

PREFERENTIAL FLOW THROUGH EARTHEN LANDFILL COVERS

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ABSTRACT

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In order to minimize infiltration of precipitation into the waste, final covers are constructed once a landfill reaches its capacity. In and to sub-humid climates, earthen final covers have been permitted. However, formation of macropores (or shrinkage cracks) and flow through relatively large pores can significantly increase percolation through earthen landfill covers during service. Most commonly used water balance models that are used for predicting percolation through earthen cover are based on Richards' equation that simulates only the micropore flow. Hence, a model that can simulate the micropore and macropore flow is required to simulate the long-term hydrology of earthen covers. In this study, validation of Root Zone Water Quality Model (RZWQM) using data collected from an instrumented field-scale test section and development of a model capable of simulating macropore flow using lattice Boltzmann method were carried out.

An instrumented field-scale test section of an earthen landfill cover, made up of 1.5 m thick compacted clay overlain by 0.3 m thick topsoil, was constructed at a landfill located in Detroit, MI and monitored for about four years. Measured annual percolation increased by an order of magnitude during the second and the third year of service. Controlled irrigation tests conducted on the test section confirmed macropore dominated flow through the test section. Estimated effective field hydraulic conductivities of the test section increased by an order of magnitude during the 4th year of service compare to the 1st year of service. Field methane tracer tests confirmed the presence and locations of macropores.

Water balance of the field test section was simulated using the model RZWQM and a commonly used numerical model UNSAT-H. For the first year data, both models simulated percolation relatively accurately. However, the numerical predictions of percolation were not accurate for the second and the third year when the effect of macropores was ignored. The macropore parameters required for RZWQM were calibrated using field irrigation test results. RZWQM predictions using calibrated macropore parameters yielded relatively accurate prediction of percolation for the second and the third years of the field data.

Measurement of macropore flow through clay in lab-scale samples is relatively challenging due to the effect of confining walls and the relatively small size of the sample. A new laboratory technique was developed to consistently fabricate clay samples containing macropores. High resolution X-ray CT images of compacted clay specimens were taken to visualize the 3D structure of macropores. A 3D lattice Boltzmann model (LBM) that can simulate saturated flow through micropore and macropore flow was developed. Verification of the LBM was carried out using analytical solutions. The LBM was validated using laboratory measurement of saturated hydraulic conductivities (k_{sat}) of compacted clay specimens containing macropores. A prediction equation is formulated to predict the rate of flow of an arbitrary shape and tortuous macropore using the flow rate of straight vertical cylinder. The predicted k_{sat} using the proposed formulation and calculated k_{sat} using the LBM matched very well.

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To my Parents
Soundararajan & Rajeswary

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KEY TO ABBREVIATIONS

1-D = one-dimensional

2-D = two-dimensional

3-D = three-dimensional

ASTM = American Society for Testing and Materials

CT = Computed tomography

GCL = Geosynthetic clay liner

HDMP = Heat dissipation matrix potential

LB = Lattice Boltzmann

LBM = Lattice Boltzmann model

NOAA = National Oceanic and Atmospheric Administration

MSW = Municipal solid waste

RZWQM = Root zone water quality model

SWS = Soil water storage

TDR = Time domain reflectometry

VWC = Volumetric water content

WCR = Water content reflectometer

CHAPTER 1: INTRODUCTION

1.1 Background

In the U.S., landfilling is the most common means to dispose of municipal solid waste (MSW). Landfill final cover is constructed to cap the landfill and to isolate the MSW from the external environment. The conventional landfill final covers recommended by Resource Conservation and Recovery Act (RCRA) consist of a hydraulic barrier layer, typically a geosynthetic material called geomembrane underlain by compacted clay, to impede percolation (Albright et al. 2004). Due to economical and sustainability reasons, the use of earthen cover as an alternative to conventional cover has been extensively tested during the last two decades (Montgomery and Parsons, 1989; Benson and Khire, 1995; Khire et al. 1997; Melchior, 1997; Benson et al. 2001; Albright et al. 2003; Scanlon et al. 2005). However, a few studies have suggested that earthen covers exhibit various degrees of macropore flow (preferential flow) during the several decades of service life (Montgomery and Parsons, 1989; Khire et al. 1999; Albright et al. 2006a, Benson et al. 2007). Macropore flow can increase the percolation into the waste significantly. However, very little data and modeling of macropore flow through earthen cover can be found in literature.

Commonly used numerical models to simulate percolation through earthen landfill covers are UNSAT-H, HYDRUS, and VADOSE/W (Khire et al. 1999, Mijares and Khire 2012, Benson et al. 2001). These models are based on classical theory of water flow as formulated by Richards' equation for flow through saturated-unsaturated porous materials that exhibit capillarity. Several studies have evaluated the ability of these models to predict field water balance (Khire et al.

1997, Benson et al 2005). However, these models do not simulate flow through macropores. Figure 1.1(a) shows a schematic of an as-built compacted clay landfill cover where the flow is dominated by micropores. The transient liquid flow in micropores is downward or upward depending on the hydraulic gradient due to the soil capillarity and gravity, respectively. Figure 1.1(b) shows a schematic of the landfill cover after the formation of desiccation cracks (macropores) where liquid flow is through micropores as well as through the macropores. Flow through macropores is predominantly downward, similar to in a conduit. Inability to model macropore flow is one of the key limitations of commonly used water balance models. Hence, models capable of simulating micropore flow as well as macropore flow need to be developed and/or validated in order to design earthen landfill covers.

Root Zone Water Quality Model (RZWQM) is a two-domain water balance model developed by Agricultural Research Service (ARS), United States Department of Agriculture (USDA) (Ahuja et al. 1995). Two-domain models use gravity gradients for macropore flow and Richard's equation for micropore flow. In this 1D vertical multilayer flow model, flow through cylindrical macropores in surface layer and cylindrical or in plane macropores in the layers beneath the surface layer can be simulated. The RZWQM model has not been used for predicting water balance of engineered earthen covers and validation of its macropore flow component has not been done using field-based data for engineered earthen covers.

For saturated flow, a numerical model based on the Lattice Boltzmann method (Succi 2001, Wolf-Gladrow 2000) was used. The lattice Boltzmann model (LBM) requires high resolution pore structure geometry that is generally developed from an X-ray Computed Tomography (CT) imaging. The LBM was studied and validated to measure the saturated hydraulic conductivity of porous media by many researchers (Succi et al. 1989; Kutay et al. 2006; Sukop et al. 2013).

However, published works are generally limited to impermeable solid medium with micropores or macropores.

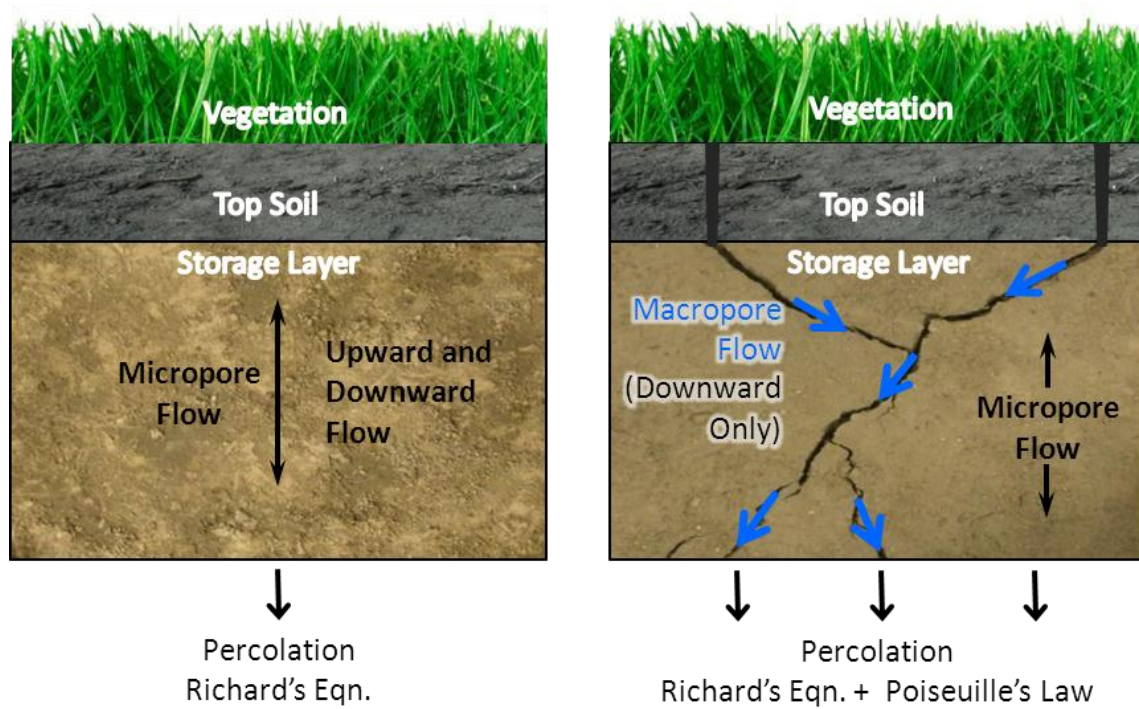


Figure 1.1: Schematic of flow through an earthen cover containing only micropores (a); versus micropores and macropores (b).

1.2 Objectives

The key objectives of this study are:

- Quantify micropore flow vs. macropore flow through an engineered earthen landfill final cover;
- Identify and validate numerical model(s) capable of simulating micropore flow and macropore flow through earthen landfill covers; and
- Develop a model based on lattice Boltzmann method that can simulate saturated flow through micropores and macropores.

1.3 Outline of the Dissertation

This dissertation is organized as seven chapters including this first chapter of introduction.

Chapter 2 presents the literature review and background on earthen landfill covers, macropore flow through earthen landfill covers, models capable of simulating macropore flow, and the relatively new numerical approach of LBM.

Chapter 3 presents the observations of macropore flow through a field test section of earthen landfill cover. Data collected from the field test section is presented. Also, field tests such as irrigation tests to evaluate macropore flow and gas injection tests used to identify the macropores are discussed in detail.

Chapter 4 presents the validation of RZWQM for water balance modeling of the earthen landfill cover using the data presented in Chapter 2. Results of micropore only flow simulations

of RZWQM were compared with the commonly used UNSAT-H model simulation results. Results of micropore and macropore flow using RZWQM are presented

Chapter 5 presents the laboratory tests conducted to evaluate the macropore flow. The challenges in developing macroporous specimen due to the self-healing nature of cracks in the lab-scale compacted clay specimens are discussed. A new technique to develop macroporous specimen in laboratory is presented. Also, calculation of macroporosity and prediction of k_{sat} using high resolution X-ray CT images are presented.

Chapter 6 presents the model developed based on LBM. Verification of LBM algorithm using analytical solution(s) is presented. Also, validation of LBM using X-ray CT images of macroporous specimens and saturated hydraulic conductivities measured in the laboratory are presented. A systematic analysis of morphology and tortuosity of macropores on macropore flow rate is presented. Moreover, formulation of an equation to predict flow rate through arbitrary shape and tortuous macropores using the flow rate of equivalent straight and vertical cylindrical macropore is presented. In addition, process of development of multiphase LBM is presented.

Chapter 7 presents the summary and conclusions.

CHAPTER 2: LITERATURE REVIEW AND BACKGROUND

According to the estimate of the United States Environmental Protection Agency (USEPA), there are about 1,750 active landfills in the U.S. as of 2006 and over 10,000 closed municipal landfills (EPA 2007). Landfill final covers are constructed to isolate the waste from the environment once the landfill reaches its capacity. The final cover recommended by Resource Conservation and Recovery Act (RCRA) consist of a hydraulic barrier layer to restrict percolation, and are generally called as conventional covers (Albright et al. 2004). The barrier layer of a conventional cover may compose of compacted clay having a relatively low saturated hydraulic conductivity (k_{sat}) or a composite barrier consisting of a geosynthetic material called geomembrane underlain by compacted clay depending on the landfill liner below the waste (EPA 1992). Due to economical and sustainability reasons, the use of earthen covers as an alternative to conventional cover, has been extensively tested during the last two decades (Montgomery and Parsons, 1989; Benson and Khire, 1995; Khire et al. 1997; Melchior, 1997; Benson et al. 2001; Albright et al. 2003; Scanlon et al. 2005). Hauser et al. (2001) estimated a potential savings of 50% on landfill cover construction costs by using earthen covers (without geomembrane) instead of conventional cover. However, according to RCRA, percolation through the designed earthen landfill covers should not be more than the percolation rate through the conventional cover. Lysimeters are used to measure percolation in short term and numerical models are used to predict the long term percolation through earthen landfill cover.

2.1 Earthen Landfill Covers

The conventional landfill final cover system required by RCRA is relatively expensive and the long term performance of the compacted clay barrier especially to erosion protection is unknown (Albright et al. 2004). Hence, alternative final covers are widely tested. Mostly the alternative final covers rely on the water-holding capability of soils and the fact that a relatively large percentage of precipitation returns to the atmosphere through evapotranspiration (Albright et al. 2004). Hence, the term “evapotranspirative (ET) covers” or “water balance covers” are often used to refer to these alternative final covers. Also, the landfill final covers without the geosynthetic materials are generally referred to as earthen landfill covers.

The earthen landfill covers are often classified into two types based on how they function: (1) monolithic covers; and (2) capillary barriers (Khire et al. 2000). Monolithic covers have relatively simple cross-sectional profile consisting of 150 to 300 mm-thick topsoil layer underlain by a storage layer of earthen material having adequate water storage capacity. The function of topsoil layer is to act as a medium for vegetative growth and erosion protection. The thickness of the storage layer is designed according to required storage for infiltration until the stored water is removed by evapotranspiration. Finer-grained soil layer is underlain by coarser-grained layer in capillary barriers. The difference in hydraulic properties between the two layers forms a capillary interface that forces water to be stored in the upper finer-grained layer thus minimizing infiltration into the underlying coarser-grained layer until the upper layer is almost saturated.

Earthen landfill covers required to provide performance that is equivalent to conventional covers with regard to reduction in percolation and for erosion protection (Albright et al. 2004;

USEPA 1992). Lysimeters are built in the field to quantify percolation through the landfill cover. Nests of sensors that measure soil suction and volumetric water content are installed along the depth of the proposed alternative earthen cover to monitor changes in the soil water storage and meteorological data is collected to assess and model the long-term percolation from earthen covers before they are permitted (Mijares 2011). Several field-scale demonstration projects have been carried out across the United States to assess the performance of earthen covers for a wide range of geo-climatic conditions.

