.

3.4.2 Mechanism of gaining additional WSC in layered vs. non-layered soil covers

The difference in hydraulic parameters of sieved separates of natural sand predetermined elevated WSC of layered covers as compared to the cover composed of non-segregated sand at FC (Table 3.7). The effect of hydraulic parameters of the coarser layer on the WSC of the entire cover will be described below on the example of the finer-over-coarser 2L tested cover.

When the 2L soil cover was at saturation, the finer layer was under hydrostatic conditions (Figure 3.24), which was indicated by total pressure head H (H=h+z), where z is depth. In the coarser layer, however, the pressure profile deviated from the hydrostatic line at all depths except for the bottom of the layer, indicating that the coarser layer could not reach saturation due to the limited flux from the finer layer. Starting from 24 hours of drainage and further, hydraulic gradient became negligible in the finer sand, which means there was almost no flow from the finer layer. Hydraulic gradient in the coarser layer, however, was close to unity. Thus, flow in the coarser layer was at the rate of hydraulic conductivity corresponding to the matric potential of the coarser layer, which became residual by that time due to drainage. The flow from the soil cover was decreasing as soil was desaturating. By 105 h of drainage, pressure profile became static in the coarser layer, although equilibrium was not reached. Therefore, inability of the finer layer to desaturate to AEV due to low hydraulic conductivity, which develops relatively fast in the coarser layer during drainage, leads to higher water contents in the upper part of layered tested soil covers, and consequently higher WSCs as compared to non-layered covers, where abovementioned mechanism is non-existent.

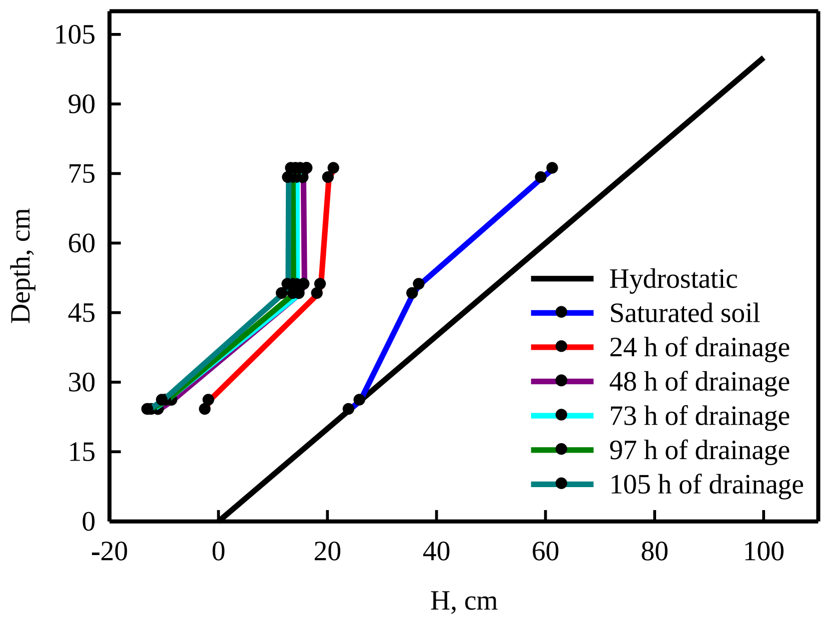


Figure 3.24 Total pressure head (H) profiles at saturation and during drainage in finer-over-coarser layered soil cover (dots are positions of tensiometers)

The mechanism in charge of enhanced WSCs in layered soils can also be explained based on matric potential data and K, water retention curves of soils comprising the soil system. The most considerable decrease in matric potential occurred in the first 24 h (Figure 3.24). Starting from 73 h, decrease was very low. After 105 h of drainage, matric potential was at -37.2 cm at 51-cm depth and -38.2 cm at 49-cm depth. As SWRCs show, the water content was much higher in the finer layer than in the coarser one at the same matric potential (Figure 3.25). The finer layer had a water content of 0.26 cm^3/cm^3 at -38 cm matric potential (Figure 3.25, point A), while the coarser layer had a water content of 0.03 cm^3/cm^3 at the same matric potential (point B). Due to the continuity of matric potential at the interface between the layers, the decrease of matric potential in the finer layer resulted in a decrease of matric potential in the coarser layer. However, the conductivity of the coarser fraction declined much faster than the conductivity of the finer for the same decrease in matric potential, and eventually the coarser layer became so poorly conductive that flow between layers become almost discontinuous. For instance, the finer layer had a much lower AEV (-70 cm) than the coarser layer (-18 cm); thus, the finer sand was able to hold more water at matric potentials between -18 and -70 cm than the coarser. By the time the finer layer reached AEV, the coarser layer became almost nonconductive ($1.7*10^{-5}$ cm/h). This is why the WSC of the finer layer in the 2L soil cover is 5.6 cm higher under the type 1 condition and 6.8 cm higher under the type 2 condition than the water storage of the coarser layer (Table 3.7).

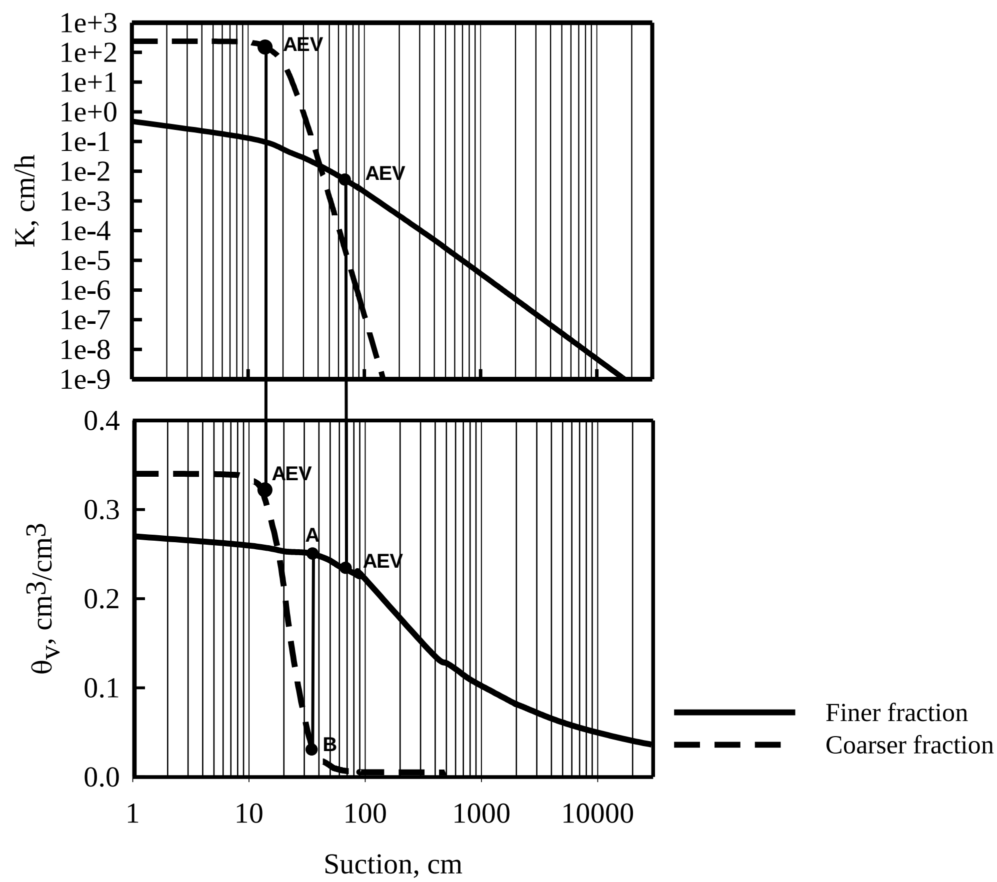


Figure 3.25 Water retention curves of finer and coarser fractions of natural sand related to hydraulic conductivity functions

The same explanation for the difference in WSCs in the upper and lower 50 cm of the cover is applicable to the 4L and the 2LT. In the 2LT, however, the storage capacity is influenced not only by the hydraulic properties of finer and coarser layers, but also by the hydraulic properties in the transition zone. In the transition zone, the water content gradually decreases from the finer to the coarser layer at approximately the same potential in all layers. Therefore, the water storage of the finer layer in this cover is lower than in the 2L cover.

In the 1L cover, there were no layers with different hydraulic parameters, and therefore, no mechanism for water content to increase at certain depths, except for due to boundary conditions. The water content gradually increased from the middle of the profile to the bottom because of the lower boundary condition (Figure 3.11, Figure 3.12). The water content profile could have almost been a straight line, if there was no influence of the lower boundary condition, as in an infinitely long profile.

As could be seen from above, although hydraulic properties of soils composing a soil system have a high influence on water content distribution, the difference in water content distribution and water storage between layered and non-layered covers not only depended on water retention properties and hydraulic conductivity as a function of matric potential, but also on the frequency and rate of precipitation (Barbour, 1990). The soil covers' performance could have been different under different initial and boundary conditions. Therefore, a better understanding of the performance and differences in water content distribution as well as the differences in residence time in layered and homogeneous covers could have been reached, if the transient water flow conditions had been considered.

3.4.3 Water content distribution and residence time in soil covers under transient conditions

The influence of the transient flow conditions on the water content distribution and the residence time in the soil covers is shown on the example of the intermittent infiltration into initially air-dry soil covers. Some characteristics of the performance of tested soil covers such as time of wetting front stagnation at the interface of the layers and others are summarized in

Table 3.12. The effects of the increasing number of layers and of the extending interlayer transitions were also examined under transient conditions.

Table 3.12 Characteristics of soil covers (SCs) performance under intermittent infiltration

	Initially air-dry water content		
	Two-layered SC	Two-layered SC with a gradual transition	Four-layered SC
Time duration of wetting front being stagnant at layer interface (h)	17	5.3	1st CB†-4.5; 2nd CB- Not available
Cumulative infiltration by the start of considerable increase in flow to a coarser layer (cm)	10.5	9	1st CB-7.5; 2nd CB-15
Time to reach a residual potential (h)	NR‡	NR	1st CB-6-8; 2nd CB- NR

CB† Capillary barrier

NR‡ Never reached

3.4.3.1 Two-layered soil cover

When the wetting front reached the bottom of the finer layer (188.4 h) during intermittent infiltration into initially air-dry 2L soil cover after the 4th water application, the matric potential was low at the bottom of the finer layer (-164.8 cm). Since the coarser layer had an almost negligible hydraulic conductivity at this potential, the wetting front was stagnant at the interface for 17 h, indicating the presence of a capillary barrier effect. The matric potential increased by more than 10 cm in the finer layer after every infiltration until 381 h, at which point it stabilized and remained almost unchanged with each consecutive infiltration (Figure 3.14). The water content in the finer layer was the highest close to the interface, because for water to enter a sublayer, the upper layer should be close to saturation (Morris and Stormont, 1997). The water content in the finer layer continued to increase until 314.3 h (28.8 h after the 7th water application), thereupon matric potential increased to about -30 cm and became almost equal in both layers. This matric potential corresponds to the water-entry value, h_{we}, into the coarser layer.

The h_{we} into the coarser soil most likely has a range of -30 to -40 cm, since the potential in this range is close to the residual water content on the drying part of the SWRC (Figure 3.9). The same principal of the h_{we} determination was used in other studies of soil covers (Baker and Hillel, 1990; Morris and Stormont, 1997; Khire et al., 2000; Yang et al., 2004). The range of the h_{we} instead of a single number was chosen, since the water-entry at the scale of a laboratory chamber could be slightly different than the water-entry in the small soil cores, which were used to measure the water retention curves. The h_{we} value used for further analysis of the measured data is -30 cm to make the analysis more conservative.

The measured WSC of the finer layer in the 2L cover (10.3 cm) was exceeded after the 7th water application, at which point the total of 10.5 cm of water was applied. In all consecutive cycles of infiltration (382.3, 478.3 h) and redistribution (314.3, 428.3, 525.3 h), the matric potential remained slightly higher on the top of the coarser layer than at the bottom of the finer (Figure 3.26). The matric potential profiles fell almost on the same line during the consecutive redistribution cycles, indicating that the finer layer could not hold any more water after 10.5 cm were applied in total. Since the matric potential was at -30 cm or above in the coarser layer, the water flow into the coarser layer, which was quite conductive at these potentials, increased. Thus, as was shown above, the performance of the soil covers not only depends on the difference in hydraulic parameters and water retention characteristics of fractions of the same sand, but also on the degree of saturation.

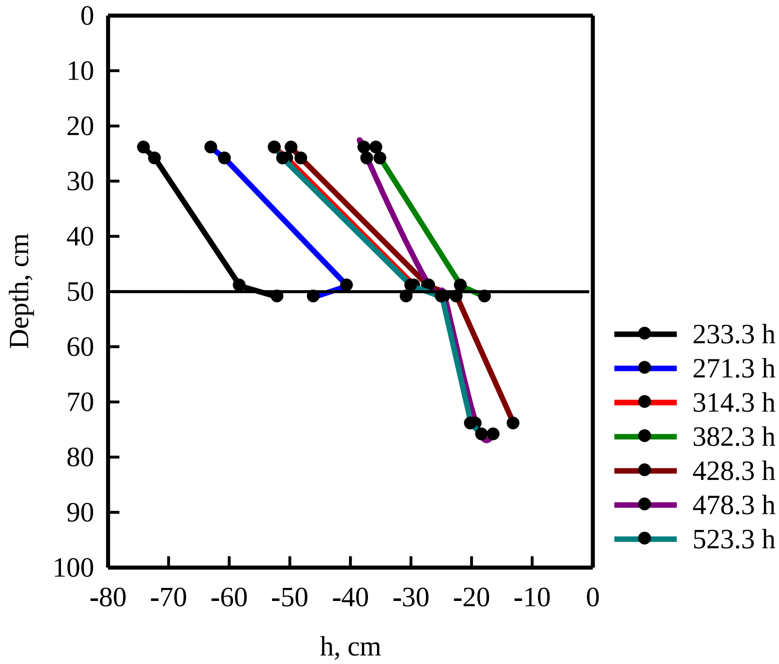


Figure 3.26 Matric potential (h) profiles for various times from the beginning of intermittent infiltration into initially air-dry two-layered soil cover with a seepage face=0 at the bottom (solid line represents the interface of the layers and dots are positions of tensiometers)

The capillary barrier temporarily formed at the interface of the finer and coarser layers had a considerable influence on residence time in the coarser layer. It took the wetting front 125.9 h to travel 6.6 cm in the coarser layer before the coarser layer became quite conductive, but it took only 155.8 h to travel the remaining 43.4 cm.

Under the constant head ponded infiltration, although the matric potential was not measured, the effect of decreased and delayed flow into the coarser layer could be seen from the infiltration rate data. The infiltration rate decreased considerably in the three replicates, when the wetting front reached the interface of the layers. In a span of several minutes it increased again and gradually decreased until the end of the experiment. For example, in the second replicate, when the wetting front reached 50 cm, the velocity of the wetting front decreased from 0.23 to 0.06 cm/h, but it increased to 0.14 cm/h only 9 min later, and then decreased again to 0.08 cm/h in 44 min. Therefore, capillary barrier effect was less pronounced under constant water head than under intermittent infiltration: the wetting front paused at the interface, but started entering the coarser layer within a few minutes.

3.4.3.2 Two-layered soil cover with a gradual transition

Similar to the 2L soil cover, the lower part of the transition zone in the 2LT was initially almost non-conductive and water accumulated mainly in the upper part of the profile during the intermittent infiltration experiment. The finer layer was drier than in the 2L cover: when the wetting front was in the middle of the transition zone, matric potential was -119 cm at 44-cm depth and -80 cm at 49-cm depth.

At 222 h, which is 27.3 h after the 5th water application, the matric potential was -54.2 cm at 44-cm and -78.8 cm at 49-cm depth. However, one hour after the 6th infiltration (cumulative infiltration=9 cm) matric potential became higher at 49-cm depth (-35.5 cm) than at 44-cm depth (-38.3). Since -50 to -60 cm range of matric potential corresponds to the lower inflection point on the drying part of the SWRC (Figure 3.3) for the layer in the middle of the transition zone (49 cm), the h_{we} into the middle of the transition zone was reached after the 6th infiltration. This means that 1.5 cm less water was required for the two-layered soil cover with transition to reach the water-entry value into the coarser layer than in the 2L soil cover. The potential stayed above -35 cm for all consecutive infiltrations at 49-cm depth and lower (Figure 3.27). Therefore, similar to the 2L cover, the matric potential never decreased to the residual in the middle of the transition zone and flow to the coarser layer was considerable for the rest of the experiment.

Since all experimental conditions were the same as well as soil used in the two-layered covers, and the only difference was in the interlayer transition, performance of the 2LT was worse than that of the 2L. Breakthrough of water into the sublayer of 2LT cover started earlier than in the 2L, because of the lower h_{we} in the middle of the transition zone. This is similar to the observations of Yang et al. (2004), who observed an earlier increase in percolation from fine sand into the sublayer of medium sand with the lower h_{we} than from fine sand into gravelly sand with the higher h_{we} (more positive). The wetting front was stagnant for 5.3 h at the interface of the layers in the middle of the cover, which is 11.7 h less than for the 2L cover.

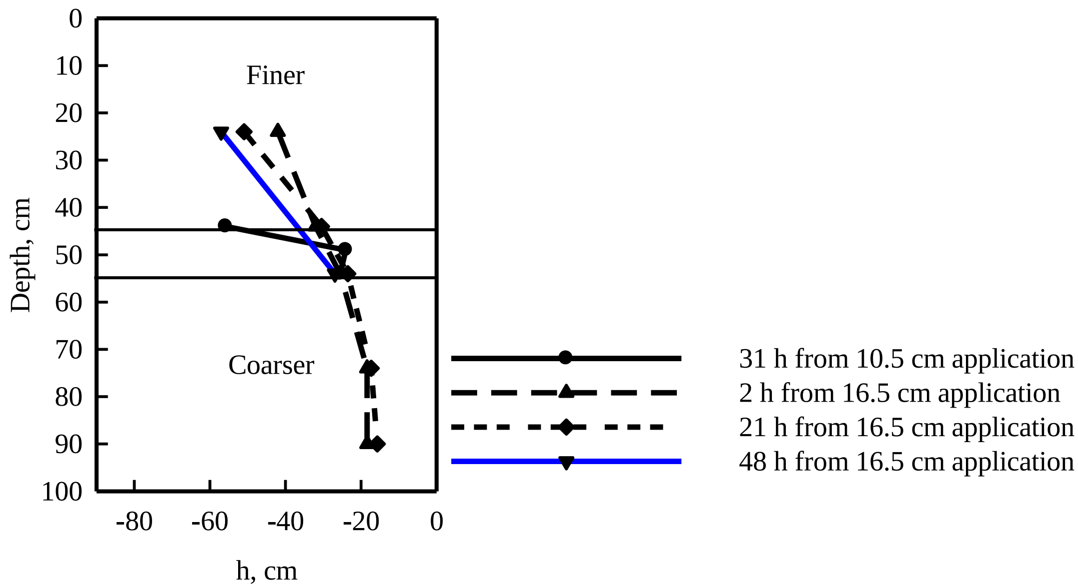


Figure 3.27 Measured matric potential (h) profiles during intermittent infiltration into initially air-dry two-layered soil cover with a gradual transition and a seepage face=0 at the bottom (shapes are positions of tensiometers, solid line delineates a transition zone).

A decreased hydraulic contrast at the layer interface caused not only a lower water content in the finer layer but also shorter residence of water in the 2LT as compared to the 2L cover. The residence time in the 2LT cover was 3.8 h less in the first 50 cm of the profile, than in the 2L. Nonetheless, the residence time was still 115.7 h longer in the 2LT than in the 1L cover under initially air-dry conditions.

The residence time was orders of magnitude lower under constant infiltration than under intermittent infiltration (Table 3.10). Such a small residence time under constant infiltration is unfavourable under field conditions due to the virtual absence of time for contaminants to decompose. Fortunately, in the Athabasca sand basin, the rainfall is limited, and the intermittent ponded infiltration is more realistic than the constant ponded condition. However, the residence time is a good index for the evaluation different cover prescriptions.

3.4.3.3 Four-layered soil cover

The 4L soil cover had more flow barriers than any other cover. Two capillary barriers formed at the interface of finer-over-coarser layers, and one hydraulic barrier formed at the interface of coarser-over-finer layers. Presence of these flow barriers could be a reason for an increased water accumulation in the cover and a longer residence time of water in the cover than in other tested covers.

The wetting front was stagnant at the interface of the first two layers for shorter time (4.5 h) than in the 2L cover (17 h). Water-entry into the first coarser layer of the 4L cover occurred two water applications earlier (after the 5th water application) than in the 2L cover, because of the smaller WSC of the finer layer in the 4L cover. The 4L cover was the only layered cover, where matric potential was able to return to the residual at the first interface of the layers between cycles of infiltration. The matric potential decreased to -30 cm after 6-8 h from the water application (Figure 3.22).

When the wetting front reached a hydraulic barrier, the matric potential at the bottom of the first coarser layer was always several centimetres higher than in the upper part of the coarser layer, which means that some of the water was accumulating at the interface of the first coarser and the second finer layer. A perched water table at the bottom of the coarser sand stayed for only a few hours after water application.

The wetting front entered the second coarser layer at 321.2 h since the beginning of the experiment. Almost immediately after 15 cm of water were applied in total (432 h), the h_{we} at 76-cm depth was reached (the matric potential increased to -29.7 cm). Since that time matric potentials were almost equal in both layers and never decreased to at least -30 cm by the end of the experiment (Figure 3.22).