Albright et al. (2004) carried out a majority of the field demonstration projects under the Alternative Cover Assessment Program (ACAP) of the USEPA. Field data from such demonstration projects is collected over a period of only few years. However, if the earthen cover is permitted for permanent use at the site, it is required that it perform satisfactory beyond the landfill's 30-year post-closure monitoring period. Montgomery and Parsons (1989), Benson and Khire (1995), and Khire et al. (1997) presented field data on macropore flow through earthen landfill cover. More detailed literature review on macropore flow through earthen covers is presented in Section 2.3.

2.2 Preferential Flow

Preferential flow includes funnel flow, finger flow, and macropore flow where water flows in paths bypassing other capillary fraction of the soil matrix (Gerke, 2006). The funnel flow is lateral redirection of infiltrating water and funneling because of the presents of textural boundaries in soil where water flows through least resistance and bypasses the less permeable

zones (Kung 1990, Gerke 2006). Finger flow results due to spatial heterogeneity in soil moisture content or air entrapment that causes instability in the wetting front leading to the formation of thin finger-like flow patterns (Hardie et al. 2011, Glass et al. 1988). Water bypass through relatively large continuous opening (macropores) in the field such as desiccation cracks due to drying and wetting, cracks due to freezing and thawing, vegetation root penetrations, inter-clod voids, rodent holes, and worm holes is called as macropore flow. Among these three kinds of preferential flow, macropore flow in the storage layer is the key concern related to performance of engineered earthen landfill covers because macropore flow could significantly increase percolation into the underlying waste (Song and Yanful 2010).

Beven and Germann (1982) presented an overview of the relevant processes and conditions that cause the macropore flow in soils. Initiation and maintenance of macropore flow in the macropore system require a supply of water exceeding all losses to the soil matrix (Beven and Germann 1982). This most commonly occurs at soil surface when rainfall intensity exceeds infiltration capacity (Beven and Germann 1982). Macropore flow reduces the surface runoff and increases total infiltration (Workman and Skaggs, 1990). Interaction between the domains, the macropore and the matrix, depends on the supply of water within the macropores and the hydraulic conditions within the soil matrix (Beven and Germann 1982). Voids of “equivalent cylindrical diameter” larger than about 0.3 - 0.5 mm are considered as macropores (Jarvis 2007).

Daniel (1984) reported 5 to 10,000 times higher k_{sat} in the field than measured in the laboratory for compacted fine grained soils. Larger clods size and hence the larger inter-clod voids in field results in higher saturated hydraulic conductivity in the field. Benson and Daniel (1990) studied the influence of clods on hydraulic conductivity of compacted clay and found that

the clod size had large influence on the k_{sat} of compacted clay, especially when compacted dry of optimum. Lower dry unit weight is associated with soils having large inter-clod voids. Soils that do not have larger inter-clod voids have higher dry unit weight (Benson and Daniel 1990). Benson and Daniel (1990) reported compacted samples with relatively large clods have up to six orders of magnitude higher k_{sat} compared to the compacted samples that contain smaller size inter-clod voids. Phifer et al. (1994) and Albrecht and Benson (2001) presented laboratory test results that demonstrate an increase in k_{sat} of compacted clay samples when subjected to wet-dry cycles. Kim and Daniel (1992), Othman and Benson (1994), and Benson and Othman (1993) showed changes in hydraulic conductivity of compacted clay due to freeze-thaw cycles.

2.3 Field Studies on Macropore Flow through Earthen Landfill Covers

Montgomery and Parsons (1989) presented three years of data of two compacted clay covers of field test section located near Milwaukee, WI (US) that had same clay layer thickness (1.22 m, CL USGS) and different topsoil thicknesses (0.15 m or 0.46 m). The shrinkage limit of the clay soil was in between 10 to 12. The percolation was relatively high during the 2nd and 3rd year compared to the 1st year. They noticed formation of cracks after the drought season. Observations from test pits excavated after two years showed occasional crack size from 6 to 12 mm wide and 1.3 to 1.4 m deep from the surface, and continuous root penetration up to 0.7 m. Moreover, they found root penetration along the crack plane up to 1.2 m from the surface. Montgomery and Parsons (1989) concluded that the increase in percolation is due to the formation of macropores and the thickness of the topsoil layer did not affect the percolation rate.

Melchior (1997) monitored two compacted clay covers at a site near Hamburg, Germany, for 8 years. Both the test sections had identical profiles, 0.6 m thick clay layer overlain by 0.25 m sand drainage layer and 0.75 cm surface layer, and different slopes, 4% and 20%. A 10 m × 50 m lysimeter was used to measure percolation. The measured percolation for the first year was between 1.9 – 8.4 mm and the percolation increased to between 150 – 201 mm during the 8th year. Observations from test pits excavated 7 years after the construction showed that the clay layer was cracked and invaded with plant roots through the entire depth. Tracer test carried out by Melchior (1997) confirmed the preferential flow paths.

Khire et al. (1997) published data for two field test sections of compacted clay covers one in Atlanta (humid climate) and another one in East Wenatchee, Washington (semi-arid climate). The test sections were 30×30 m² in areal extent and 12.2 ×18.3 m² pan-type lysimeter was used to measure the water balance. The test sections consists of 0.9 m of compacted clay (ML-CL USCS) overlain by 0.15 m thick topsoil at site in Atlanta and 0.6 m of compacted clay (MH USCS) overlain by 0.15 m thick topsoil at the site in Wenatchee. The measured annual percolation at Wenatchee was about 7.5 mm during the 1st year and it increased to about 22 mm during the 3rd year. During the 3rd year, the measured cumulative percolation showed step like increase. Test pit excavated within the test sections showed cracks at the Wenatchee site and no sign of cracks at Atlanta site. Also, they observed breakthrough while the water content at the deepest water content sensor remained relatively low and constant. Hence, Khire et al. (1997) concluded that the percolation measured at Wenatchee was possibly influenced by macropore flow.

Albright et al. (2006a) studied the field performance of a compacted clay landfill cover located in Albany, Georgia (humid climate) for 4 years. A $10 \times 20 \text{ m}^2$ pan-type instrumented lysimeter was used to measure the water balance. The test section consisted of 0.45 m of compacted clay (SC USCS) overlain by 0.15 m of uncompacted clay (SC USCS). They observed increase in percolation about eight months after the construction following a 7-week drought. Measured cumulative percolation during the first seven months of the year was 44 mm and the measured cumulative percolation increased to 230 mm during the next five months. They noticed desiccation cracks at the end of drought season. Also, the pattern of percolation changed from steady and relatively independent of timing of precipitation before the drought to rapid and closely related to timing of precipitation events after the drought. Moreover the hydraulic conductivity from laboratory tests, field tests, and from percolation measurements before and after the drought showed an increase by about three orders of magnitude over the service life of the cover. Dye tracer test and soil structure analysis confirmed the presence of the cracks. They concluded that the formation of macropores due to desiccation or freeze-thaw cycling resulted in the preferential flow.

2.4 Macropore Flow Models

Water balance models which can simulate macropore flow fall under two categories: dual-permeability/porosity models and two-domain models. The dual permeability/porosity models use the Richards' equation for the macropore region. HYDRUS-1D is one of the dual permeability/porosity models (Simunek et al. 1998, 2008; Simunek and van Genuchten 2008). One of the limitations of the dual permeability models is that the models simulate upward flow in

the macropores during evapotranspiration (Kohne et al. 2009). On the other hand, two-domain models implement gravity flow in macropore flow and Richard's equation for micropore flow. RZWQM is a two-domain water balance model developed by Agricultural Research Service (ARS), United States Department of Agriculture (USDA) (Ahuja et al. 1995). A detailed literature review of RZWQM is presented in Section 2.5.

A relatively new numerical technique used to model fluid flow through macropores in two or three dimensional is LBM. The LBM was studied and validated to measure the saturated hydraulic conductivity of porous media by many researchers (Succi et al. 1989, Kutay et al. 2006, Sukop et al. 2013). Also, LBM is capable of simulating interfaces between fluids without the need of interface tracking (Sukop and Or 2004). Three approaches are at the research level for multiphase LBM (Sukop and Or 2004). Gunstensen et al. (1991) presented a multiphase model where two immiscible fluids were given different colors (red and blue) and the collision rules were modified to obtain the surface tension between two fluids. Shan and Chen (1993) proposed a multiphase and multicomponent model which applies interactions similar to van der Waals attractions between fluid particles. Another approach called "Free energy" was presented by Swift et al. (1996). However, the free energy approach has been criticized as a "top-down" approach where macroscopic properties such as the surface tension are supplied directly to the model (Chin et al. 2002, Sukop and Or 2004). A detailed literature review on LBM is presented in Section 2.6.

2.5 Root Zone Water Quality Model

The USDA-Agricultural Research Services developed RZWQM that includes a macropore flow model along with a water balance model (DeCoursey and Rojas, 1990). Ahuja et al. (1993) carried out numerical analysis on the influence of macropore flow and chemical transport by systematically changing the rainfall sequence, macropore radius, and initial soil water content, and using three chemicals for a constant macroporosity. They considered a 1.5 m deep soil profile of a silty clay loam. They found that the macropore size (diameter 2 mm vs. 0.25 mm) has only a small effect for a fixed macropore volume fraction (0.05%), hence one needs to only know the overall maximum macropore flow rate than the macropore size distribution in order to characterize the field macropore flow. However, Ahuja et al. (1993) did not compare the model results with field or lab data. Ahuja et al. (1995) evaluated and refined the macropore component using a column experiment (15 cm diameter and 30 cm long) with a 3 mm diameter artificial vertical hole.

Kumar et al. (1998) carried out field evaluation of macropore flow component RZWQM using data collected for three years from subsurface drains located at 1.2 m deep and 28.5 m apart in corn plots near Nashua, Iowa. They used the first year data to calibrate the model and the following two years data to validate the model. Saturated and unsaturated hydraulic properties were estimated using one of the approaches given in RZWQM. They interpreted the macroporosity from infiltration experiments. However, they calibrated the saturated hydraulic conductivity of surface layer and lateral saturated hydraulic conductivity using the data. Also, they assumed the diameter of the cylindrical macropore. They concluded that a single value of macroporosity for all years may not produce accurate results.

Malone et al. (2001, 2004) evaluated the macropore component of RZWQM for chemical transport using undisturbed block samples ($30 \times 30 \times 30 \text{ cm}^3$) and pan lysimeters ($61 \times 61 \text{ cm}^2$), respectively. They calibrated the soil parameters related to hydrology using all the measured data (eg. saturated hydraulic conductivity) and tested only the chemical sub-component of macropore flow. Malone et al. (2001) concluded that chemical transport through macropore flow was sensitive to effective macroporosity, macropore radius, and effective soil radius. Malone et al. (2004) concluded that the RZWQM can be used to simulate chemical (metribuzin) transport in the field when macropore flow and hydrology are accurately simulated.

2.6 Lattice Boltzmann Model

Succi et al. (1989) demonstrated the adherence of the LBM to Darcy's law for a complex 3D porous media. They used artificial porous media and imposed no-slip boundary condition for solids (impermeable solids). Cancelliere et al. (1990) compared the numerical (LBM) analysis of flow through artificial porous media developed using sphere solid shape with permeability theories. Their LBM implementation was similar to Succi et al. (1989). They concluded that at solid fractions less than 0.2, the simulated permeabilities match with the predictions of Brinkman's effective-medium theory, whereas at higher solid fractions, good match is achieved with Kozeny-Carman equation.

Shan and Chen (1993) presented LBM (herein called SC model), which has the capability of simulating multiphase and multicomponent immiscible fluids with constant temperature. Shan and Chen (1994) discussed the application of SC model to single component multiphase (SCMP)

fluid simulations. Martys and Chen (1996) studied the flow of a multicomponent fluid subject to gravitational and surface tension forces in complex 3D porous media using SC model.

Dardis and McCloskey (1998) and Freed (1998) independently proposed an alternative approach to model Darcy flow in LBM in which the permeability of the media is related to a momentum sink (damping). They found that assigning solid porosity parameter (n_s) at each node to represent the effect of structure on measured fluid flow is good enough to produce results that match well with predictions. This approach allows avoiding the requirement of a detailed micropore structure (geometry) when modeling flow through micropores.

Spaid and Phelan (1997) published a modification to standard LBM equivalent to solving a Brinkman formulation to simulate fluid flow through macropores and micropores. The Brinkman equation (Brinkman 1947) is a generalized Darcy's equation that allows the matching of boundary conditions at an interface between macropores and micropores (Martys 2001). Martys (2001) presented an improvement to the Brinkman equation approximation. The Brinkman's equation (Brinkman 1947) is as follows,

$$\nabla p = \mu_e \nabla^2 u - \frac{\mu}{K} u \quad \text{Eq. 1}$$

where P is the pressure; u is the velocity; K is the intrinsic permeability; and μ_e is an effective viscosity parameter (a parameter that allows for matching of the shear stress boundary condition across the free-fluid (macropore/porous medium interface). Since the hydraulic conductivity k is $k = K\gamma/\mu$, where γ is the unit weight, the equation Eq. 1 can be rewritten as follows,

$$\nabla p = \mu_e \nabla^2 u - \frac{\gamma}{k} u \quad \text{Eq. 2}$$

It should be noted that the first part in the right side of Eq. 1 is actually the Stokes' equation, which is solved by the LBM formulations, whereas the second part is the Darcy's equation. In macropore space, since k is infinite, second part goes zero and the Stokes' equation holds. Whereas in the permeable medium, since the velocity is small, the first part negligibly small value and second part dominates (Darcy's law). The second component can be implemented in LBM as a body force term (a_k) applied to the permeable solid regions that causes momentum sink as suggested by Martys (2001) (Eq. 3)

$$a_k = -\frac{\gamma}{\rho k}u = -\frac{g}{k}u \quad \text{Eq. 3}$$

where ρ is the density of the fluid; and g is the gravitational acceleration. This body force term is added to body force term in standard LBM. In addition to adding the body term, the relaxation time to be used in the permeable medium is modified as,

$$\tau_e = 3\frac{\mu_e}{\rho} + 0.5 \quad \text{Eq. 4}$$

where τ_e is the modified relaxation time assigned for lattice nodes in permeable medium.

Kutay et al. (2006) conducted saturated fluid flow in granular materials using 2D and 3D LBM. They used 3D geometries of compacted aggregates and asphalt specimens generated from X-ray Computed Tomography (CT) technique as input for the LBM. The compacted samples were 10 cm diameter and 13 cm height. They verified the accuracy of the LBM by comparing the results with analytical solutions of simple geometries and hydraulic conductivity measurements on the compacted aggregates and hot mix asphalt specimens. They concluded that the results of

LBM simulations were in excellent agreement with those obtained from analytical calculations and laboratory measurements.