Water stayed 34.6 h longer in the 4L cover than in the 2L cover under initially air-dry conditions. Therefore, the addition of two more layers to the 2L soil cover did not lead to the considerable increase in residence time. Overall, as could be seen the difference in hydraulic parameters of the layers composed of separates of a single texture had a pronounced effect on minimizing the flow to the lower part of the soil cover even under very unfavourable conditions of frequent and intense rainfalls. These conditions were approximated by the intermittent infiltration.

3.4.4 Modeled intermittent infiltration experiment

The model for intermittent infiltration into the initially air-dry 2L cover underestimated the matric potential. The flux to the coarser layer started to increase later than in the same experimental cover: 390.6 h after the first water application. Thus, three more cm of water were required for a breakthrough into the coarser layer than in the experiment. In simulation, the matric potential increased during infiltration at the top of the coarser layer, but never became higher than -39 cm and decreased to -44 cm by the end of the redistribution. Thus, unlike in the experiment, residual matric potential was reached at the end of each simulated redistribution. The cumulative infiltration was estimated quite accurately (16.3 cm as compared to the applied 16.5 cm in the experiment).

In the 2LT cover, the matric potential was at -52.6 cm at 49-cm depth by the end of the redistribution after the 8th water application. The modeled 2LT required two more water applications to reach the h_{we} in the middle of the transition zone than the tested cover. Water-entry into the middle layer of the transition zone was on the lower end of -50 to -60 cm range, since HYDRUS tended to underestimate matric potential. During each consecutive infiltration, the matric potential always remained higher at 49-cm depth than the residual potential into the middle of the transition zone even two days after infiltration. Therefore, it can be concluded that there were more similarities in the modeled and experimental performance of the 2LT than there were between the modeled and experimental performance of the 2L cover. The cumulative infiltration was comparable to that measured in the experiment (0.6 cm lower than the actual amount of water applied). The hydraulic conductivity was overestimated at low potentials, which affected the flux calculation.

In the 4L cover, an increased flux to the first coarser layer started to be observed 6.3 hours after the 4th water application (6 cm), when the matric potential increased to -39.6 cm on top of the first coarser layer (150.3 h). Therefore, the time to reach the h_{we} into the coarser layer coincides with that from the experiment. Similar to the experimental data, the matric potential increased up to -36 cm a few hours after infiltration, but decreased to the residual potential (-47.4 cm) by the end of the redistribution during the rest of the experiment.

The matric potential at 76-cm depth increased to -41.9 cm at 354.7 h and continued to increase to -28.5 cm even during the redistribution, which indicated that flow to the coarser layer increased two water applications earlier than in the experiment. Similar to the experiment, residual potential was not reached in the second coarser layer. Cumulative infiltration (16.9 cm) and *K* were somewhat overestimated.

According to the modeling results the 1L cover had a 0.01 cm/h flux from the bottom of the cover at the end of the intermittent infiltration experiment, whereas the flux was negligible from all layered covers under initially air-dry water content and the seepage face=0 lower boundary condition. This also explains the lower water storage and residence time of water in the 1L cover.

In general, the performance of experimental and modeled soil covers under intermittent infiltration was similar, although matric potential was underestimated in all covers. Simulated performance of the 2L cover differed from the observed in the experiment more than for other covers. The main reason for this could be the highest susceptibility of the 2L cover to preferential flow among tested covers, since preferential flow was not considered in the model. Some difference in simulated and measured data could also be a result of a hysteresis phenomenon that was not taken into account in the model, but definitely existed in the experiment due to numerous cycles of wetting and drying. However, incorporation of abovementioned factors would complicate the model beyond the scope of this thesis.

3.4.5 Stability of the wetting front and its influence on water residence time in soil covers

Results of infiltration experiments show that there was an apparent influence of initial conditions on the stability of the wetting front and residence time. The degree of the stability also varied depending on the degree of soil saturation.

A comparison of the wetting fronts in layered and non-layered covers under intermittent infiltration shows that flow was more stable in the 1L cover. This result is consistent with research findings of others. Infiltration into non-layered soil with uniform water content and without air compression is unconditionally stable (Hill and Parlange, 1972; Diment and

Watson, 1985; Wang et al, 1998, etc.). Meanwhile, cases of preferential flow have been observed in non-layered coarse-textured soil under conditions such as constant nonponded unsaturated infiltration with a medium to high infiltration rate (Babel et al., 1995; Yao and Hendrickx, 1996). In the covers tested in this study, the wetting front was comparatively stable even under non-constant infiltration. This could be because there was sufficient time between infiltrations for water flow through the system to stabilize and become slow during the intermittent infiltration.

Congruous to the results of this study, finer-over-coarser layered soil systems are considered to be more susceptible to instabilities than the non-layered soil (Hill and Parlange, 1972; Diment and Watson, 1985; Hillel, 1980, 1998). The degree of susceptibility to preferential flow differed in the given study with initial water contents. Under FC, the wetting front had a more irregular shape and was less uniform in all covers under both types of infiltration. The influence of intra-layer heterogeneity, such as slight variation in density and microlayering, is the most likely reason for this result; since, although care was taken to pack the covers as uniformly as possible, some microlayering still appeared. The method of packing chosen for use in this study is a widely used method developed by Glass et al. (1989). After completion of experiments, literature was found that indicated this method tended to produce slight heterogeneity (Glass and Nicholl, 1996). Glass and Nicholl (1996) found out that non-vertical finger movement or "meandering" was a characteristic of soil packed by this method as, for example, in the work of Hill and Parlange (1972). The meandering was especially pronounced in the two-layered soil covers (Figure 3.16, Figure 3.19) tested in the current study and was partly suppressed by the finer layers in the 4L cover at FC (Figure 3.23). Due to the meandering, the flow paths touched each other and merged; thus, by the time the wetting front reached the bottom of the cover all of the paths usually merged into one front and the conducting volume of soil became larger. The greater irregularity of the wetting front at FC than under initially air-dry conditions can be attributed to the fact that in air-dry soil the water content is very low and fairly uniformly distributed. The heterogeneity appears less at low water content, as all pores are almost equally filled and much dispersion is exhibited (Tindall and Kunkel, 1999). Generally, although the heterogeneity had some effect on the shape of the wetting front at FC, the matric potential and other data showed that the flow was comparatively stable in the 2LT and in the 4L cover and stable in the 1L cover.

Unstable flow is more evident and easily initiated in extremely dry soils, rather than in soils at high water contents, because many pores are non-conductive and the conducting volume may be insufficient to conduct a whole flux, making flow to constrict to fingers (Diment and Watson, 1985; Bauters et al., 2000; Wang et al., 2003). Although the wetting front was less uniform at FC in this study, the water distribution patterns were more heterogeneous than unstable. There was approximately the same level of instability under FC, based on the instability criteria applied, as there was under initially air-dry conditions in layered covers. The wetting front was classified as stable in the 1L cover and unstable in the 2L cover and partially unstable in the 4L cover under both initially air-dry and FC conditions. The only difference was that, in the 2LT the wetting front was stable under initially air-dry and partially unstable under FC conditions. As was mentioned above, heterogeneity of water distribution resulted from some heterogeneity in packing and had a more pronounced effect under the higher initial water content. Although artificially created heterogeneity slightly obscured the actual picture of the wetting front propagation, the infiltration experiments were conducted under two extreme water contents and both of them showed similar stability. Thus, it can be concluded that the stability of the front would be very similar under FC to that under initially air-dry conditions in soil covers composed of the size fractions of coarse-textured soil if soil was packed very uniformly. Since it is extremely difficult to achieve ideal homogeneous packing in the laboratory (Glass and Nicholl, 1996), and heterogeneity of field soil systems is typically even higher, the conducted experiments serve as approximation of flow under field conditions.

All layered covers tested under intermittent infiltration had lower wetting front velocities and lower infiltration rates under FC than under initially air-dry water content, at least in the first part of the experiment. The velocity was higher only in the 1L cover under higher water content (see Appendix A), indicating that the flow was fully stable only in the 1L cover. The above is consistent with the shape of the wetting front in the 1L cover, as the wetting front observed in this cover was the most uniform among other covers and did not meander even at FC, as opposed to the layered covers under FC.

The 2L cover is the only cover that had a substantially longer residence time under FC than under initially air-dry water content. The increased density of the finer layer is a probable reason for the 33.7 h longer residence time under FC than under initially air-dry conditions, since SWRC showed that the finer layer shrank during drainage after wetting. The shrinkage was also observed under initially air-dry conditions; however, there was no simultaneous shrinkage of the entire layer. The residence time could have increased due to a gradual increase in the number of fine particles in the first few centimetres of the finer layer and the formation of a thin crust during multiple cycles of infiltration. Moreover, the wetting front velocity was lower only during the first 300 h, when the wetting front traveled through the finer layer.

The residence time was higher at FC in the 4L cover than under initially air-dry conditions (Table 3.9); nonetheless, the difference was only 2.2 h. Longer residence time at FC could be due to the same reasons as in the 2L cover; however, the difference in time was less due to the major shrinkage in the finer layer, which was half as deep in the 4L cover as in the 2L cover. The wetting front velocity was generally higher under initially air-dry conditions in the 4L cover than under FC (see Appendix A). Velocities under both soil's water contents became almost equal towards the end of the experiment. Increased residence time at FC could also be caused by the higher initial packing density of finer layers in the 4L cover as compared to the 2L and 2LT.

The residence time in the 2LT was lower than in the 2L cover under both initially air-dry and FC water contents. One of the reasons for this could be a shorter stagnation of water at the interface and faster propagation of the wetting front in general due to the reduced textural and hydraulic contrast between layers. The other reason could again be a shrinkage of the finer layer as in the 2L.

In the second part of the profile of the 2LT at FC, the smaller left path merged with the wider and faster moving right-hand one (Figure 3.19c). The velocity of the front was found to increase below 63-cm depth. Glass and Nicholl (1996) also found that moving downward fingers tend to merge. The finger with the lower flow rate is "sucked" into the higher flow rate finger; thus, forming a wider finger with higher velocity.

Similar to the 2L cover, the wetting front traveled faster under initially air-dry conditions than under FC in the 2LT. When the wetting front went through the entire 2LT, it covered less area than in the 2L cover, since the profile was drier in the 2LT, retained less water as was indicated by the WSC. This finding is supported by previous studies which also concluded that fingers are usually wider in soil at higher water content, whereas they are narrower and longer at lower water contents (Diment and Watson, 1985; Bauters et al., 2000, etc.).

There is little difference in the shape of the wetting front under intermittent ponding compared to constant head ponding under initially air-dry conditions. However, generally constant ponded infiltration is more susceptible to instabilities than the intermittent infiltration, as high infiltration rates favour the compression of air ahead of the wetting front (Wang et al., 1998). Since wetting fronts under ponding are usually quite sharp (especially in coarse-textured soil like sand), some air can be compressed during the fast propagation of such fronts (Wang et al., 1998). Ponded infiltration is also mostly gravity-driven; hence, it is easier for fingers to develop, when sufficient capillary force is absent to smooth out any forming preferential flow paths or fingers (Glass and Nicholl, 1996). The uniformity of the wetting front under both types of upper boundary conditions can be caused by the insufficient contrast in pore size distributions and hydraulic conductivities of the finer and coarser layers for fingers to develop. Based on the infiltration rate criterion, it can be concluded that the wetting front is more stable under constant infiltration than under intermittent infiltration.

The wetting front was more stable in the 2LT and 4L cover than in the 2L cover. As was previously described, some instabilities that developed in the coarser layers were smoothed out by finer layers in the 4L cover. Thus, creation of more than the 2L soil system or extension of the interface between layers even in the 2L system tended to have a stabilizing effect on the wetting front.

Overall, the wetting front was comparatively stable in all tested covers under all tested conditions. The predicted by instability criteria potential for preferential flow was fairly small and there were no narrow, fast-moving fingers formed as was observed for many other laboratory and field studies with higher textural contrast between layers (Hill and Parlange, 1972; Diment and Watson, 1985; Flury et al., 1994; Bauters et al., 2000; Wang et al., 2003, etc.). Therefore, the finer-over-coarser layered soil systems composed of separates of sand texture are not as prone to instabilities. In addition, the residence time increased as the number of layers increased under both initial water contents (Table 3.10-Table 3.10) further substantiating the above conclusion.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Summary and conclusions

Most mining operations inevitably result in the generation of large piles of waste rock and overburden, many of which contain trace amounts of ore or contaminants hazardous to humans and/or the environment. To prevent the spreading of these contaminants from waste rock to the environment, a method, which incorporates the compaction of waste rock and placement of a soil cover on top, is starting to be widely used. Often coarse-textured soil is the only available on-site material. Coarse-textured soil has low WSC and relatively high hydraulic conductivity. Thus, in order to create a reclamation cover which is able to support vegetation and sufficiently limit deep percolation, the available on-site soil should be separated, if possible, into size fractions and laid into the finer-over-coarser cover. However, such finer-over-coarser soil systems have not been fully investigated. One of the issues that required further investigation was related to the ability of the cover composed of sieved fractions of the same coarse-textured soil to have considerably higher WSC as opposed to the cover of non-segregated material. Other issues were related to preferential flow and residence time of water in such covers. Although a finer-over-coarser layering sequence may have increased water storage, it is susceptible to preferential flow. The preferential water flow may lead to an enhanced flow rate through the cover and a reduced residence time as well as water storage. Thus, the investigation of the extent of finer-over-coarser soil covers' susceptibility to preferential flow and the effect it has on the water residence time was warranted.

This study addressed the issue with WSC through the determination of water contents in the 1L and layered soil covers at FC under two different lower boundary conditions. One of the conditions simulated compacted waste rock at the bottom of the cover and the other one simulated a shallow water table. To address the preferential flow and residence time issues, infiltration experiments were conducted under different initial and boundary conditions.

Comparison of WSCs of soil covers measured at FC showed that storage capacity increases with an increasing number of layers under both lower boundary conditions (compacted waste rock at the bottom and shallow water table). Water storage capacities of layered soil covers under compacted waste rock (type 1 boundary condition) were statistically significantly higher than those of non-layered covers composed of the natural sand. Although the statistical significance could not be determined for the shallow water table (type 2 condition), measured WSCs had a reasonable agreement with the simulated results. Water storage capacity was the highest in the cover with the greatest number of layers (4L soil cover). Under both types of conditions, WSCs of the 2LT were lower than those of the 2L covers.

The contrast in hydraulic properties of finer and coarser fractions in layered soil covers was enough to form a flow barrier. The capillary barrier considerably limited percolation of water into the coarser layer for a longer time in the 2L soil cover as compared to the 2LT. The 4L soil cover had the best performance as compared to other tested covers. Laboratory experiments and simulations showed comparatively similar trends in reaching the water-entry value and residual matric potential in coarser layers, although the matric potential was underestimated for the coarser layer in all covers.

Infiltration experiments showed that the wetting front was stable in all initially air-dry covers under constant ponding conditions. Under intermittent ponding, the wetting front was stable in the 1L cover under both initial water contents and in the 2LT under initially low water content. Unstable flow was observed only in the 2L soil cover under both initial water contents. Other covers were partially unstable under both initial water contents. There was more heterogeneity in the wetting front under FC, because of a slight heterogeneity in packing. Generally, the wetting front was more diffuse at FC. Stability of the front was very similar under initially air-dry and FC conditions, except for the 2LT. Overall, although the wetting front was wavy and had an irregular shape in some covers, no narrow, persisting fingers that would move faster than the rest of the front have developed. However, the 2L soil systems tended to be more susceptible to preferential flow than the 1L ones. Extension of the textural transition zone had a stabilizing effect on the wetting front in the 2L cover. Addition of more than two layers to the soil cover also led to suppression of a slight instability developed in the 2L cover. The wetting front was stable in the cover composed of natural sand, and the finer-over-coarser layered soil covers composed of fractions of natural sand were also found to have limited susceptibility to preferential flow.

Since wetting fronts were comparatively stable in all covers, residence time of water increased with an increasing number of layers in given soil covers. Residence time was considerably longer under FC than initially air-dry conditions only in the 2L cover, and residence time was similar under initially air-dry and FC conditions in the 4L soil cover. The prolonged residence time was explained by the increased density of finer layers due to the shrinkage and the increase of fine particles on top of the finer layer as a result of multiple cycles of infiltration. The longest residence time in the first half of the profile was observed in the 2L soil cover under FC. Residence time was orders of magnitude lower under constant than under intermittent infiltration.

The two hypotheses of this thesis were confirmed: WSC does increase with an increasing number of layers in soil covers, where layers are composed of sieved fractions of coarse-textured soil, and such soil covers are not very susceptible to preferential flow even when layered into finer-over-coarser soil systems. Limited susceptibility to preferential flow does not lead to a decrease in residence time, and the residence time increases with increasing number of layers.

4.2 Recommendations for design

Among soil covers tested in this study, the 4L soil cover seems to be the best option for mine waste reclamation. The 4L soil cover has the highest WSC, the longest residence time, almost no susceptibility to instabilities under both initially air-dry and FC water contents, and has more flow barriers than the 2L system. The 4L soil cover tested in this study had abrupt interfaces between layers. However, an abrupt layer interface is difficult to achieve under field conditions. Usually, some degree of transition between layers is present, leading to the decreased water storage of the soil cover as compared to the soil cover with abrupt transition between layers. It can be extrapolated from the results of this study that the 2L soil cover with a more nonlinear textural transition will have a higher water storage than the 1L cover. Depending on the applications, this increase in water storage could be sufficient to support vegetation, and if limited precipitation is expected, there is the possibility that the capillary barrier of such cover will limit a large amount of water percolating from the finer layer. An increase in the number of flow barriers from the 2L cover to the 4L cover has also been found to be beneficial. However, the construction of such multilayered covers might not be worthwhile, since the performance of such 4L cover with extended interlayer transitions may not be much different from the 2LT cover.

The choice of optimal soil cover design depends on many factors, including climatic conditions, type of vegetation to grow on a soil cover, budget, purposes of a cover, etc. In terms of climatic conditions, in arid regions, for example, with sparse and low intensity rainfalls, 2L or even 1L covers could be sufficient. In regions with frequent and intense rainfalls, 4L covers with more flow barriers may be a better option. Design of the cover also depends on the type of vegetation. For example, 1L and 2L covers may be optimal for tap-rooted species, whereas 4L covers may be better for deep-rooted plants, since this cover stores more water at 50-75-cm depth than other covers.

In cold semi-arid regions, such as North of Saskatchewan, where frost-free period is only 97 days a year on average (Acton, 1998), the 1L cover may have higher freezing depth as compared to the two-layered covers and the 4L. The layered covers have the finer layer as the first layer, which freezes to lower depth as compared to the coarser soil, since larger mineral surface and the extensive network of fine pores in finer soil would interrupt ice formation (Balland et al., 2006). As was mentioned by Balland et al. (2006), finer-textured soils can be prone to super-cooling, and may thereby remain unfrozen to some extent, even when temperature is below zero. In this sense layered soil covers will perform better than the 1L cover, since percolation below a cover would be lower in layered covers, when thawing starts. If freezing depth is within 25 cm in the finer material, then the 4L cover with three flow barriers may limit the deep percolation better than other tested covers. However, if partial snowmelt occurs during a winter, there will be more water on the soil surface in the layered covers than in the coarser-textured 1L cover due to the fact that the finer layer may be at higher water content and there could be some ponding of water on top of the layer before freezing. These factors may cause higher runoff from the cover. Moreover, a thin ice-rich soil layer may form, when soil refreezes after partial thawing, impeding infiltration of snowmelt water, which was found to further enhance runoff in other studies (Iwata et al., 2011). Even though layered covers may have higher snowmelt runoff from them in spring, they still would be recommended for covering hazardous wastes in cold semi-arid climates, since they are able to limit percolation of water into wastes better than the 1L cover, which is a more important factor to consider, when constructing a reclamation cover. Runoff could be limited by adding a thin layer of gravel on top of the finer layer. Moreover, since covers containing finer soil freeze to lower depth, they are more susceptible to partial snowmelt during winter and may not be able to supply as much water as the 1L cover for excessive runoff, when consistently positive temperatures establish in spring.

4.3 Future Research

Understanding of physics of unsaturated finer-over-coarser layered soil systems has considerably improved over the last few decades; however, the issues related to these soil systems that require further investigation still exist. There are still many unanswered questions left concerning soil covers with interlayer transition zones. One of such questions is whether the performance and WSC of 4L covers with transitions will be significantly different from 2L soil covers with the same transition zone. In order to find an optimal degree of transition between layers, different lengths of transition zones could be investigated in terms of its influence on WSC and susceptibility to preferential flow. Some degree of transition in a layered cover should provide higher water storage than that of 1L cover and, at the same time, keep susceptibility to unstable flow minimized.

Since intermittent infiltration experiments were conducted without replication, more experiments are required to derive firmer conclusions on the performance and flow stability in soil covers composed of fractions of coarse-textured soil under conditions of non-constant infiltration. Replication is also required to obtain the statistical significance for WSC between not only the 1L, and the 2L, but also the 4L covers. Additional studies are necessary to better explain the considerably longer residence time of water in the 2L cover at FC than under initially air-dry conditions as well as the more diffuse nature of the wetting front at FC.

Flow stability of soil covers tested in this work could be evaluated based on the stability analysis of Diment and Watson (1985). Their analysis is much more complex, because it is based on Richards' equation and describes the perturbation problem for non-sharp wetting fronts, which is more applicable to covers tested in this work, especially at FC. Application of a model, taking the preferential flow into account in water flow simulations to the covers tested in this study, would further clarify the susceptibility of soil covers to preferential flow.