Sukop and Or (2004) demonstrated the ability of SC single component multiphase model to simulate multiphase flow in slit and simple angular pores. Pan et al. (2004) studied the SC multicomponent model to simulate immiscible fluid flow through sphere packs. They found encouraging agreement as compared to experimental data for two-phase displacement process, where one fluid (non-wetting) enters the system and replaces the other fluid (wetting).

Korner et al. (2005) presented a multiphase LBM for free surface modeling. In this model, the density distribution function evolves only in the liquid region. That is the Boltzmann algorithm is applied only in the liquid region. Hence, capturing of the interface is necessary for the free surface model. Also, the free surface model cannot be used to study the liquid-liquid or liquid-vapor systems where the individual phases effect each other (Attar and Korner, 2009). The model is suitable only for those liquid-gas systems where the gas phase has negligible effect on liquid phase (Attar and Korner, 2009). The model requires keeping track of the mass exchange between cells. The interface advection is identified from the mass fraction variable that is updated by recording the inflow and outflow of mass using the distribution function. Also, this particular model requires an additional boundary condition at the interface cells because the distribution functions coming from gas cells after advection are unknown. Owing to the extreme complexity in the implementation of this approach, this model is not considered in this study.

Misici and Palpacelli (2005) studied the water percolation through coffee using multiphase LBM based on an innovative methodology that includes ‘color indices’ for different fluid phases. More detail on Misici and Palpacelli (2005) model is presented in Section 6.5. Huang and Lu

(2009) analyzed the relative permeability of heterogeneous porous media through numerical study using single component SC model.

Sukop et al. (2013) studied the saturated non-Darcy flow in macroporous limestone aquifer samples using 3D LBM. They used 3D images of limestone aquifer samples from X-ray CT as input for the LBM. The domain size of $9 \times 9 \times 9 \text{ cm}^3$ was chosen such that the irregular boundary of samples lies inside the domain. The simple no-slip wall boundary condition was used for solid rock boundaries. They observed reduction in the apparent hydraulic conductivity as the applied gradient increased to levels representative of those observed in the field due to non-Darcy flow. Newmen and Yin (2013) presented the effect of geometry on the flow transition (from Darcy flow to non-Darcy flow) using LBM. They used synthetic 2D porous media for their simulations. Again they used the no-slip boundary condition for the solids. They found that geometries that are microscopically heterogeneous experience early change from Darcy flow to non-Darcy flow systems due to the contrast in the size of pore bodies and the size of pore throats.

2.7 Synthesis of Previous Work and Motivation for Current Study

The field data presented by Montgomery and Parsons (1989), Melchior (1997), Khire et al. (1997), and Albright et al. (2006) suggest that macropore flow influences percolation in earthen landfill covers during service. However, a systematic quantitative evaluation of macropore flow through earthen landfill cover needs to be carried out. Also, there is a lack of published work on modeling the macropore flow through earthen landfill covers. Khire et al. (1997) and Khire and Saravanathiiban (2013) used UNSAT-H to predict percolation through earthen landfill covers

that had macropores. However, they pointed out that the model does not simulate flow through macropores and hence underestimates percolation. Hence, there is a need to develop model capable of simulating flow through micropore as well as macropore to design earthen landfill cover that meet long-term performance criteria.

The two-domain model RZWQM is capable of simulating gravity flow through cylindrical macropores. Ahuja et al. (1993) carried out numerical analysis using macropore flow component of RZWQM. Ahuja et al. (1995), Kumar et al. (1998), Malone et al. (2001), and Malone et al. (2004) conducted laboratory or field evaluation of the macropore component of RZWQM. However, previous studies on validation of macropore flow module of RWQM have primarily concentrated on chemical transport. The hydraulic properties of soils were not measured. The hydraulic properties of soils were calibrated based on model predictions. There is no published study that validates RZWQM for water balance of engineered earthen landfill covers. Hence, validation of RZWQM for water balance modeling of engineered earthen landfill cover and macropore flow module of the model using field measured data is required.

LBM for fluid flow through porous media has been validated by researchers (Succi et al. 1989, Cancelliere et al. (1990), Kutay et al. 2006, and Sukop et al. 2013). However, published work on flow through macropores of porous media using LBM is limited to impermeable solids. Although permeable solids (micropores) algorithms are published, an extended work on porous media with micropore flow (i.e., flow through the ‘solid’ areas) and macropore flow has not been done. The major reason for the lack of interest in permeable solids is probably the fact that flow through micropores is negligibly small during saturated flow as compared to the flow through macropores. However, micropore flow may dominate during unsaturated flow through soils.

Hence a comprehensive physically based model to simulate flow through micropore and macropore and a systematic analysis is the first step towards modeling unsaturated flow through soils that has macropores.

CHAPTER 3: FIELD OBSERVATION OF MACROPORE FLOW

3.1 Field-Scale Test Section

A compacted clay final cover test section with instrumentation was constructed in late October 2009 at a MSW landfill located in Detroit, Michigan (Mijares 2011). The climate at the site is classified as sub-humid and the average annual precipitation is approximately 83 cm (32 in). The annual potential evapotranspiration (PET) to precipitation ratio is about 1.3. A typical cross section passing through the test section is shown in Figure 3.1. Percolation through the test section was measured using a pan lysimeter. The lysimeter consisted of a trapezoidal excavation of the test section having areal dimensions of about 8.5 m x 8.5 m and 0.6 m deep. The lower boundary of the lysimeter was impermeable (Mijares et al. 2012). The lysimeter was filled with clean pea gravel. The hydraulic conductivity of the pea gravel was equal to 1 cm/s.

The upper boundary of the gravel layer was vented to the atmosphere using a perforated HDPE pipe to maintain atmospheric pressure on the lysimeter. The storage layer of the test section was constructed using a 1.5 m thick native glacial till (clay) which was overlain by a 0.3 m thick topsoil layer. The liquid limit (LL) and the plasticity index (PI) of the clay are 29 and 13, respectively. The shrinkage limit (SL) of the clay as predicted using the LL and the PI based on a procedure presented in Holtz and Kovacs (2010) is 13.25. Percentage of fines in the clay soil is about 78%. The clay soil and topsoil were classified as CL and ML, respectively according to the Unified Soil Classification System (USCS). The optimum water content and maximum dry unit weight of the clay for Standard Proctor (SP) effort was 13.4% and 18.5 kN/m³, respectively. The

clay was compacted at 4% dry of optimum water content in 30 cm thick lifts using a sheepfoot compactor. The average dry unit weight was about 98% of the maximum dry unit weight.

Water content reflectometer (WCR) (Model: CS616, Manufacturer: Campbell Scientific, Inc.) and heat dissipation-based matric potential (HDMP) sensors (Model: CS431, Manufacturer: Campbell Scientific, Inc.) were installed at six vertical locations in three nests within the test section to measure the volumetric water content (VWC) and matric suction, respectively. A detailed temperature depended calibration was carried out to develop the calibration curve for WCRs. The ground freeze and thaw was monitored using a thermistor sensor inserted into the topsoil about 10 cm below the ground surface. Pressure transducers (Model CS431) having measurement range of 0 to 90 cm with 0.1% accuracy were used to monitor the level of water in the lysimeter to measure percolation. Calibration curves were developed to estimate the volume of water collected in the lysimeter and to estimate percolation from the measured water level in the lysimeter (Mijares 2011). The site had a weather station to record air temperature, precipitation, solar radiation, barometric pressure, and relative humidity.

The saturated hydraulic conductivity of the storage layer was measured immediately after the construction of the compacted clay test section, that is before the test section experience any wet-dry cycles, using a 1 m by 1 m single-ring infiltrometer (ASTM 2010b, Guyonnet et al. 2000) and the average value of the saturated hydraulic conductivity was 4.4×10^{-6} cm/s (Mijares et al. 2012). More details pertaining to the field test section and instrumentation can be found in Mijares (2011).

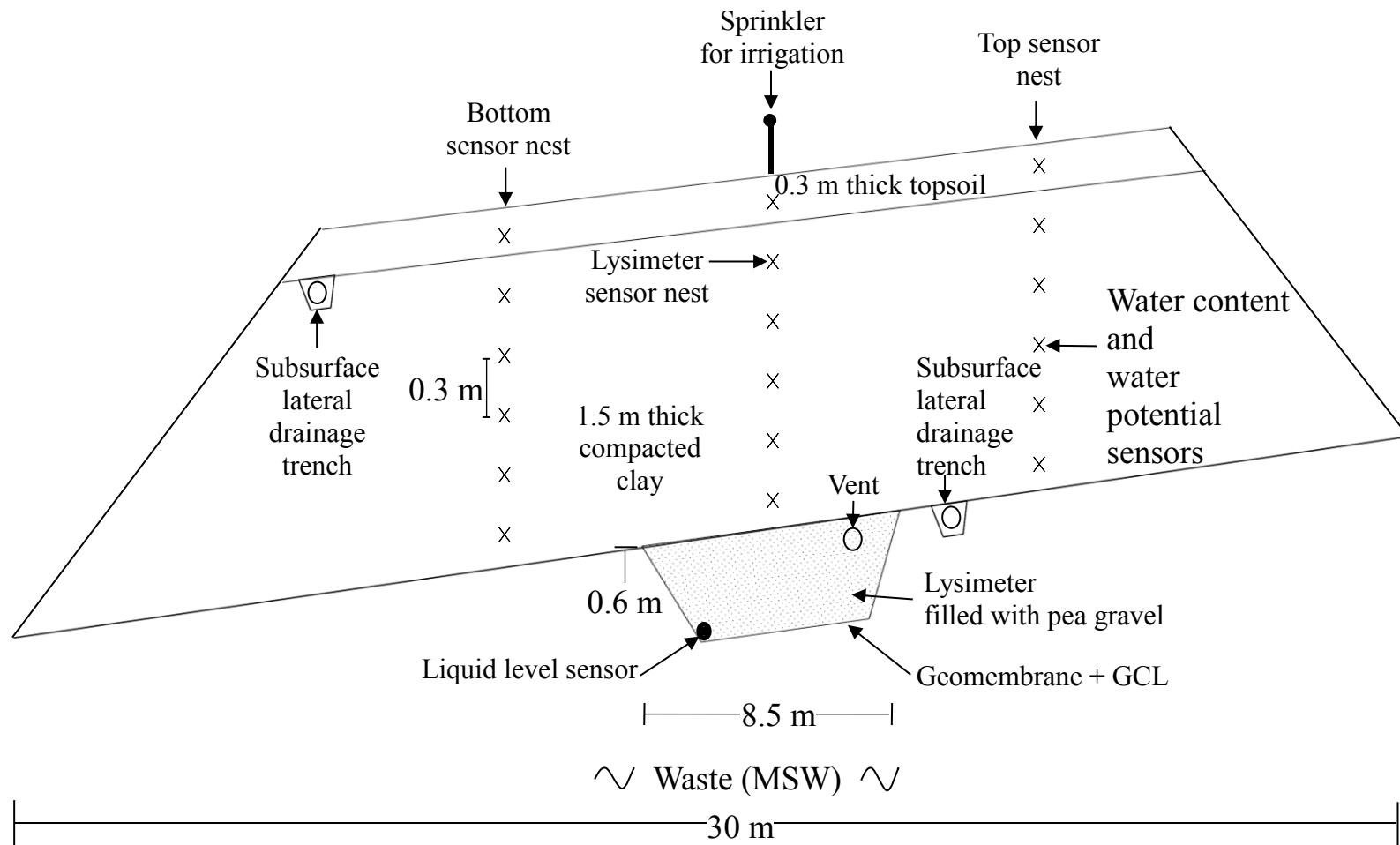


Figure 3.1: Cross section of the compacted clay field test section (not to scale)

3.2 Temperature Specific Calibration of Water Content Sensors

Time domain reflectometry (TDR) is the most common method used for measuring in situ VWC non-destructively (Benson and Wang, 2006). However, conventional TDR (GHz frequency) can be expensive due to required specialized electronic interfaces or multiplexers (Udawatta and Anderson, 2011; Benson and Wang, 2006). Newer TDR system such as water content reflectometer (WCR) includes all of the electronics in the head of the probe and hence easy to use compared to conventional GHz frequency TDR. However, the WCR operates at lower frequency (MHz range) that makes the water content measurement more sensitive to factors like soil type or clay content, temperature, and soil electrical conductivity (Benson and Wang, 2006). Also, the dielectric permittivity, which is used as an indirect measurement of soil water content, varies with the temperature (Udawatta and Anderson, 2011). Hence, a detailed soil, compaction, and temperature specific calibration was carried out for the WCRs to measure in situ water content.

Figure 3.2 shows a photograph of a CS616 WCR. The WCR consists of two metallic rods, each 30 cm long and 0.32 cm diameter with 3.2 cm spacing, connected to a probe head. Voltage pulse is generated inside the probe head and propagates along the rods. The pulse travels back to the probe head once it is reflected at the end of the rod and triggers the next pulse. The travel time varies depending on dielectric permittivity of the soil in which the rods are inserted. The data logger records the reflection as period after the reflections are divided by a scaling factor (Udawatta and Anderson, 2011; Benson and Wang, 2006). With a proper calibration equation, the measured period in microseconds is calibrated to read volumetric water content.

Soil samples collected from the field were compacted in a 5 gallon bucket with the dimension of 30 cm diameter and 36 cm height. In order to saturate the sample from bottom up, geocomposite (geotextile and geonet) was placed at the bottom of the bucket and connected to two tygon tubes along two diametrically opposite edges of the geonet. Field compaction criteria were used to compact the soil in 5 gallons bucket. For the storage layer clay soil, sample was compacted in five lifts. Each lift was about 6.6 cm thick. Achieved dry density and molding water content were 18.05 kN/m^3 and 9.4%, respectively. Density of the field topsoil was measured using Shelby tube samples collected from the field test section and the average dry density was 14.45 kN/m^3 . Topsoil sample was compacted in two lifts. Sample was gradually saturated and the weight of the sample was recorded continuously. The topsoil reached about 95% saturation and the clay soil reached about 93% saturation. Once the sample was as saturated as it can be, a WCR and a CS 650 sensor, about 10 cm apart, were inserted in the soil vertically. The CS 650 was used to record soil temperature. The TDRs were connected to data logger. The sample was sealed and placed in an environmental chamber. The sample in the environmental chamber with TDRs connected to the data logger is shown in Figure 3.3. Initially the chamber was set to room temperature, and WCR period and temperature of the sample was monitored. Once the period and temperature reached steady state, the water content of the sample, period, and temperature were recorded. Then the chamber temperature was changed by $\pm 10^\circ\text{C}$. The temperature was varied from 5°C to 35°C and at each temperature the period was recorded at steady state. Then the sample was dried to next target water content. Target water contents were set in an interval of 0.05 VWC. WCR periods were recorded with varied temperature at each target water contents.