REFERENCES

Abdelouas, A. 2006. Uranium mill tailings: geochemistry, mineralogy, and environmental impact. Elements 6 (2): 335-341.

Abdolahzadeh, A.M., B. L. Vachon, and A.R. Cabral. 2011. Evaluation of the effectiveness of a cover with capillary barrier effect to control percolation into a waste disposal facility. Can. Geotech. J. 48: 996-1009.

Acton, D. F., G. A. Padbury, and C. T. Stushnoff. 1998. The Ecoregions of Saskatchewan. Canadian Plains Research Centre. Univ. of Regina, Regina, Canada.

Akindunni, F., R. W. Gillham, and R. V. Nicholson. 1991. Numerical simulations to investigate moisture-retention characteristics in the design of oxygen-limiting covers for reactive mine tailings. Can. Geotech. J. 28: 446-451.

Albright, W. H., C. H. Benson, W. G. Glendon, T. Abichou, S. W. Tyler, and S. A. Rock. 2006. Field Performance of three compacted clay landfill covers. Vadose Zone J. 5: 1157-1171.

Alfnes, E., W. Kinzelbach, and P. Aagaard. 2004. Investigation of hydrogeologic processes in a dipping layer structure: 1. The flow barrier effect. J. Contam. Hydrol. 69: 157-172.

Arya, L. M., J. L. Feike, M. Th. van Genuchten, and P. Shouse. 1999. Scaling parameter to predict the soil water characteristic from particle-size distribution data. Soil Sci. Soc. Am. J. 63: 510-519.

Assoline, S., and D. Or. 2006. Anisotropy factor of unsaturated and saturated soils. Water Resour. Res. 42: W12403.

Babel, M.S., R. Loof, and A. Das Gupta. 1995. Fingered preferential flow in unsaturated homogeneous coarse sand. J. Hydrological Sciences 40: 1-17.

Baker, R.S., and D. Hillel. 1990. Laboratory tests of a theory of fingering during infiltration into layered soils. Soil Sci. Soc. Am. J. 54: 20-30.

Balland, V., J. Bhatti, R. Errington, M. Castonguay, and P. A. Arp. 2006. Modeling snowpack and soil temperature and moisture conditions in a jack pine, black spruce and aspen forest stand in central Saskatchewan (BOREAS SSA). Can. J. Soil Sci. 86: 203-217.

Barbour, S. L. 1990. Reduction of acid generation in mine tailings throuh the use of moisture-retaining cover layers as oxygen barriers: Discussion. Can. Geotech. J. 27: 398-401.

Barbour, S. L., and E. K. Yanful. 1994. A column study of static nonequilibrium fluid pressures in sand during prolonged drainage. Can. Geotech. J. 31: 299-303.

Bauters, T.W.J., D.A. DiCarlo, T.S. Steenhuis, and J.-Y. Parlange. 1998. Preferential flow in water-repellent sands. Soil Sci. Soc. Am. J. 62: 1185-1190.

Bauters, T.W.J., D.A. DiCarlo, T.S. Steenhuis, and J.-Y. Parlange. 2000. Soil water content dependent wetting front characteristics in sands. J. Hydrol. 231-232: 244-254.

Benes, P. 1999. The environmental impacts of uranium mining and milling and the methods of their reduction. Chemical separation technologies and related methods of nuclear waste management 53: 225-246.

Boateng, S. 2007. Probabilistic unsaturated flow along the textural interface in three capillary barrier models. J. Environ. Eng. 133 (11): 1024-1031.

Butts, M. B., and K. H. Jensen. 1996. Effective parameters for multiphase flow in layered soils. J. Hydrol. 183: 101-116.

Carrillo, M.L., K.J. Letey, and S. R. Yates. 2000. Unstable water flow in a layered soil: I. Effects of a stable water-repellent layer. Soil Sci. Soc. Am. J. 64: 450-455.

Chen, C.-R., J. L. Zatzl, and E. Reilly. 1993. Ion-pairing of dyclonine with dyes. Drug development and industrial pharmacy 19 (11): 1265-1282. doi: 10.3109/03639049309074400.

Cherrill, H. E., and A. Phillips. 1997. The capping landfill — towards the re-use of material which would otherwise be waste. Geoenvironmental engineering, London, UK.

Clothier, B. E., S.R. Green, and M. Deurer. 2008. Preferential flow and transport in soil: progress and prognosis. European J. Soil Science 59: 2-13.

Clothier, B.E., D.E. Scotter, and J.P. Kerr. 1977. Water retention in soil underlain by a coarse-textured layer: theory and field application. Soil Sci. 123 (6): 392-399.

Coppola, A., M. Kutilek, and E.O. Frind. 2009. Transport in preferential flow domains of the soil porous system: measurement, interpretation, modeling, and upscaling. J. Contam. Hydrol. 104: 1-3.

Dane, J. H., and G. C. Topp (co-ed.). 2002. Methods of soil Analysis. Part 4 - Physical Methods. SSSA Book Ser. 5. Madison, WI.

De Rooij, G.H. 2000. Modeling fingered flow of water in soils owing to wetting front instability: a review. J. Hydrol. 231-232: 277-294.

Dexter, A.R. 2004. Soil physical quality. Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. Geoderma 120: 201-214.

DiCarlo, D. 2007. Capillary matric potential overshoot as a function of imbibition flux and initial water content.Water Resour. Res. 43: W08402.

Diment, G.A., and K.K. Watson. 1983. Stability analysis of water in unsaturated porous materials. 2. Numerical studies. Water Resour. Res. 19: 1002-1010.

Diment, G.A., and K.K. Watson. 1985. Stability analysis of water in unsaturated porous materials. 3. Experimental studies. Water Resour. Res. 21 (7): 979-984.

Diment, G.A., K.K. Watson, and P.J. Blennerhassett. 1982. Stability analysis of water in unsaturated porous materials. 1. Theoretical considerations. Water Resour. Res. 18 (4): 1248-1254.

Dingman, S. L. 2002. Physical hydrology. 2-nd ed. Prentice Hall, NJ.

Egorov, A.G., R.Z. Dautov, J.L. Nieber, and A.Y. Sheshukov. 2003. Stability analysis of gravity-driven infiltrating flow. Water Resour. Res. 39 (9): SBH 12 1-14.

Fayer, M. J., and G. W. Gee. 2006. Multiple-year water balance of soil covers in a semiarid setting. J. Environ. Qual. 35: 366-377.

Flury, M, H. Fluhler, W. Jury, and J. Leuenberger. 1994. Susceptibility of soils to preferential flow of water: a field study. Water Resour. Res. 30 (7): 1945-1954.

Gerke, H.H. 2006. Preferential flow descriptions for structured soils. J. Plant Nutr. Soil Sci. 169: 382-400.

Gerke, H.H., P. Germann, and J. Nieber. 2010. Preferential and unstable flow: from the pore to the catchment scale. Vadose zone J. 9: 207-212.

Glass, R.J., and M.J. Nicholl. 1996. Physics of gravity fingering in immiscible fluids within porous media: an overview of current understanding and selected complicating factors. Geoderma 70: 133-163.

Glass, R.J., T.S. Steenhuis, and J.-Y. Parlange. 1989. Wetting front instability. 2. Experimental determination of relationships between system parameters and twodimensional unstable flow field behaviour in initially dry porous media. Water Resour. Res. 25 (6): 1195-1207.

Green, W.H., and G.A. Ampt. 1911. Studies on soil physics. Part 1. The flow of air and water through soils. J. Agric. Sci. 4: 1-24.

Haynes, R.H. 1998. The Canadian system of soil classification. 3rd ed. NRC-CNRC. Ottawa, Ontario.

Hendrickx, J.M.H., and T. Yao. 1996. Prediction of wetting front stability in dry field soils using soil and precipitation data. Geoderma 70: 265-280.

Hill, E.D., and J.-Y.Parlange. 1972. Wetting front instability in layered soils. Soil Sci. Soc. Am. Proc. 36: 697-702.

Hillel, D.1980. Applications of soil physics. Academic press. London.

Hillel, D. 1998. Environmental soil physics. Elsevier. Academic press. San Diego. USA.

Hillel, D., and R.S. Baker. 1988. A descriptive theory of fingering during infiltration into layered soils. Soil Sci. J. 146 (1): 51-56.

Ho, C. K., and S. W. Webb. 1998. Capillary barrier performance in heterogeneous porous media. Water Resour. Res. 34 (4): 603-609.

Huang, M., S. L. Barbour, A. Elshorbagy, J. D. Zettl, and B. C. Si. 2011. Infiltration and drainage processes in multi-layered coarse soils. Can. J. Soil Sci. 91: 169-183.

Iwata, Y., M. Nemoto, S. Hasegawa, Y. Yanai, K. Kuwao, T. Hirota. 2011. Influence of rain, air temperature, and snow cover on subsequent spring-snowmelt infiltration into thin frozen soil layer in northern Japan. J. Hydrol. 401: 165 - 176.

Iwata S., T. Tabuchi, B. P. Warkentin. 1995. Soil-water interactions: mechanisms and applications. 2nd ed. New York, NY.

Jansik, D. P., D. Wildenschild, and N. D. Rosenberg. 2011. Flow processes in the dry regime: the effect on capillary barrier performance. Vadose Zone J. 10: 1173-1184.

Johannesen, D., L. Haji, and B. Zettl. 1997. Progressive reclamation work at Cameco-Uranerz Key lake operations (1978-1995). Canadian Plains Proceedings 28: 89-103.

Jury, W. A., and H. Fluhler. 1992. Transport of chemicals through soil: mechanisms, models, and field applications. Adv. Agron. 47: 141-201.

Jury, W. Z., Wang, and A. Tuli. 2003. A conceptual model of unstable flow in unsaturated soil during redistribution. Vadose Zone J. 2: 61-67.

Jutla, A.S. 2006. Hydrologic modeling of reconstructed watersheds using a system dynamics approach. M.Sc. thesis. Univ. of Saskatchewan, Saskatoon.

Kabeya, N., M. Katsuyama, M. Kawasaki, N. Ohte, and A. Sugimoto. 2007. Estimation of mean residence times of subsurface waters using seasonal variation in deuterium excess in a small headwater catchment in Japan. Hydrological Processes 21: 308-322.

Kapoor, V. 1996. Criterion for instability of steady-state unsaturated flows. Transport in porous media 25: 313-334.

Khire, M. V., H. B. Craig, and P.J. Bosscher. 2000. Capillary barriers: design variables and water balance. J. Geotechnical and Geoenvironmental engineering 126 (8): 695-708.

Kung, K.-J.S., T.S. Steenhuis, E.J. Kladivko, T.J. Gish, G. Bubenzer, and C.S. Helling. 2000. Impact of preferential flow on the transport of adsorbing and non-adsorbing tracers. Soil Sci. Soc. Am. J. 64: 1290-1296.

Lee, N. H. 1999. Evaluation of cover materials for a large scale test facility at Key Lake. M.Sc. thesis. Univ. of Saskatchewan, Saskatoon, Canada.