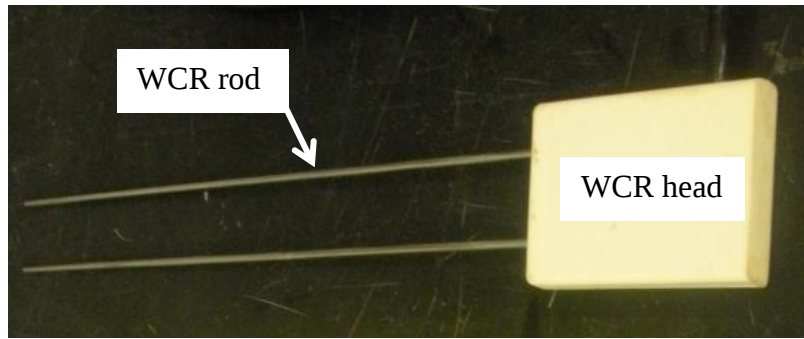


Figure 3.2: Photograph of WCR



Figure 3.3: Drying of compacted soil sample in a temperature chamber for WCR calibration.

Variation of WCR period with temperature for constant water contents are shown in Figure 3.4. The period changes linearly with temperature. Clay (Figure 3.4a) shows slightly more sensitivity to temperature compared to topsoil (Figure 3.4b). At saturated water content, the period of topsoil increased from 31.94 μs at 5°C to 36.13 μs at 36°C whereas, the period of clay increased from 32.07 μs at 5°C to 37.14 μs at 34°C. Clay content of the soil influences the sensitivity of WCR to temperature. Figure 3.5 shows the surfaces fitted to the calibration data. Topsoil data was fitted using a 3rd order polynomial equation (Figure 3.5(a)) and the clay was fitted using a 2nd order polynomial equation (Figure 3.5b). The calibration equations are as follows:

Topsoil:

$$\begin{aligned} \text{VWC}(T, \tau) = & -2.56 - 5.4e^{-3}T + 0.26\tau - 1.6e^{-4}T^2 + 6.7e^{-4}T\tau - 8.5e^{-3}\tau^2 + 2.5e^{-7}T^3 + 5.8e^{-6}T^2\tau \\ & - 1.98e^{-5}T\tau^2 + 1.0e^{-4}\tau^3 \end{aligned} \quad \text{Eq. 3.1}$$

Where, T is the soil temperature; and τ is the period in μs .

Clay (storage layer):

$$\text{VWC}(T, \tau) = 0.333 - 0.042\tau + 0.0013\tau^2 + 0.01T - 5.6e^{-4}T\tau + 5.9e^{-5}T^2 \quad \text{Eq. 3.2}$$

Eq. 3.3 presents calibration equation for the clay without the effect of temperature (Mijares 2011),

$$\text{VWC}(\tau) = -0.615 + 0.0689\tau - 0.00255\tau^2 + 3.86e^{-5}\tau^3 \quad \text{Eq.3.3}$$

Calibration equations were used to measure VWC of the field test section from measured WCR periods. Figure 3.6 presents the VWC measured using WCR at 45 cm depth of lysimeter

nest using soil specific calibration equation (Eq. 3.3), and soil and temperature specific calibration equation (Eq. 3.2) along with the temperature measured using a co-located HDMP sensor. During winter when the temperature goes below 10°C, water content is underestimated by about 40% to 50% and during the summer when temperature goes above 23°C, water content is overestimated by about 10% if temperature specific calibration is ignored (Eq. 3.3). The water content measurement is not impacted by temperature when the temperature is around 20°C.

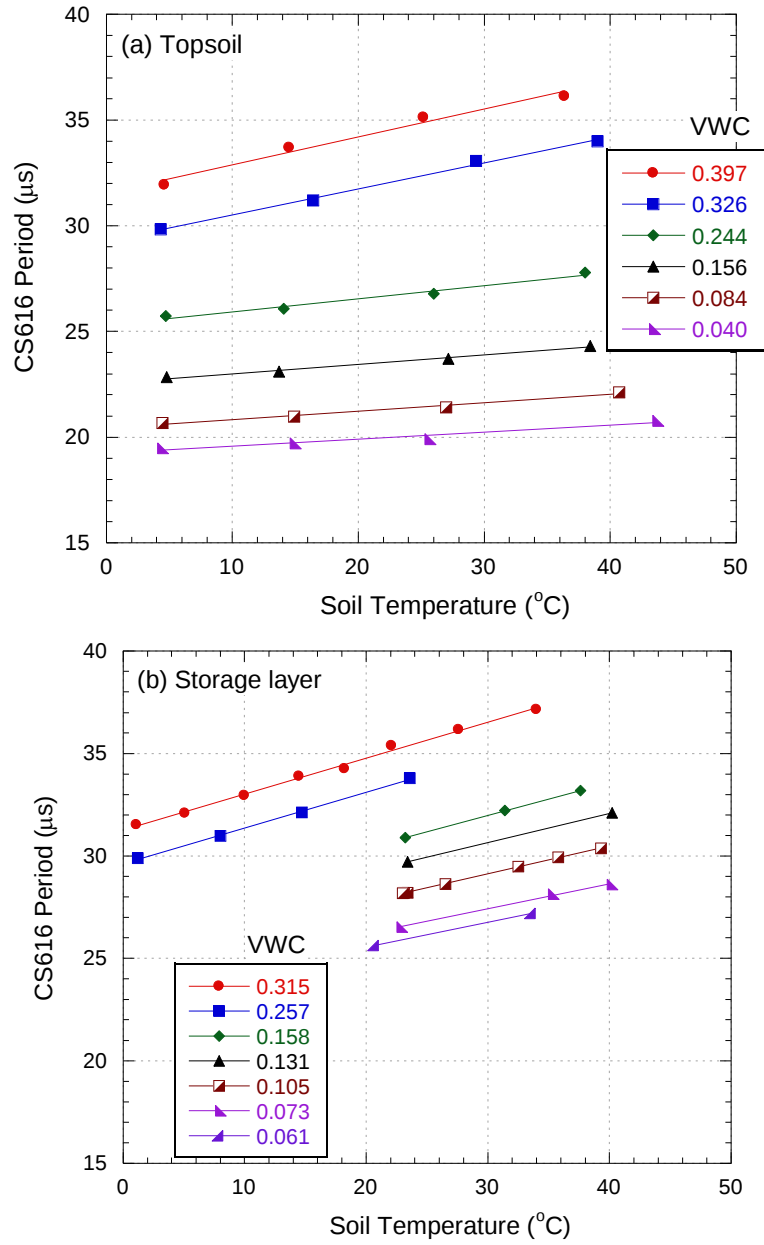


Figure 3.4: Variation of WCR period with soil temperature and VWC: Topsoil (a); and Storage layer (b).

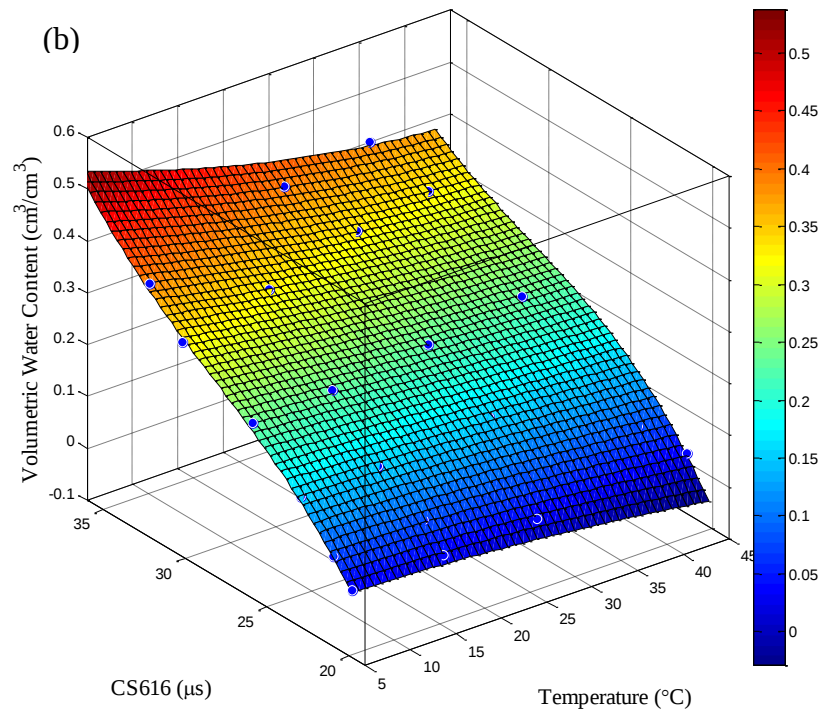
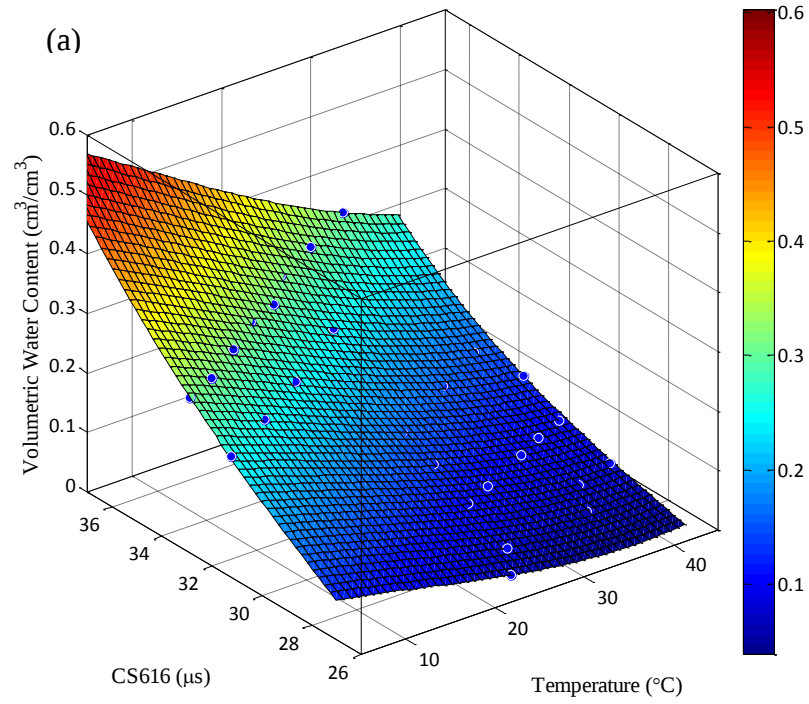


Figure 3.5: VWC versus WCR period and soil temperature for storage layer (a), and topsoil (b).

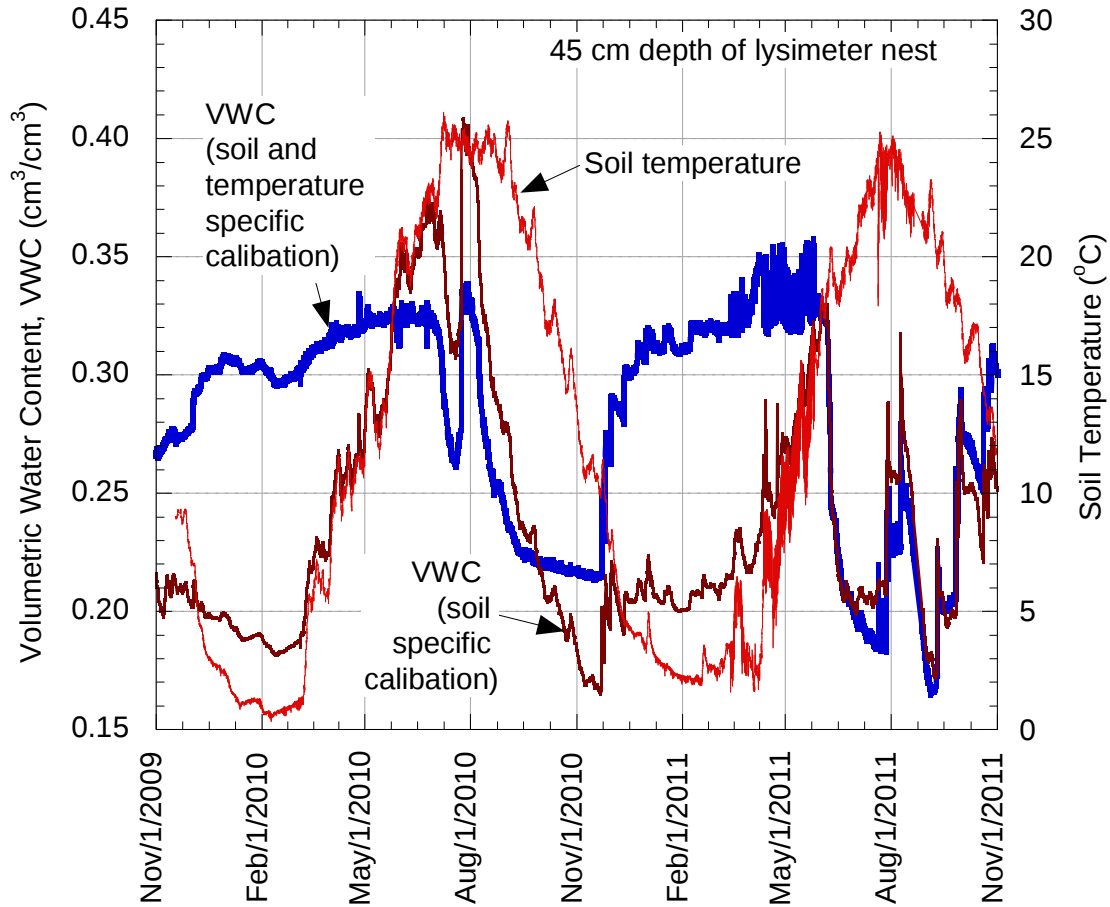


Figure 3.6: Comparison of measured VWC with and without temperature specific calibration of WCR.

3.3 Field versus Laboratory Measured k_{sat}

k_{sat} was measured using the falling head and rising tail flexible wall permeameter test (ASTM 2010a). The soil was prepared by passing through size 4.8 mm (No. 4) sieve. The sample was compacted at Standard Proctor effort in 10.2 cm diameter and 11.6 cm tall compaction mold according to ASTM (2007). However, an additional 5 blows per lift were required (i.e., 30 blows

per lift) to achieve the field dry unit weight. The achieved dry unit weight of the compacted sample was 17.9 kN/m^3 . The compacted sample is shown in Figure 3.7a and the sample during flexible wall test is shown in Figure 3.7b. Confining pressure of 68.8 kPa was applied during the flexible wall tests. The influent and effluent pressures were maintained at 55.0 kPa and 13.8 kPa, respectively. The test was continued for about a week until the ratio between inflow and outflow reached unity and the measured k_{sat} reached a steady-state.

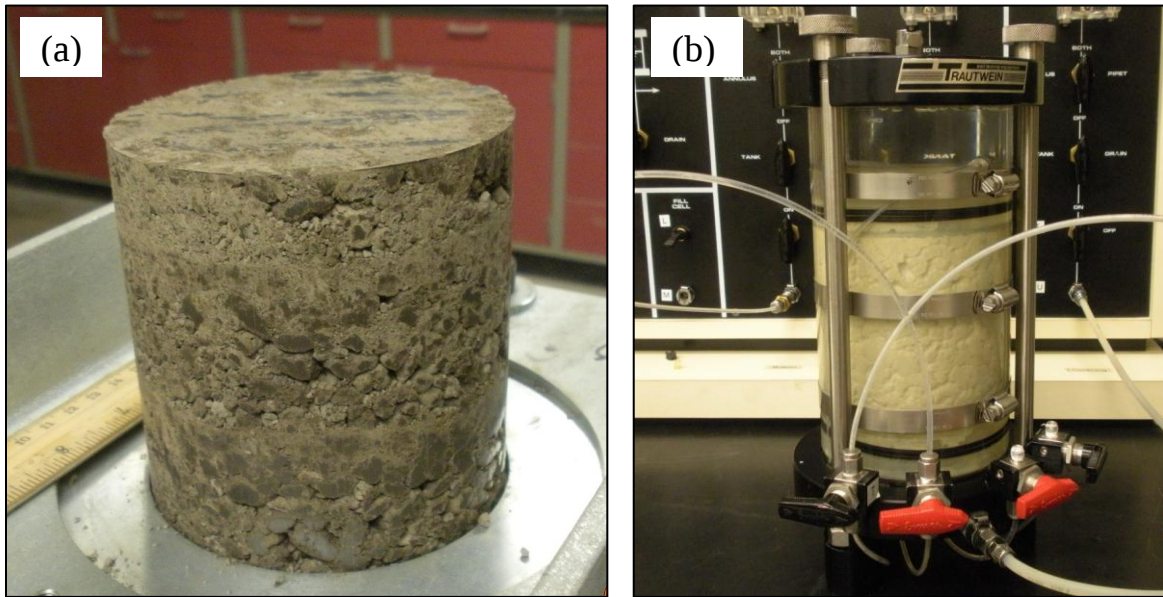


Figure 3.7: Compacted clay sample (a); and flexible wall permeameter (b).

The laboratory measured k_{sat} was $6.6 \times 10^{-8} \text{ cm/s}$. The field k_{sat} measured using single-ring infiltrometer immediately after the test section construction was $4.4 \times 10^{-6} \text{ cm/s}$ (Mijares et al. 2012) which is one order in magnitude greater compared to the k_{sat} measured using the flexible wall permeameter. The effect of clod size was not well captured in the lab-scale test is most likely the reason for this difference (Benson and Daniel 1990). In addition, the influence of

higher effective stress in the lab versus what the soil experienced in the field may be another reason for lower k_{sat} measured by flexible wall permeameter (Trast and Benson 1995).

3.4 Soil Water Storage (SWS)

SWSs of the storage layer were calculated by integrating the water contents measured at three sensor nest locations using WCRs (using temperature specific calibration equation). The SWSs for the top nest, lysimeter nest, and bottom nest are presented in Figure 3.8. Also, degree of saturation (S) of the storage layer is presented on the right vertical axis of Figure 3.8. The peak S (field saturation) for the bottom, the lysimeter, and the top nests were about 90%, 88%, and 82%, respectively. The SWS of the bottom nest is always higher than the other two nests due to lateral flow. However, lysimeter nest shows more drying than top nest during dry season. The percolation collected in lysimeter is removed from the system in addition to evapotranspiration. On the other hand, for the top nest and the bottom nest percolation entered into the waste can be pulled back into the storage layer during drying. Hence, the top nest holds more water than the lysimeter nest. The influence of bottom boundary on water balance of earthen cover is presented in Mijares and Khire (2012).

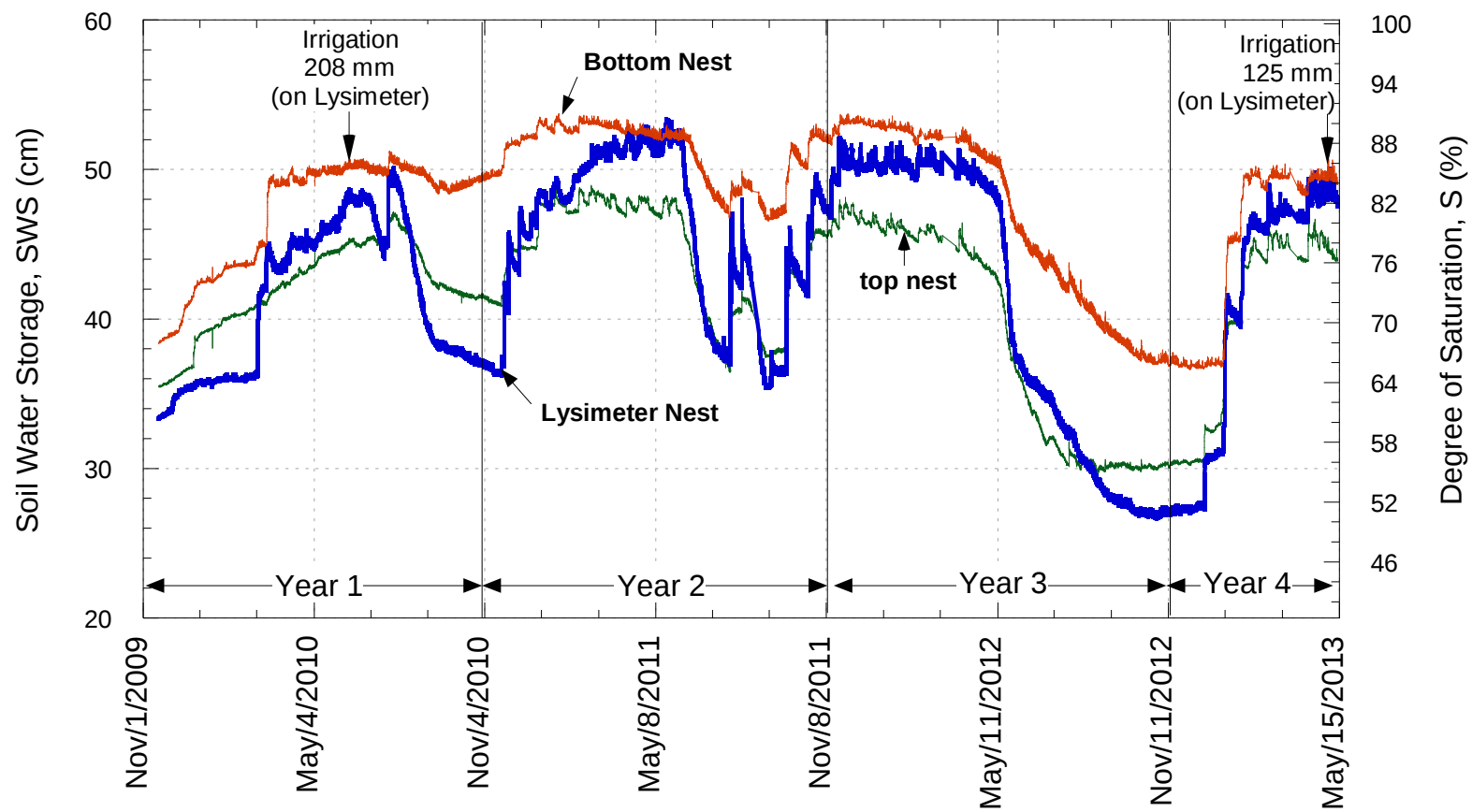


Figure 3.8: Soil water storage of storage layer

Compared to the first year, during the second and the third years, higher SWSs were noticed in all three nests. Increase in precipitation during the second year could be the reason for the increase in the SWSs for the second year. Precipitation recorded during the second year was 1,104 mm and it represents a relatively wet year with 98 percentile precipitation. However, unlike the SWSs of the lysimeter and the top nests, SWS of the bottom nest showed relatively steady value for long duration during the first year indicating field saturation. And, during the second year the SWS of the bottom nest further increased and stayed steady. The sudden increase in SWS of the bottom nest during the second year could be because of the formation of macropores due to wet-dry cycles or animal activity. Macropore flow increases infiltration and decreases the surface runoff which leads to higher SWS (Workman and Skaggs 1990). Because the SWSs of the top and the lysimeter nests did not show the indication of field saturation during the first year, the increase in SWSs during the second and the third year cannot be regarded as the influence of macropore flow based on the SWSs alone. Also, water content measurements are point measurements which do not capture the flow in between sensors. Unless macropore penetrate through the WCR rods, the WCRs will not capture the rapid macropore flow. Hence, SWS alone cannot be used to identify the presence of macropore flow in landfill earthen covers.

3.5 Percolation

Measured percolation from the lysimeter and recorded precipitation are presented in Figure 3.9. Precipitation recorded at the site did not include snow because the tipping bucket at the site did not have heater to melt the snow. Hence, precipitation recorded by National Oceanic and Atmospheric Administration (NOAA) weather station located within 5 km of the site is plotted in

Figure 3.9 for comparison. Recorded precipitation at the site underestimates the precipitation by about 8% to 18%. During the first year, precipitation was about 792 mm, while cumulative percolation was 7 mm. During the second year, the precipitation was 1,104 mm, while cumulative percolation was about 75 mm. And, during the third year, the precipitation was 828 mm, while percolation was about 136 mm. The reason for about an order increase in percolation during the second year compared to the first year is partly due to record high precipitation during the second year. Annual precipitation of the NOAA weather station during the last 50 years is presented in Figure 3.10(a) that showed the second year (2010) was the wettest year in the 50 year history. Precipitation received during the first year (2009) is equal to about 35 percentile. During the second year (2010), precipitation received at the site corresponds to about 98 percentile. Also, the precipitation received during winter and spring for the second year was 482 mm (44% of total precipitation) whereas the winter and spring precipitation for the 1st year was only 241 mm (30% of total precipitation). The solar radiation is lower during winter and spring season compare to summer which results in less evapotranspiration (ET). Recorded solar radiation and recorded average temperature at the site is presented in Figure 3.10(b). During winter solar radiation drops below 500 MJ/m²/day and during summer solar radiation is as high as 18,000 MJ/m²/day. Also, ET is limited by presence of snow (Albright et al. 2010, Apiwantragoon 2007). Moreover, presence of snow reduces surface runoff hence increases infiltration which results in higher percolation (Albright et al. 2010). In addition, snowmelts directly applied to the cover.

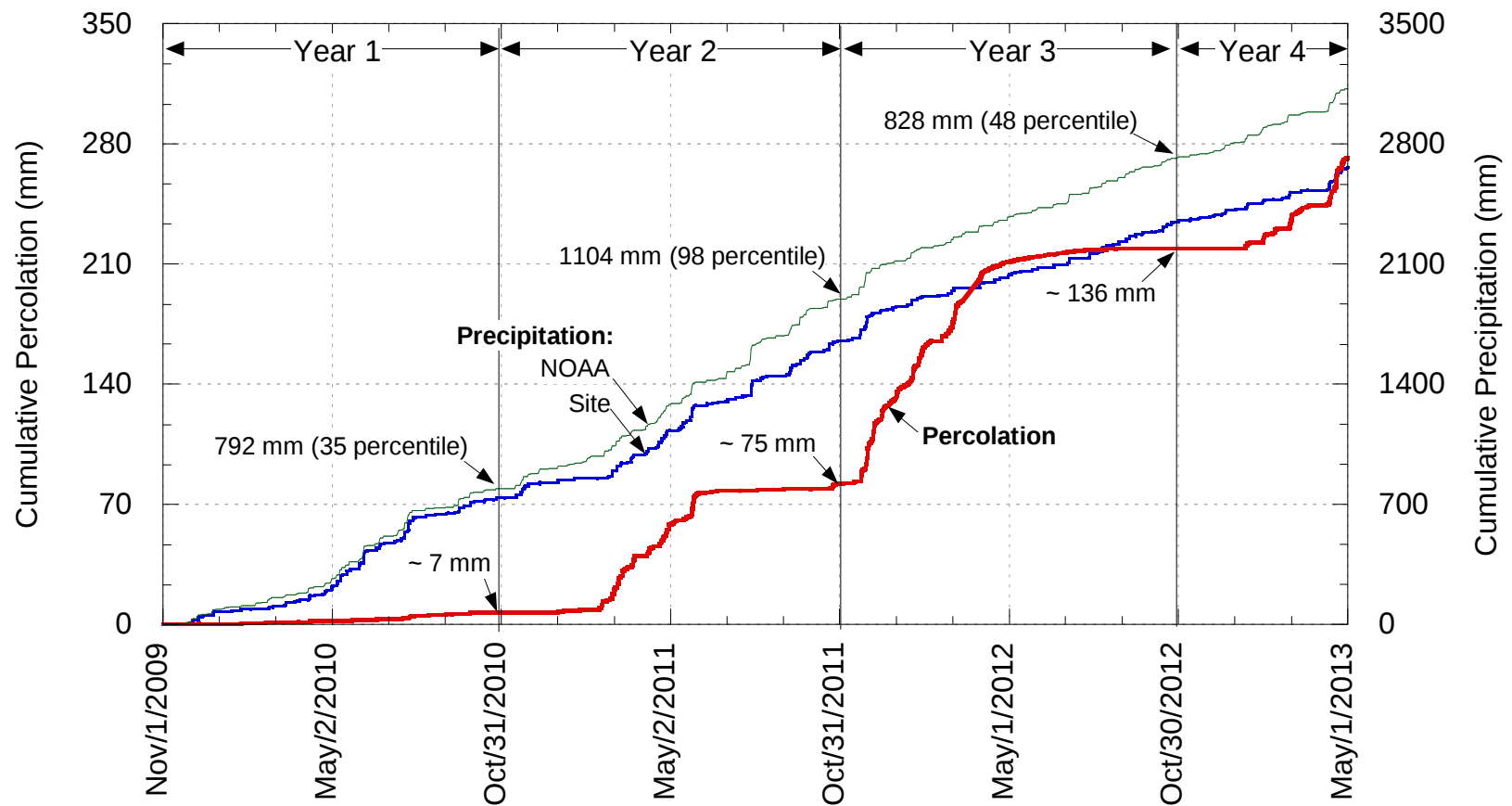


Figure 3.9: Measured percolation and precipitation recorded at site vs. data collected by NOAA weather station