Lee, K. S. 2007. Effects of hysteresis in k-S-p relationships on the performance of mine-waste soil covers. Geosciences J. 11 (3): 241 - 247.

Liu, G., and B.C. Si. 2008. Analytical modeling of one-dimensional diffusion in layered systems with position-dependant diffusion coefficients. Adv. Water Resour. 31: 251-268.

Liu J., J. Zhang, J. Feng. 2008. Green–Ampt model for layered soils with non-uniform initial water content under unsteady infiltration. Soil Sci. Soc. Am. J. 72 (4): 1041-1047.

Lottermoser, B. G., and P. M. Ashley. 2006. Physical dispersion of radioactive mine waste at the rehabilitated Radium Hill uranium mine site, South Australia. Australian Journal of Earth Sciences 53: 485 - 499.

MacKenzie, M. D., and S. A. Quideau. 2012. Laboratory-based nitrogen mineralization and biogeochemistry of two soils used in oil sands reclamation. Can. J. Soil Sci. 92: 131-142.

McLeod, M., L.A. Schipper, and M.D. Taylor. 1998. Preferential flow in a well drained and a poorly drained soil under different overhead irrigation regimes. Soil Use Manage. 14: 96-100.

Morris, C. E., and J. C. Stormont. 1997. Capillary barriers and subtitle D covers: Estimating equivalency. J. Environ. Eng. 123 (1): 3-10.

Morris, C. E., and J. C. Stormont. 1999. Parametric study of unsaturated drainage layers in a capillary barrier. J. Geotechnical and Geoenvironmental Engineering 125 (12): 1057-1065.

Nemez, E. 2013. Substitution of amaranth as dye in edge wicking test. B.Sc. thesis. Linköping Univ., Linköping, Sweden. http://liu.diva-portal.org/smash/get/diva2:634831/FULLTEXT01.pdf (accessed September 27, 2013).

Nezhad, M. M., A. A. Javadi, and F. Abbasi. 2011. Stochastic finite element modelling of water flow in variably saturated heterogeneous soils. Int. J. Numer. Anal. Meth. Geomech. 35: 1389 - 1408.

Nyhan, J. W. 2005. A seven-year water balance study of an evapotranspiration landfill cover varying in slope for semiarid regions. Vadose Zone J. 4: 466-480.

O'Kane, M. A. T. 1995. Instrumentation and monitoring of an engineered soil cover system for acid generating mine waste. M.Sc. thesis. Univ. of Saskatchewan, Saskatoon, Canada.

Onody, R. N., A. Posadas, and S. Crestana. 1995. Experimental studies of fingering phenomena in two-dimensions and simulation using a modified invasion percolation model. J. Appl. Phys. 78 (5): 2970-2976.

Philip, J. R. 1957a. The theory of infiltration: 1. The infiltration equation and its solution. Soil Sci. 83 (5): 345-357.

Philip, J. R. 1957b. The theory of infiltration: 2. The infiltration equation and its solution. Soil Sci. 83 (6): 435-448.

Philip, J. R. 1957c. The theory of infiltration: 3. Moisture profile and relation to experiment. Soil Sci. 84 (2): 163-178.

Philip, J. R. 1957d. The theory of infiltration: 4. Sorptivity and algebraic infiltration equations. Soil Sci. 84 (3): 257-264.

Philip, J. R. 1957e. The theory of infiltration: 5. The influence of the initial moisture content. Soil Sci. 84 (4): 257-264.

Philip, J. R. 1958a. The theory of infiltration: 6. Effect of water depth over soil. Soil Sci. 86 (6): 278-286.

Philip, J. R. 1958b. The theory of infiltration: 7. Soil Sci. 86 (6): 333-337.

Philip, J. R. 1975. Stability analysis of infiltration. Soil Sci. Soc. Am. Proc. 39: 1042-1049.

Porro, I. 2001. Hydrologic behavior of two engineered barriers following extreme wetting. J. Environ. Qual. 30: 655-667.

Qian, T., L. Huo, D. Zhao. 2010. Laboratory investigation into factors affecting performance of capillary barrier system in unsaturated soil. Water Air Soil Pollut. 206: 295-306.

Raats, P.A.C. 1973. Unstable wetting fronts in uniform and non-uniform soils. Soil Sci. Soc. Am. Proc. 37: 681-685.

Ritsema, C. J., and L. W. Dekker. 1994. Soil moisture and dry bulk density patterns in bare dune sands. J. Hydrol. 154: 107-131.

Scanlon, B. R., R. C. Reedy, K. E. Keese, and S. F. Dwyer. 2005. Evaluation of evapotranspirative covers for waste containment in arid and semiarid regions in the south-western USA. Vadose Zone J. 4: 55-71.

Scott, H.D. 2000. Soil physics. Agricultural and environmental applications.1-st ed. Iowa State University press. USA.

Selker, J.S., T.S. Steenhuis, and J.Y. Parlange. 1992. Wetting front instability in homogeneous sandy soils under continuous infiltration. Soil Sci. Soc. Am. J. 56 (5): 1346-1350.

Sililo, O., and J. H. Tellam. 2000. Fingering in unsaturated zone flow: a qualitative review with laboratory experiments on heterogeneous systems. Ground Water 38 (6): 864-871.

Simms, P. H., and E. K. Yanful. 1999. Some insights into the performance of an experimental soil cover near London, Ontario. Can. Geotech. J. 36: 846-860.

Šimůnek, J., M. Šejna, H. Saito, M. Sakai, and M. Th. van Genuchten. 2009. The HYDRUS-1D Software Package for Simulating the One-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media. V. 4.08. Univ. of California, Riverside. CA.

Smesrud, J. K., and J.S. Selker. 2001. Effect of soil particle size contrast on capillary barrier performance. J. Geotechnical and Geoenvironmental Engineering 127 (10): 885-888.

Spies, J. 2010. Layering of Medium and Coarse Sand Increases Soil Water Storage. B. Sc. thesis. Univ. of Saskatchewan, Saskatoon, Canada.

Stange, C. F., and R. Horn. 2005. Modeling the Soil Water Retention Curve for Conditions of Variable Porosity. Vadose Zone J. 4: 602-613.

Stormont, J.C., and C. E. Anderson. 1999. Capillary barrier effect from underlying coarser soil layer. Journal of Geotechnical and Geoenvironmental Engineering 125 (8): 641-648.

Stormont, J. C., and C. E. Morris. 1998. Method to estimate water storage capacity of capillary barriers. J. Geotechnical and Geoenvironmental Engineering 124 (4): 297-302.

Tallon, L. K., M. A. O'Kane, D. E. Chapman, M. A. Phillip, R. E. Shurniak, and R. L. Strunk. 2011. Unsaturated sloping layered soil cover system: Field investigation. Can. J. Soil Sci. 91: 161-168.

Tindall, J.A., and J. R. Kunkel. 1999. Unsaturated zone hydrology for scientists and engineers. Prentice-Hall. NJ.

Ursino, N. 2000. Linear stability analysis of infiltration, analytical and numerical solution. Transport in Porous Media 38: 261-271.

Van Genuchten, M. T. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44: 892 - 898.

Veihmeyer, F. J., and A. H. Hendrickson. 1950. Soil moisture in relation to plant growth. Ann. Rev. Plant Physiol. 1: 285-304.

Vogel, T., and M. Císlerová. 1988. On the reliability of unsaturated hydraulic conductivity calculated from the moisture retention curve. Transport in Porous Media 3: 1-15.

Walter, M. T., J.-S. Kim, T. S. Steenhuis, J.-Y.Parlange, A. Heilig, R. D. Braddock, J. S. Selker, and J. Boll. 2000. Funneled flow mechanisms in a sloping layered soil: laboratory investigation. Water Resour. Res. 36 (4): 841-849.

Wang, Z., J. Feyen, and C. J. Ritsema. 1998. Susceptibility and predictability of conditions for preferential flow. Water Resour. Res. 34 (9): 2169-2182.

Wang, Z., L. Wu, T. Harter, J. Lu, and W. A. Jury. 2003. A field study of unstable preferential flow during soil water redistribution. Water Resour. Res. 39 (4): SBH 1-1-11.

Wang, Z., W. A. Jury, A. Tuli, and D.-J. Kim. 2004. Unstable flow during redistribution: controlling factors and practical implications. Vadose Zone J. 3: 549-559.

Welter, D. C. 2009. Evaluation of preferential processes in reclamation soil covers. M.Sc. thesis. Univ. of Saskatchewan, Saskatoon, Canada.

White, I., P. M. Colombera, and J. R. Philip. 1976. Experimental study of wetting front instability induced by sudden change of pressure gradient. Soil Sci. Soc. Am. J. 40: 824-829.

Woyshner, M. R., and E. K. Yanful. 1995. Modelling and field measurements of water percolation through an experimental soil cover on mine tailings. Can. Geotech. J. 32: 601-609.

Yanful, E. K., S. M. Mousavi, and L.-P. De Souza. 2006. A numerical study of soil cover performance. J. Environ. Manage. 81: 72-92.

Yanful, E. K., S. M. Mousavi, and M. Yang. 2003. Modeling and measurement of evaporation in moisture-retaining soil covers. Advances in Environmental Research 7: 783-801.

Yang, H., H. Rahardjo, and E.C. Leong. 2006. Behaviour of unsaturated layered soil columns during infiltration. J. Hydrological Engineering 11 (4): 329-337.

Yang, H., H. Rahardjo, E.C. Leong, and D.G. Fredlund. 2004. A study of infiltration on three sand capillary barriers. Can. Geotech. J. 41: 629 - 643.

Yao, T., and J.M.H. Hendrickx. 1996. Stability of wetting fronts in dry homogeneous soils under low infiltration rates. Soil Sci. Soc. Am. J. 91: 133-147.

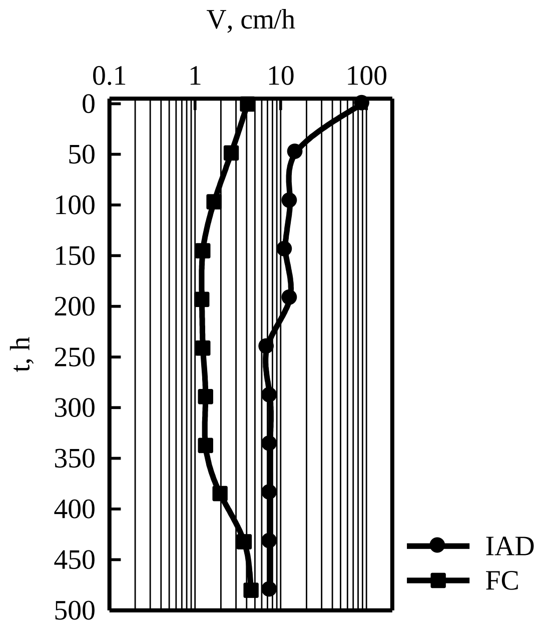
Zettl, J. D., S. L. Barbour, M. Huang, B. C. Si, and L. A. Leskiw. 2011. Influence of textural layering on field capacity of coarse soils. Can. J. Soil Sci. 91: 133-147.

Zhu, J., and D. Sun. 2010. Capillary pressure-dependent anisotropy of layered unsaturated soils. Can. J. Soil Sci. 90: 319-329.

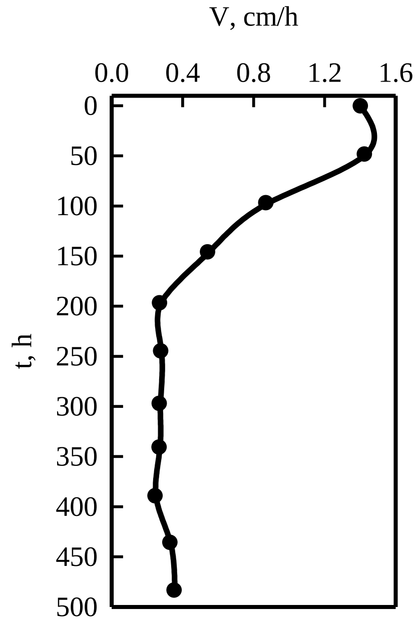
Zornberg, J. G., L. LaFountain, and J. A. Caldwell. 2003. Analysis and design of evapotranspirative cover for hazardous waste landfill. J. Geotechnical and Geoenvironmental Engineering 129 (6): 427-438.

APPENDIX A

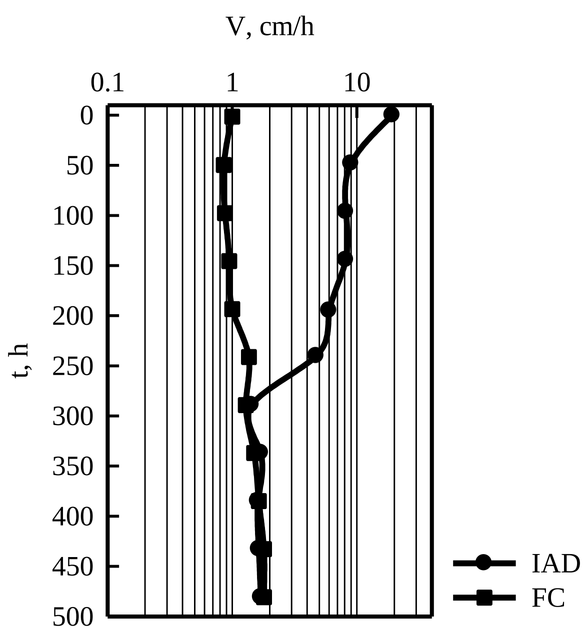
INFILTRATION RATE AND WETTING FRONT VELOCITY OF SOIL COVERS UNDER INTERMITTENT INFILTRATION



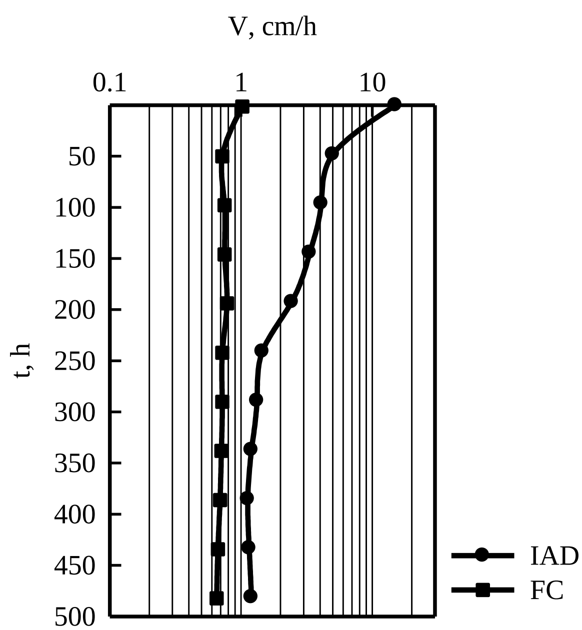
A1. Infiltration rate (V) into homogeneous soil cover under two water contents



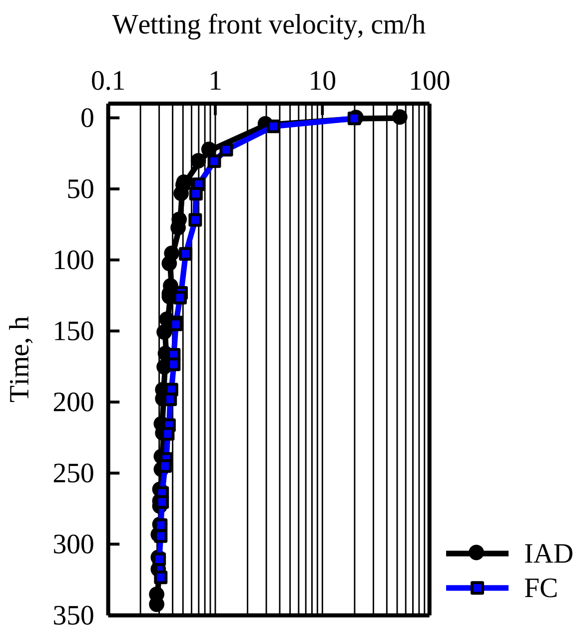
A2. Infiltration rate (V) into two-layered soil cover under FC water content



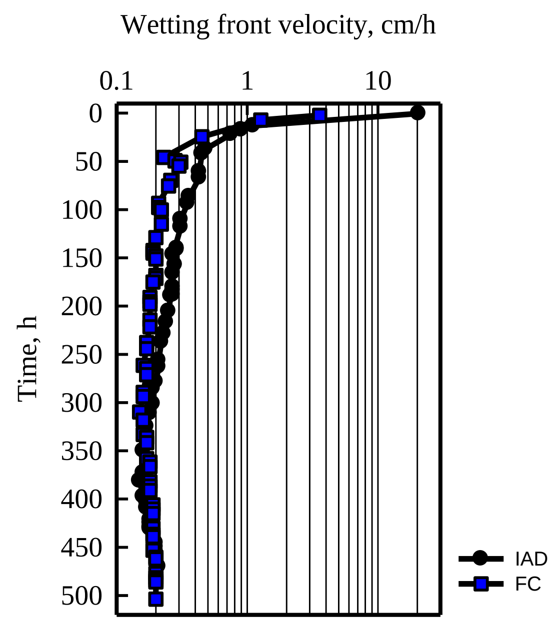
A3. Infiltration rate (V) into two-layered soil cover with a gradual transition under two water contents



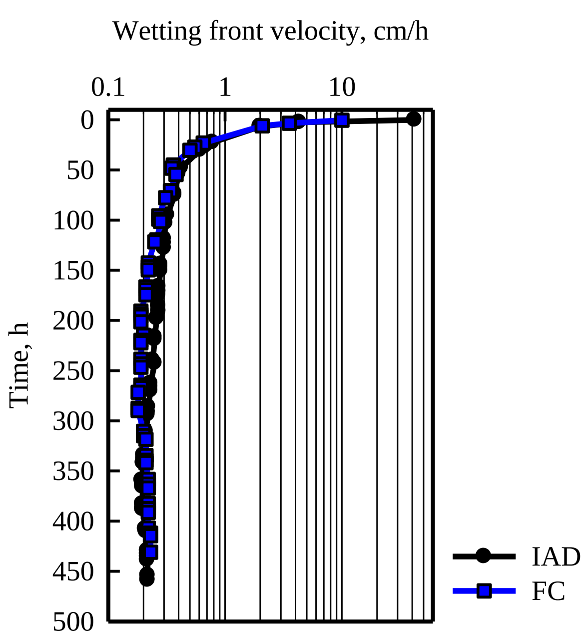
A4. Infiltration rate (V) into four-layered soil cover under two water contents



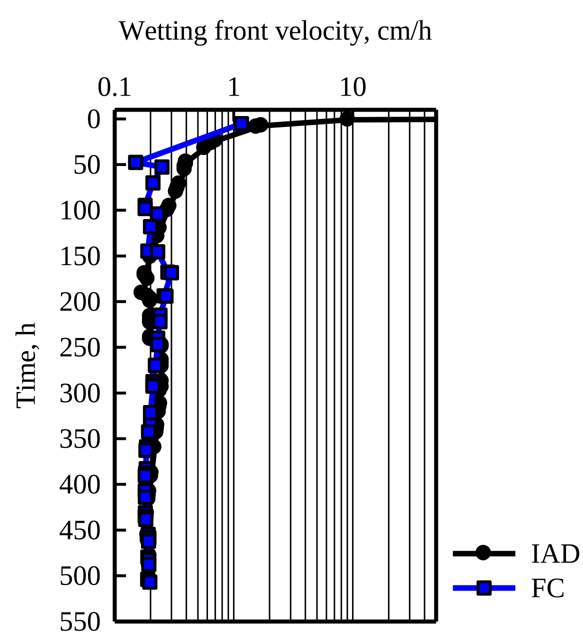
A5. Velocity of the wetting front propagation in homogeneous soil cover under two water contents



A6. Velocity of the wetting front propagation in two-layered soil cover under two water contents



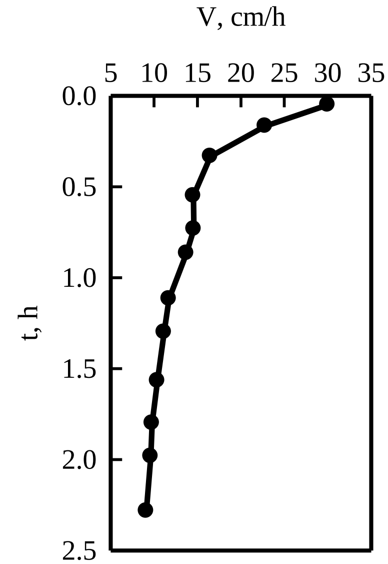
A7. Velocity of the wetting front propagation in two-layered soil cover with a gradual transition under two water contents