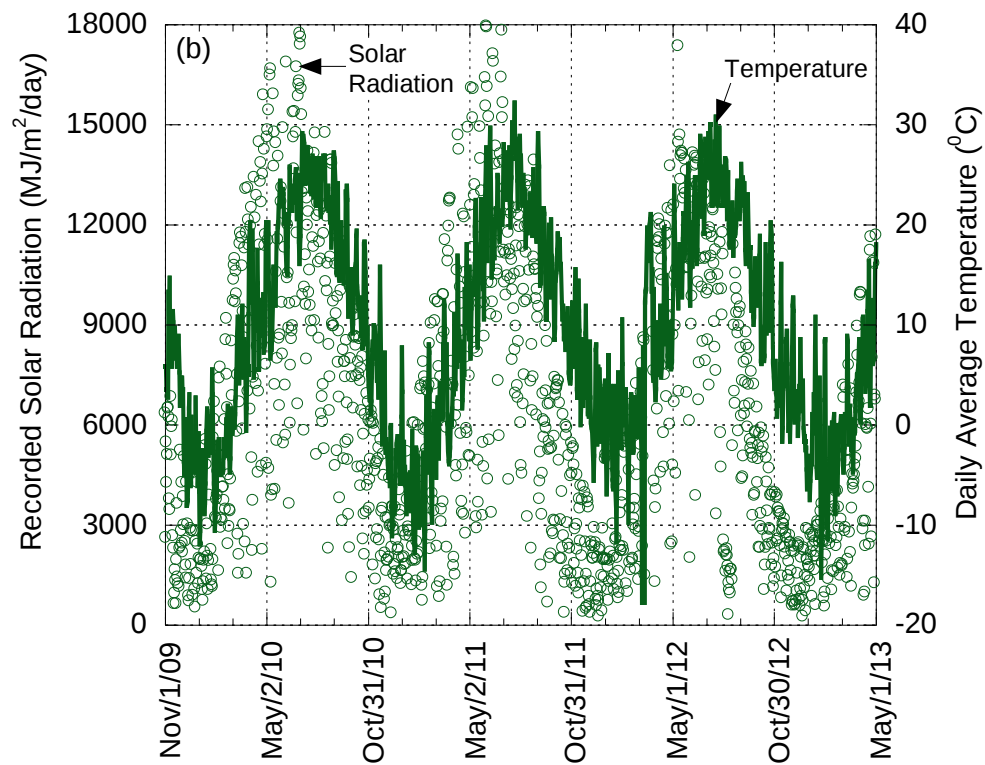
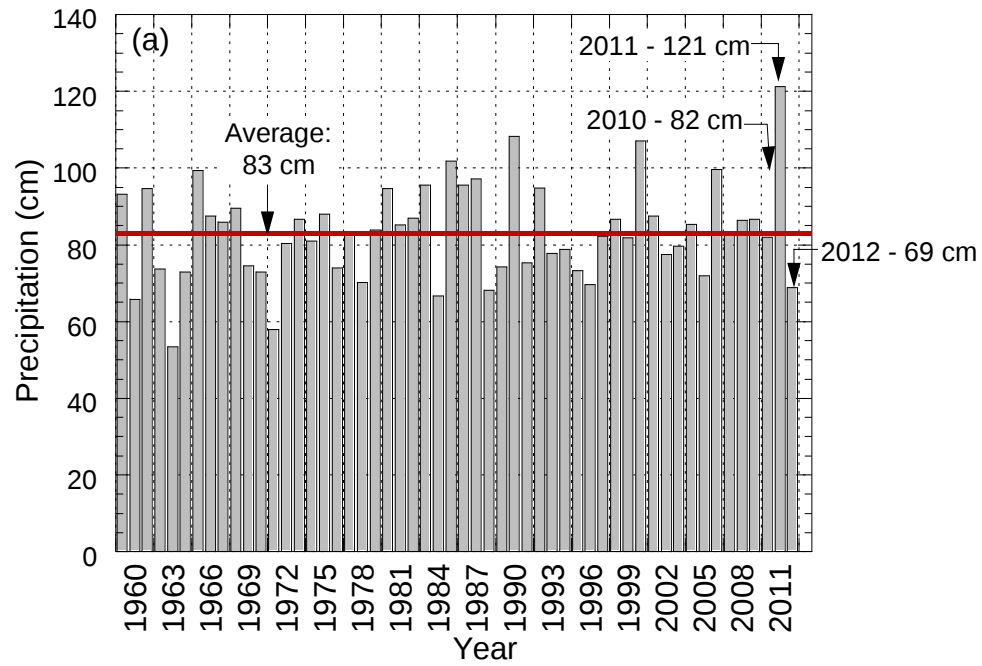


Figure 3.10: Historical precipitation (a); and recorded solar radiation and air temperature (b).

Measured cumulative percolation during the third year was about 20 times that of the first year and about two times that of the second year cumulative percolation. However, precipitation received during the third year was only 42 percentile and winter and spring precipitation was 480 mm (58% of total precipitation) which is about the same as the second year. The peak solar radiation during the third year was below 15,000 MJ/m²/day whereas peak solar radiation during the 1st and 3rd year was as high as 18,000 MJ/m²/day. Also, average solar radiation for the 3rd year was about 6,000 MJ/m²/day which is less than average solar radiation of 7,500 MJ/m²/day and 6,750 MJ/m²/day for the 1st and the 2nd year, respectively. Lower solar radiation in the 3rd year resulted in less ET in the 3rd year. Hence, compared to the 1st and the 2nd years, the test section was at field saturated condition (about 86%) for relatively longer period of time during winter and spring of the 3rd year (Figure 3.8). Hence, the increase in percolation during the third year could be partly because test section stayed close to saturation for a relative longer period of time.

Moreover, macropores such as shrinkage cracks and animal barrows were noticed on the surface of the test section during the second year and after. The PI and SL of the clay suggest medium level of susceptibility for desiccation cracking (Holtz and Kovacs 2010). These macropores might have contributed to higher percolation observed in the 2nd and the 3rd years in addition to the reasons discussed previously. Gradual slope of the percolation vs. time plot is typical of micropore flow. Whereas, sharp increase in the rate of flow is indicative of macropore flow (Khire et al. 1997). Hence, cumulative percolation plot indicated the presence of macropore flow better than the SWS of the test section. However, only the use of this data (increase in total precipitation, winter and spring precipitation, and the SWSs) makes it harder to derive conclusions on macropore flow.

3.6 Irrigation Tests

Irrigation tests were carried out on the test section to induce breakthrough and estimate field-scale near saturation hydraulic conductivity. Centrifugal pump was used to pump water from a storage reservoir into a rotating vane sprinkler jet installed on a 2.2 m tall fence post inserted within the lysimeter area (Figure 3.1). The pumping rate was about 7 lpm (112 gph). Figure 3.11 shows a photo of the field setup. The white flags in Figure 3 indicate the wetted area which was circular having a diameter of about 8.4 m. Two irrigation events were carried out on 8 June and 10 June, for 9 hours and 12 hours, respectively (Mijares et al. 2012). The surface application rate achieved was about 1 cm/h. During the two irrigation days, the site also received precipitation equal to 0.75 mm and 4.83 mm on 8 June and 9 June, respectively. The SWS of the cover estimated by integrating the water contents measured by the sensors located within the lysimeter nest (Figure 3.8) before the irrigation was 48.0 cm on 8 June and 48.1 cm on 10 June. The SWSs correspond to about 81% of S of the storage layer.

About 3.5 years after the construction of the test section and about 3 years after the first irrigation test, the second irrigation test was carried out in May 2013. Similar to the first irrigation test, water was pumped from the storage reservoir. The pumping rate achieved was about 7.8 lpm (124 gph). Wetted area due to the irrigation was circular having an average diameter of 10.7 m. Two irrigation events were carried out, on 3 May and 4 May, for 13 and 11 hours, respectively. The surface application rate achieved was about 0.52 cm/h. The SWS of the test section on 3 May before the irrigation was 48.6 cm (82% of S) and it increased to 49.3 cm (83% of S) on 4 May before the second irrigation application.

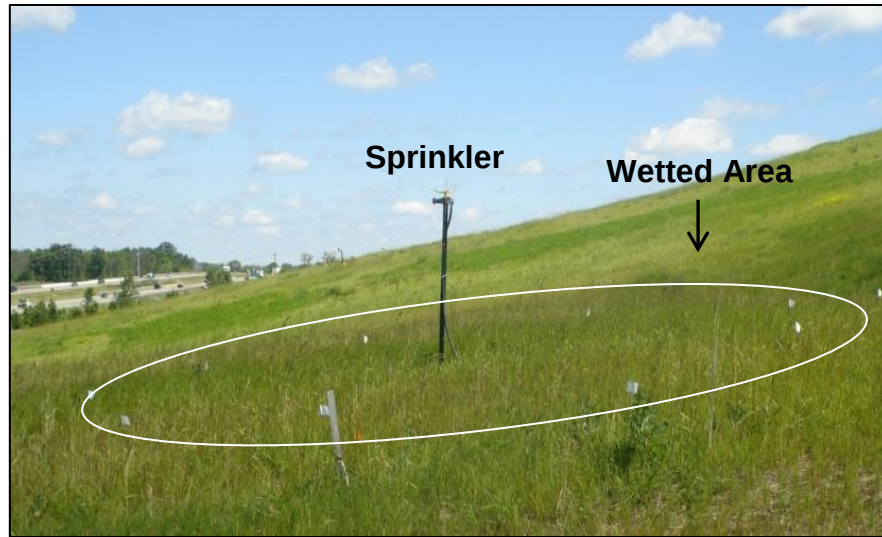


Figure 3.11: Irrigation setup and the wetted area.

Figure 3.12 presents cumulative percolation following the irrigation events. While no distinct breakthrough was observed within 45 days after the first irrigation test, after 45 days, following a major precipitation event (~ 75 mm), significant percolation (~ 2 mm) was collected during a relatively short period of time immediately after the storm even that occurred in late July 2010. The S of storage layer was about 84% during the breakthrough. The slope of the percolation plot during the 45 day period after the first irrigation event is relatively gradual and it increases sharply following the storm event. The gradual increase is typical of capillary flow through micropores. Whereas, the sharp change in the rate of flow is indicative of macropore flow (Khire et al. 1997). Hydraulic conductivity of the clay was estimated by assuming unit gradient through the cover when the breakthrough occurred in late July.

During the second irrigation test, the breakthrough occurred within 4.5 hours after the irrigation started and continued for a period of about 4 days (Figure 3.12). Total 10.5 mm of

percolation was collected during this relatively short period. The average degree of saturation of the cover was about the same as that during the first irrigation test ($\sim 84\%$). The rate of surface application of water during the second irrigation test was less than that during the first test. Thus, the relatively rapid breakthrough and relatively high magnitude of percolation are indicative of formation of macropores in the clay cover during the service period. The estimated hydraulic conductivities of the storage layer during breakthrough events are discussed in Section 3.6.

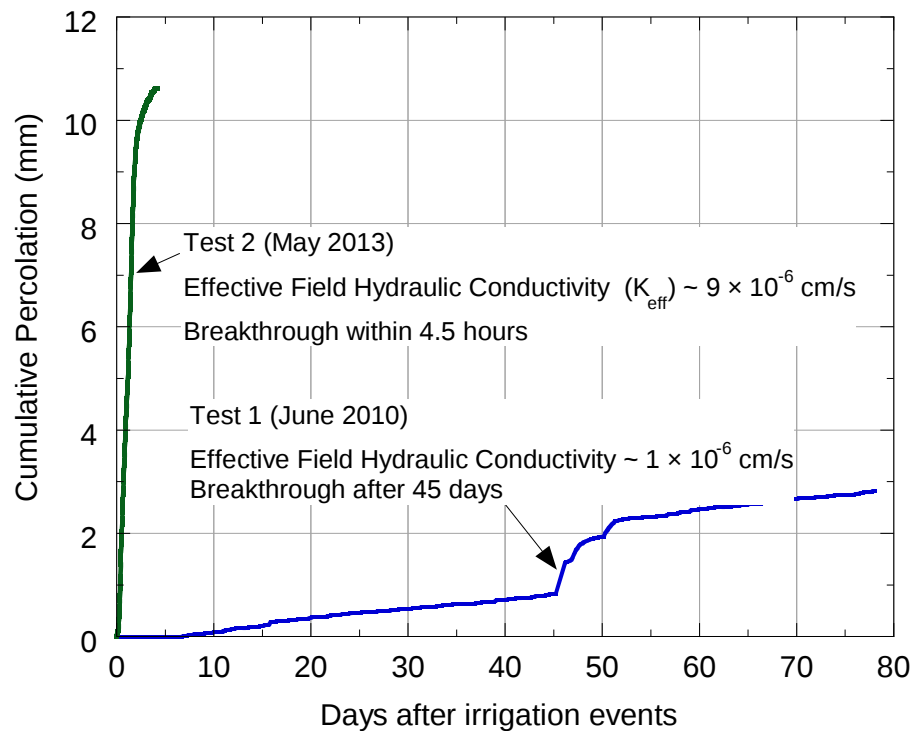


Figure 3.12: Comparison of measured percolation during irrigation tests.

Figure 3.13 present the water contents before, during, and after the two irrigation tests. Cumulative precipitation and irrigation and cumulative percolation are also presented on the same plots to assess the effect of irrigation on the flow through the cover. In order for the plot to

be legible, water content measurements from all six depths within the cover are not shown in Figure 6. During the third year of service, the WCR at the 15 cm depth went bad hence the water contents at 15 cm depth was predicted using measured suction from co-located potential sensor (HDMP) and in-situ soil water characteristic curve (SWCC) developed using sensor data. More details on in-site SWCC are presented in Section 4.3.1 and Saravanathiiban and Khire (2014a). The estimated water content is presented in Figure 3.13b.