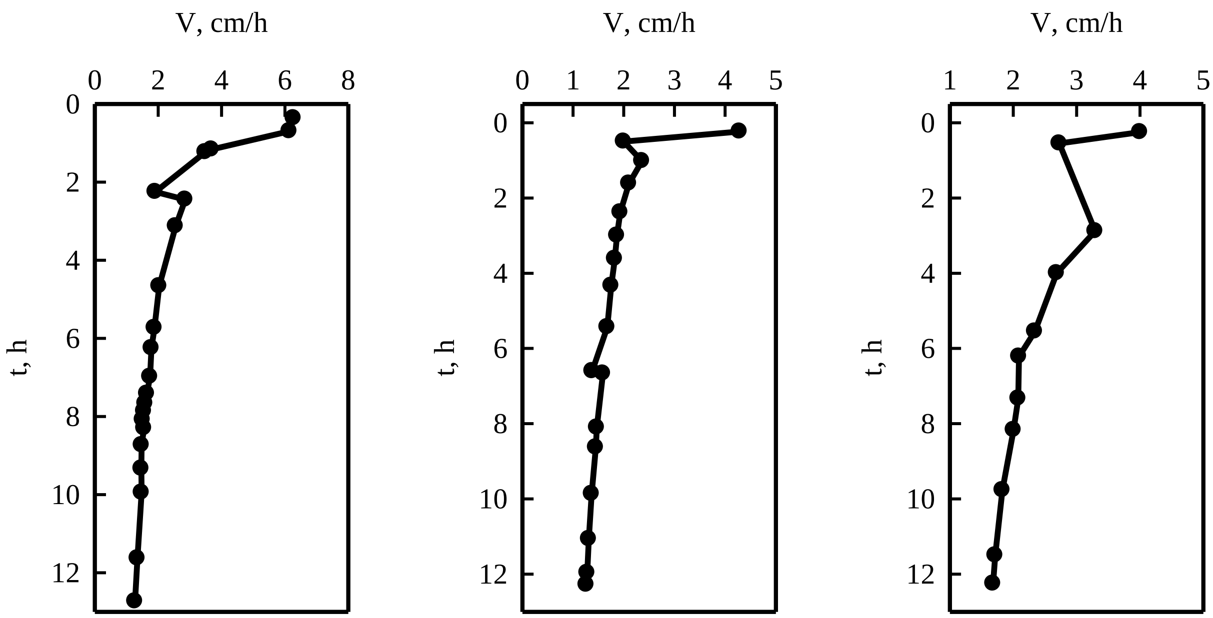
A8. Velocity of the wetting front propagation in four-layered soil cover under two water contents

APPENDIX B

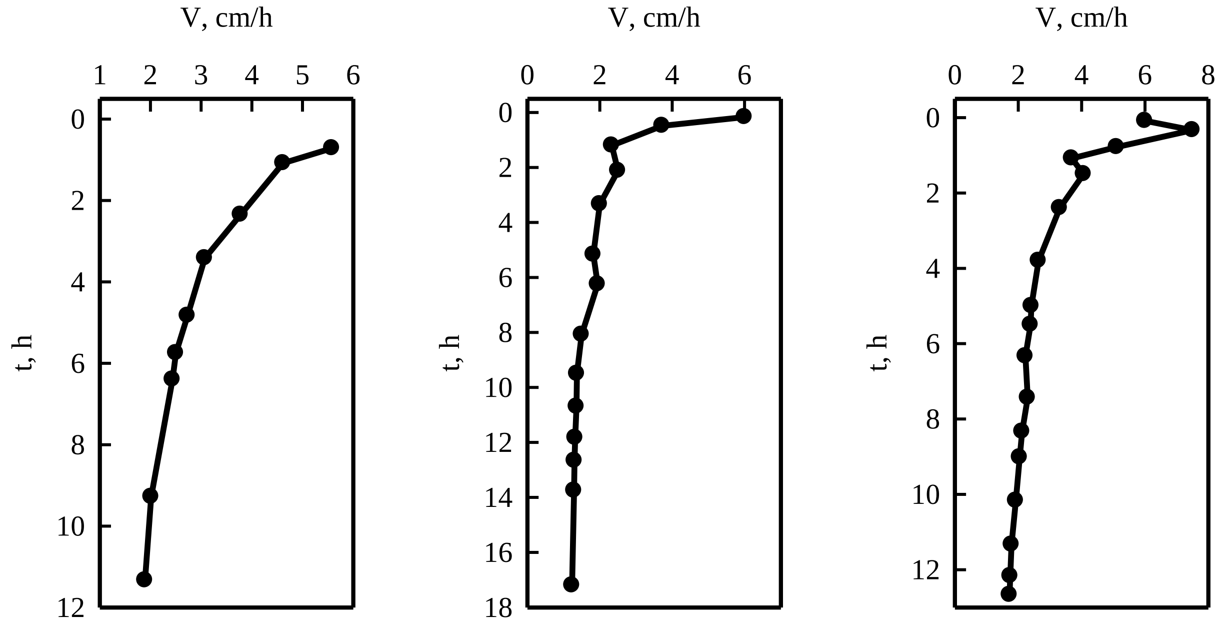
INFILTRATION RATE AND WETTING FRONT VELOCITY OF SOIL COVERS UNDER CONSTANT HEAD INFILTRATION, INITIALLY AIR-DRY CONDITIONS



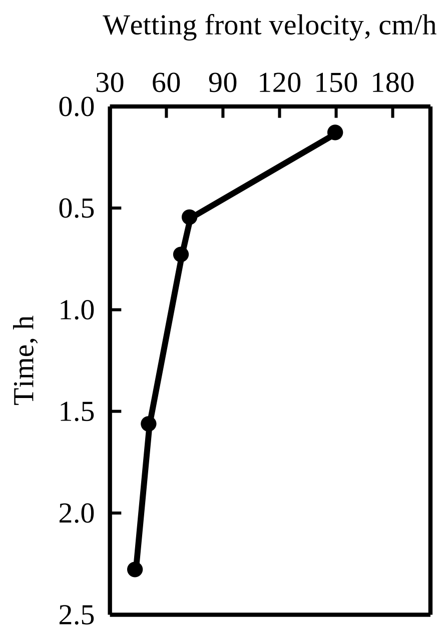
B1. Change of infiltration rate (V) over time (t) in homogeneous soil cover



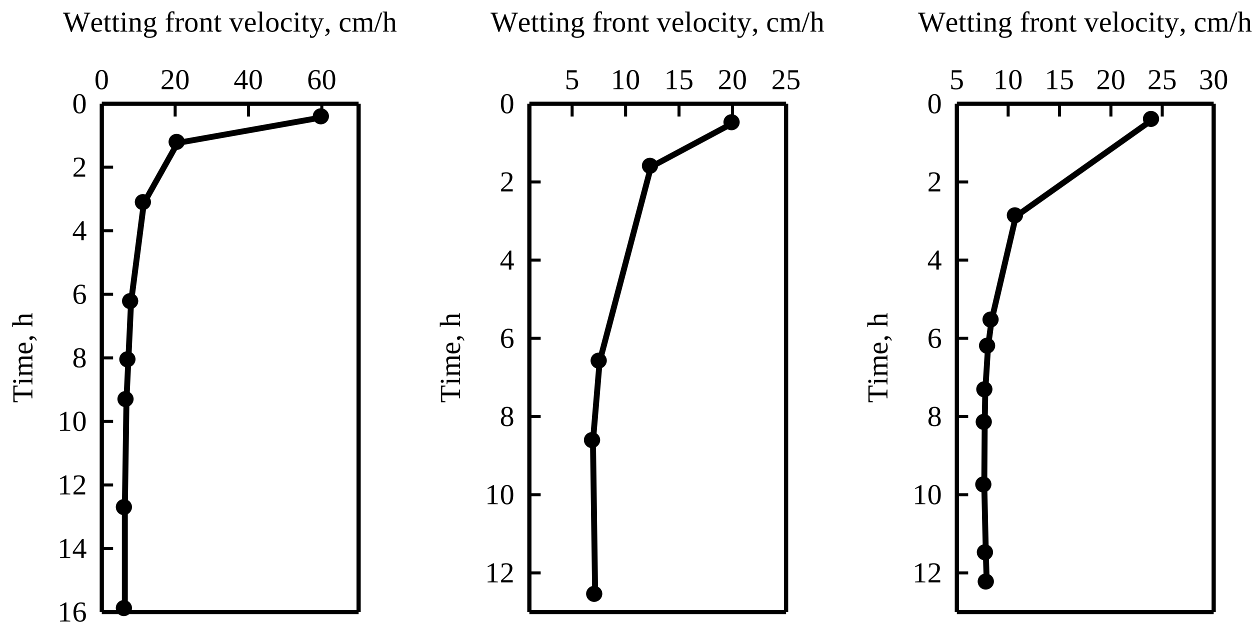
B2. Change of infiltration rate (V) over time (t) in 3 replicates of two-layered soil cover



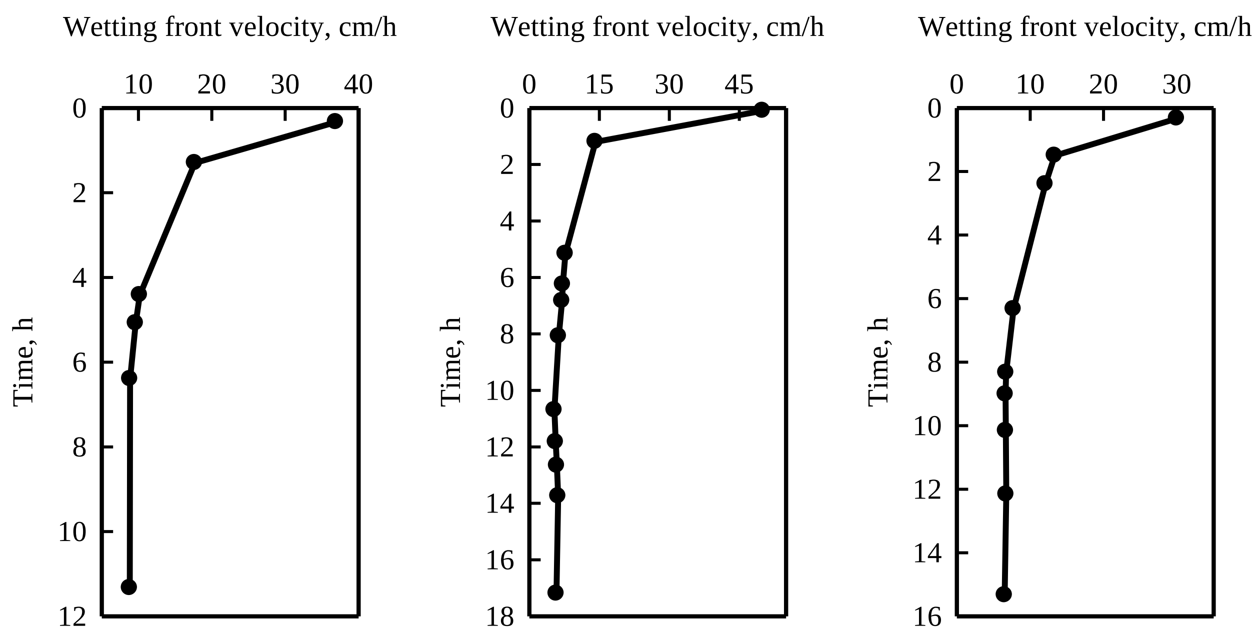
B3. Change of infiltration rate (V) over time (t) in 3 replicates of two-layered soil cover with a gradual transition



B4. Velocity of wetting front propagation in homogeneous soil cover



B5. Velocity of wetting front propagation in two-layered soil covers (3 replicates)



B6. Velocity of wetting front propagation in two-layered soil covers with a gradual transition (3 replicates)