During the first irrigation test, water content at 15 cm depth reached saturation while water contents at 75 cm and 165 cm depths showed insignificant increase indicating only a little portion of water applied infiltrate into storage layer. For about 45 days after the first irrigation test, the water contents at 15 cm and 75 cm depth gradually decreased (test section was drying) and the water content at 165 cm depth gradually increased as small amount of percolation was collected by the lysimeter. Following a major precipitation event (~ 75 mm) in late July 2010, the water content at 15 cm and 75 cm depths rapidly increased and significant percolation (~ 2 mm) was collected during a relatively short period of time. During the second irrigation test, water contents at 75 cm depth showed slight increase, and water contents at 165 cm depth did not change (Figure 3.13) while significant breakthrough occurred.

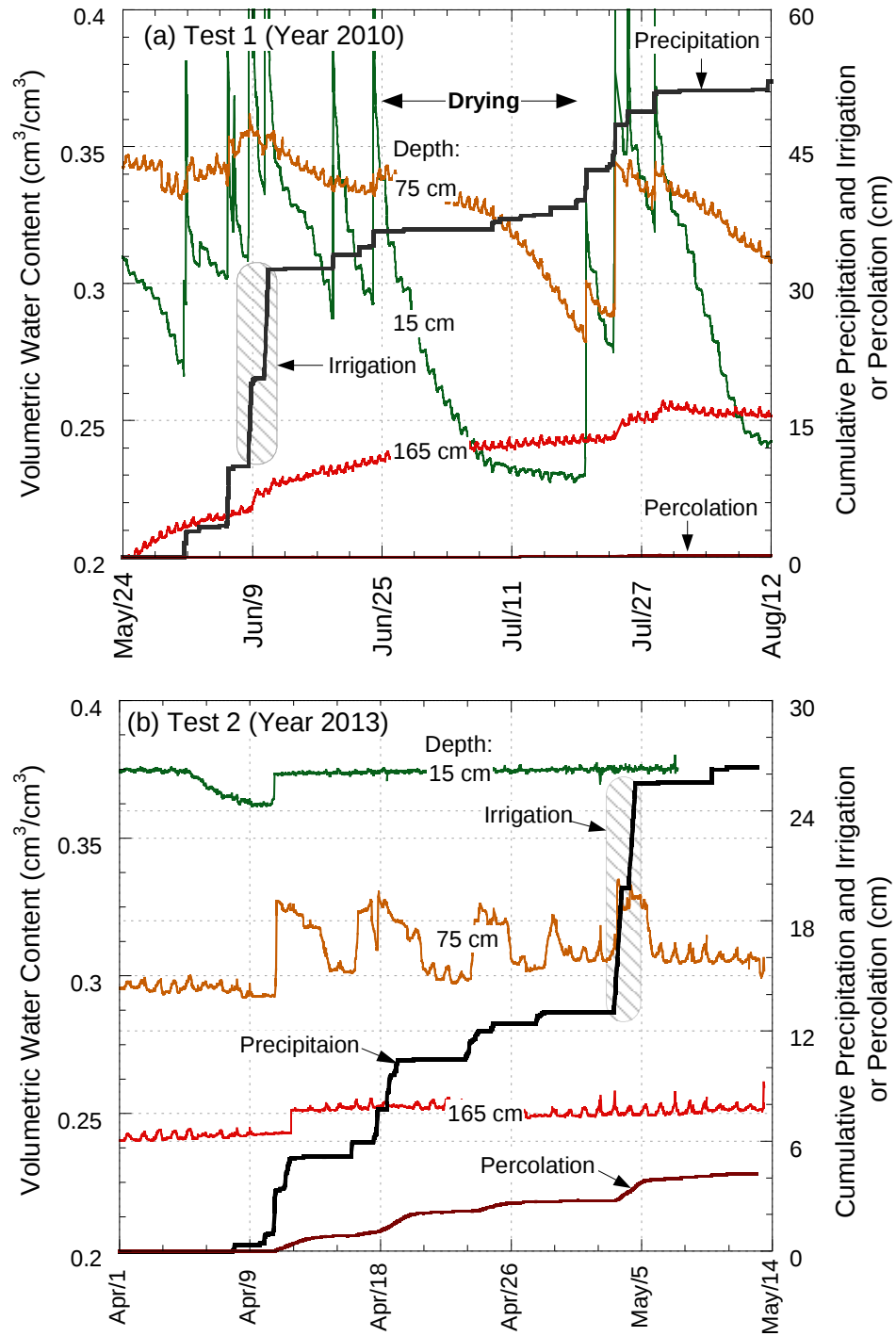


Figure 3.13: Soil water content of cover, cumulative precipitation and irrigation during irrigation Test-1 (a); and Test-2 (b).

Measured onset of percolation did not show any correlation with precipitation during the 1st year except one event after about 5 weeks of drying (July 2010). However, water content at 15 cm depth increased after every major (> 3 mm/d) precipitation events. This observation suggests that the storage layer had not significantly structurally changed since construction and the hydraulic conductivity of the cover was close to as-built. On the other hand, significant percolation can be noticed immediately after every major storm event during the third year. Moreover, percolation occurred within few hours after precipitation events. The rapid percolation onsets after precipitation events suggest that the macropores were formed and were relatively deep. After precipitation events, water content at 75 cm depth showed gradual increase before dry period and it rose rapidly after the dry period (Figure 3.13). However, water content at 165 cm depth showed gradual increase during the 1st and the 3rd years. The gradual increase in water contents at certain depths and rapid increase at other arbitrary depths suggest that the macropore network was not densely connected. Because distanced macropores would allow water flow bypassing the water content sensors at some depths and would flow through the sensors at some other depths. Densely connected macropore network would increase the water content at all depths (Albright et al. 2006a). Hence, rapid percolation events and rapid increase in water contents at only few depths suggests relatively less dense but deep enough macropores in the cover.

3.7 Effective Field Hydraulic Conductivity

Effective field hydraulic conductivity (k_{eff}) was estimated using measured percolation assuming unit hydraulic gradient and steady-state flow. Similar approach was followed by Meerdink et al.

(1996) and Albright et al. (2006a, 2006b). Though the assumptions made in the calculation of k_{eff} are simplistic, k_{eff} represents the in-service field hydraulic conductivity of the storage layer (Albright et al. 2006b). In the absence of ponding, field k_{sat} is expected to be greater than k_{eff} (Albright et al. 2006b). If k_{eff} is estimated during similar field saturation level, then k_{eff} should be relatively similar. Hence, k_{eff} can be used as an indicator to identify the change in field k_{sat} .

k_{eff} of the test section was estimated when the breakthrough occurred after the irrigation events. For the first irrigation test, the breakthrough occurred in late July 2010 was used to estimate the k_{eff} . Estimated k_{eff} was 1×10^{-6} cm/s. Relatively steady percolation measured for 2 hours was considered for k_{eff} estimation. This k_{eff} corresponds to S of 84% based on the water contents measured during breakthrough. Estimated k_{eff} during the second irrigation test was 9×10^{-6} cm/s which was about two times higher than the field k_{sat} measured using SRI. Estimated k_{eff} from the two irrigation tests correspond to the same S ($\sim 84\%$). After 3.5 years in service, k_{eff} of the clay has increased by a factor of nine. The increase in k_{eff} indicates the increase in field k_{sat} and confirms the presences of macropore flow in the cover.

Also, k_{eff} was estimated for the entire monitoring period using percolation measured after major storm events. Minimum of 2 hours of percolation was identified and used for k_{eff} estimations. During the first year, only few percolation events can be noticed. During the second year to the fourth year, frequent percolation breakthrough occurred after every major precipitation event. Estimated k_{eff} and S of the storage layer are presented in Figure 3.14. The S was mostly between 80-87% during the breakthroughs. However, k_{eff} showed an increasing trend from the second year of service onwards. During the first year, average estimated k_{eff} was about 9×10^{-7} cm/s. The maximum k_{eff} of 4.3×10^{-5} cm/s was estimated during the second year. About

62 mm of rainfall was recorded within 8 days previous to the maximum k_{eff} event and the test section was at its maximum S of 87.5%. Note that the second year was the wettest year in the 50 year history as mentioned previously. Except the two higher values of k_{eff} (above 2×10^{-5} cm/s) during the second year, k_{eff} follows an increasing pattern from about 9×10^{-7} cm/s to about 1×10^{-5} cm/s. Hence, k_{eff} of the test section increased by at least an order of magnitude in about four year of service due to the formation of macropores.

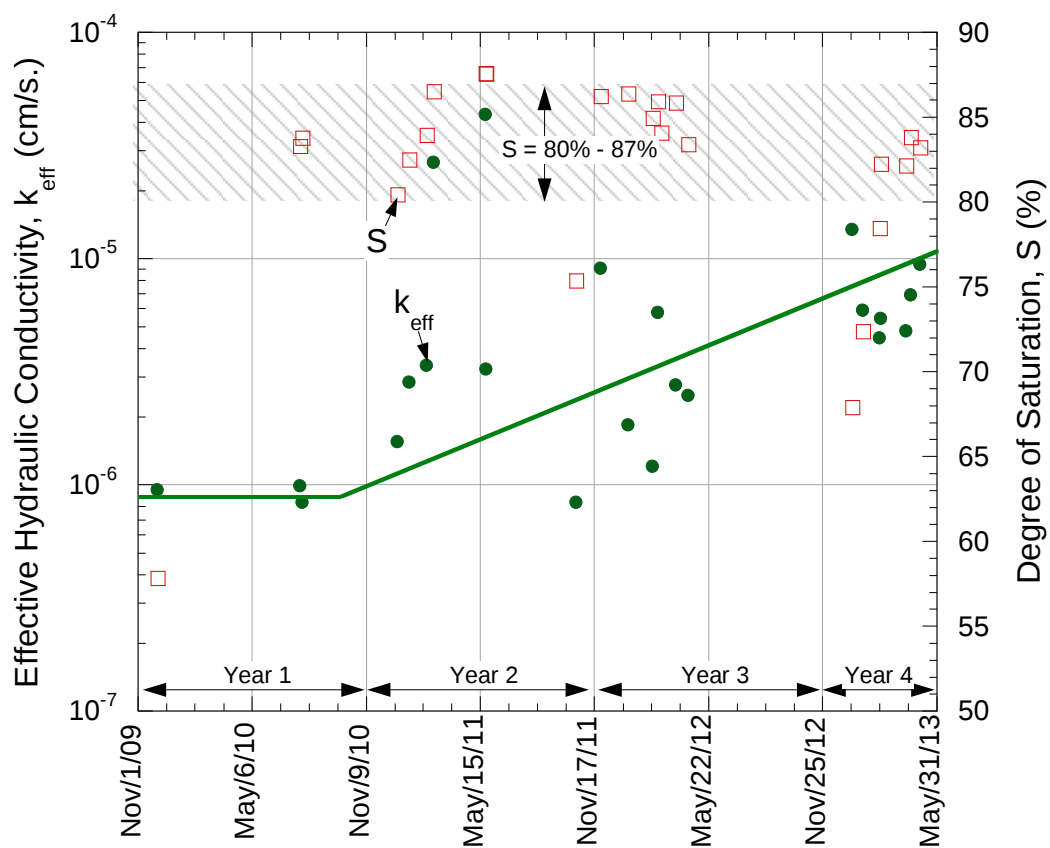


Figure 3.14: Estimated k_{eff} and degree of saturation (S) of the storage layer.

3.8 Gas Injection Tests and Identification of Macropores

Field gas injections test was carried out to evaluate the methane (CH_4) oxidation capability of the compacted clay cover and the gas test data was used to locate, confirm, and characterize macropores. CH_4 and carbon dioxide (CO_2) in about 1:1 ratio by volume, were mixed and injected into the lysimeter for about five months starting from 13 September 2012. Flow meters with regulators were used to monitor and maintain the inflow rate of gas. The average flow rate of CH_4 and CO_2 injected were about 660 g/day and 1100 g/day, respectively. Flux chambers and gas probes were used to measure CH_4 flux and the gas concentrations within the cover at various depths. Figure 3.15 and Figure 3.16 present the cross sectional view and plan view, respectively, of the test section with gas injection point, flux chambers, and gas probes. Flux chamber measurements were conducted on top surface as well as side slopes. Nine flux chambers were used to monitor CH_4 flux and these chambers were moved to new locations from time to time to increase the flux measurement locations. Flux measurements were carried out at total 17 locations. The flux chambers used were of two sizes: 0.65 m L $\times$ 0.65 m W $\times$ 0.20 m H and 1.0 m L $\times$ 1.0 m W $\times$ 0.3 m H. Collars were placed on the surface of the test section and sealed using bentonite clay.

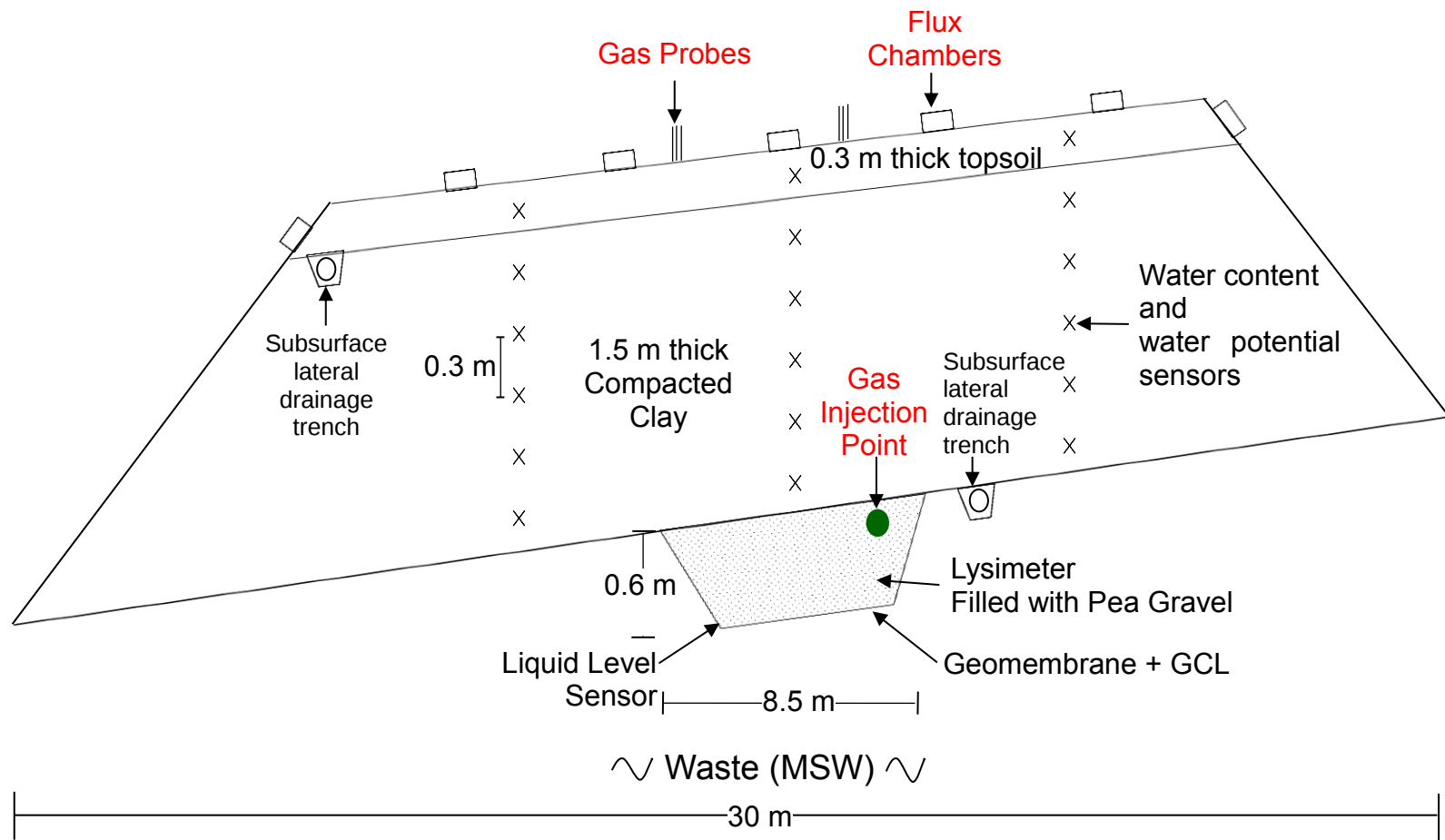


Figure 3.15: Schematic of the field test section with flux chambers and gas probes.

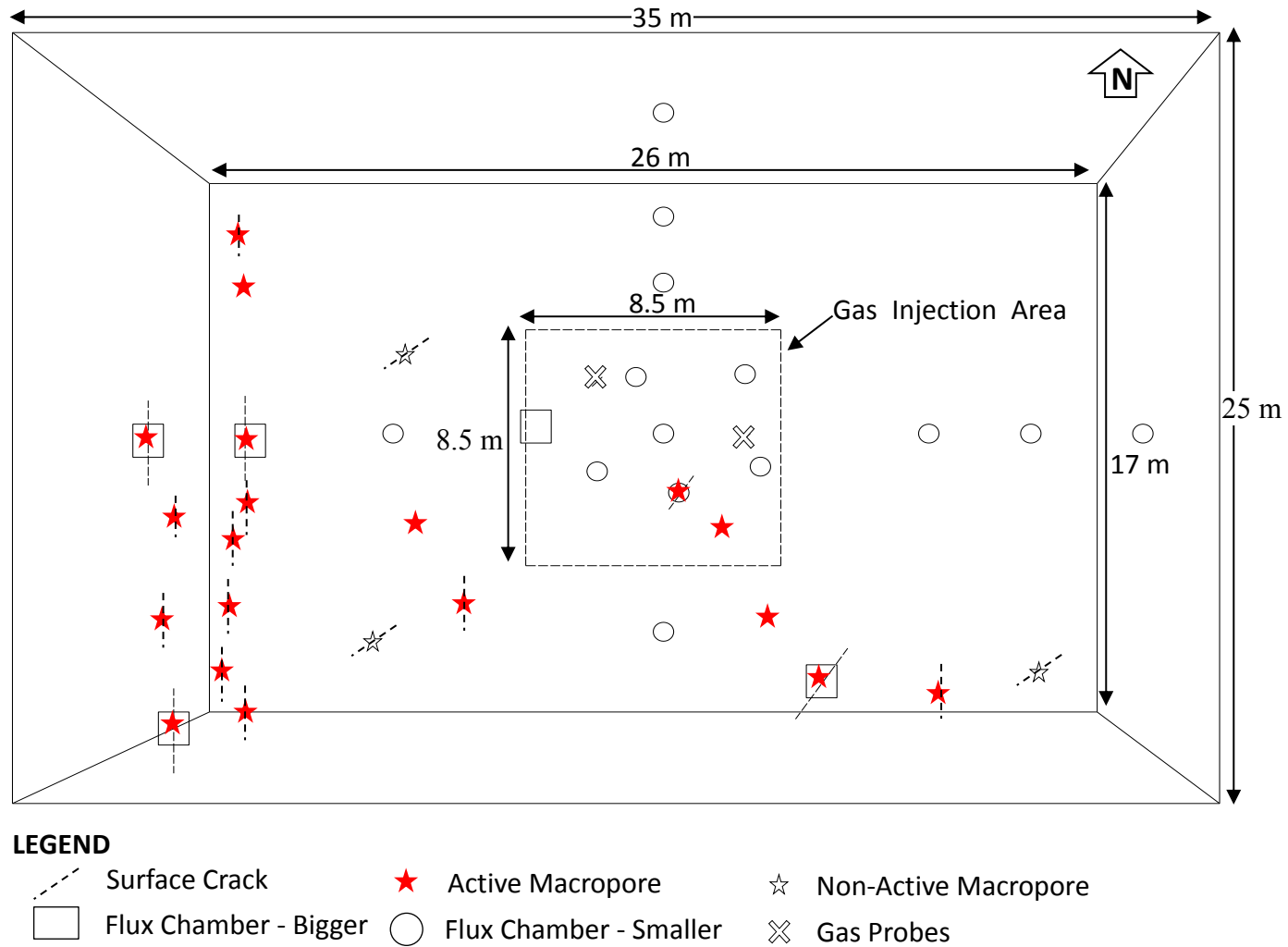


Figure 3.16: Plan view of the field test section showing the flux chamber, gas probes, and observed macropore locations.

During sampling, three to six samples were collected from each chamber sequentially over a 20 – 30 minutes of period using 140 ml syringes and filled into Tedlar bags (Zefon International, Inc.) or glass vials. Glass vials are commonly used to collect gas samples to test using gas chromatography GC. Tedlar bags were used in this study to collect samples to test using portable detectors. The bags allow supplying the sample in natural flow rate of the sampler pump in detectors. 500 milliliters of Tedlar bags and 20 ml glass vials were used. The vials were tested using GC (Gas Chromatography) to measure the concentrations of CH₄ and CO₂.

A dual detector portable total organic/inorganic vapor detection instrument, Toxic Vapor Analyzer (TVA-1000B) was used for gas survey on the cover surface and to test the samples in addition to GC. Gas survey on the ground surface of test section was carried out to locate the macropores. The TVA uses an FID (Flame ionization detector) and a PID (photoionization detector). FID is highly sensitive to hydrocarbons. However, FID does not differentiate different gases rather measures bulk concentration of hydrocarbons in the sample. PID is sensitive to aromatics, unsaturated hydrocarbons, and chlorinated hydrocarbons (Instruction Manual 2003). Also, PID can measure some inorganic compounds (eg. ammonia, carbon disulfide, chloroform, and ethylamine). However, PID does not detect methane. Hence, an elevated reading of FID and no response in PID might indicate presence of methane (Instruction Manual 2003). FID and PID were calibrated using standard gas cylinders before every field visit. Even though FID lacks the specificity of gas chromatographs, it requires less operator proficiency, provides rapid results, and is less expensive (Robbins et al., 1990). Duplicate samples were collected from flux chambers to compare the concentration measured from FID and GC. About one hundred samples were analyzed in GC and compared with TVA measurement which showed that the TVA measurements are within $\pm 10\%$. Gas surveying was carried out once every two weeks.

Those macropores identified on the ground surface were located and their surface dimensions were measured. The typical shape of the macropores was elongated or cylindrical at surface. The widths of the macropores were few mm to about 4 cm and the length of the macropores ranged from 1 cm to 60 cm (Khire and Saravanathiiban 2013). Only one surface crack was identified in the lysimeter area. Many elongated cracks (tension cracks) were located towards the downslope side of the test section. While the most common reasons for the formation of macropores in compacted clay covers is desiccation, freeze-thaw, root penetrations, and animal or rodent burrows, the test section built at the site in this project may also have developed tension cracks because of the slope and the location of the test section which hangs on the side slope (1V:4H) of the landfill.

The gas surveying carried out using portable FID during CH₄ gas injection tests were used to locate unidentified macropores in the test section. Hot-spots of CH₄ gas identified using portable FID was marked as active macropores. Some of the cracks which were visible did not conduct CH₄ gas and those were identified as non-active macropores. This suggests that not all surface cracks are deep enough or connected. Surface crack was not visible at few hot-spots indicated by portable FID. Cracks could have formed in storage layer but those were not connected to surface or at surface level the crack could have been filled over during rainfall or heavy wind.

Locations of flux chambers, gas probes, surface macropores, active macropores, and non-active macropores are shown in Figure 3.16. Five flux chambers were placed enclosing macropores in order to measure the methane flux through macropores. Measured chamber fluxes are shown in Figure 3.17. The average flux varied between 0.1 g/day/m² to 80 g/day/m². Micropore flux chambers (enclosed intact ground surface) (F1, F4, F6, F8, F11, F12, F13, F15,

F18, and F19) had average chamber flux less than 1 g/day/m² while surface crack chambers (F3, F7, F9, F16, and F17) had average chamber flux between 8 to 80 g/day/m². Flux chambers F2, F5, F10, and F14 had flux between 3 to 10 g/day/m². This higher flux compare to micropore flux chambers suggests possibility of macropore presents in flux chambers F2, F5, F10, and F14. Measured average methane fluxes through surface crack flux chambers were about two orders of magnitude higher than average methane flux through micropore flux chambers. CH₄ oxidization capacity of cover was estimated using the procedure published in Chanton et al. (2008). The CH₄ oxidization capacity of cover estimated for flux chambers enclosing macropore were zero for three chambers and 1.8% and 3% for rest of the two chambers while CH₄ oxidization capacity of the intact portion of the cover was up to 30%. Two orders of magnitude higher methane flux and almost zero CH₄ oxidization capacity of flux chambers enclosing macropores indicates that those macropores were well formed and reached deep enough to the lysimeter.

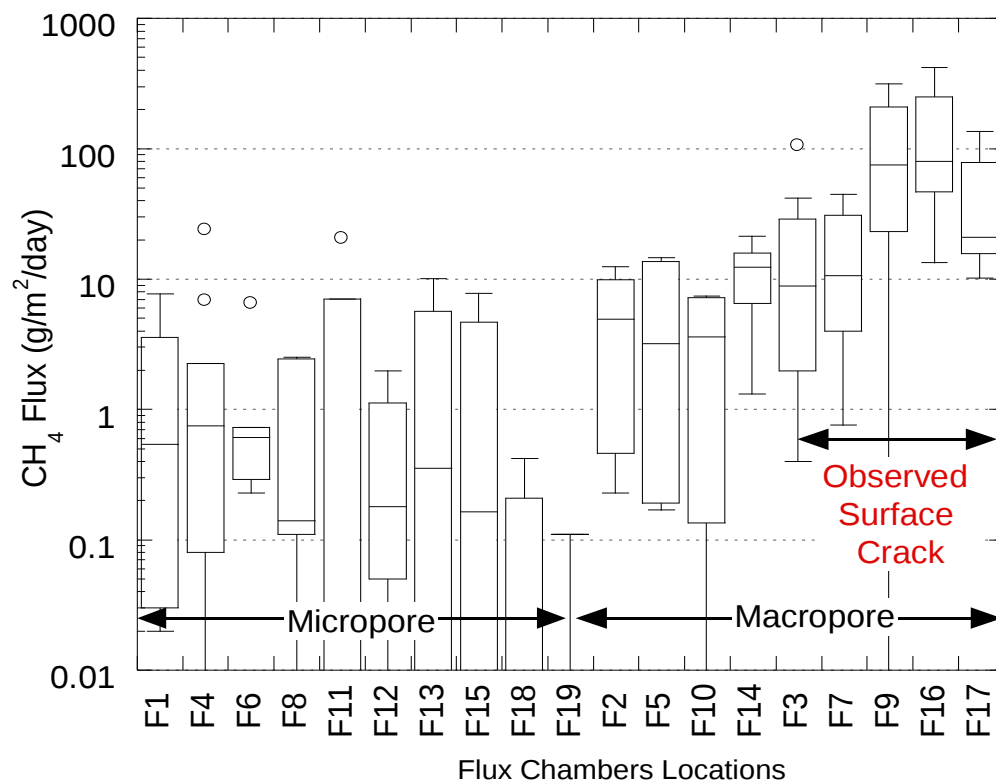


Figure 3.17: Measured chamber fluxes from October 12, 2012 to January 4, 2013

CHAPTER 4: WATER BALANCE MODELING

Water balance modeling was carried out using these two public domain numerical models: (1) UNSAT-H; and (2) RZWQM.

4.1 UNSAT-H Model

UNSAT-H is a public domain, 1-D, finite difference, water flow and heat transfer model, and widely used for earthen landfill final cover modeling (Fayer 2000, Khire et al. 1997, Khire et al. 2000, Benson et al. 2005, Bohnhoff et al. 2009, Mijares and Khire 2012). 1-D modeling is considered adequate for modeling hydrology of earthen landfill covers (Khire et al. 1997). Benson et al. (1994) indicated that error in the water balance by ignoring the lateral flow is relatively small (less than 1.5%). Moreover, measured lateral flow in the field test section confirmed that the flow is predominantly 1-D in the vertical direction (Mijares and Khire 2012). Hence, 1-D UNSAT-H model was used to simulate percolation through the field test section.

In UNSAT-H model, infiltration is simulated in two stages. The first stage is flux-controlled, that is the infiltration rate is controlled by water supply (Fayer 2000). During the second stage, the infiltration rate is based on the ability of the soil profile to transmit water downward. The infiltration rate is a function of the time from the onset of precipitation, the initial water content, the hydraulic properties of the surface soil, and the hydraulic properties of the layers deeper within the profile (Hillel, 1980, Fayer, 2000). Surface runoff is not explicitly simulated in UNSAT-H, however if rainfall or irrigation rate is greater than the infiltration capacity, the

excess water results as surface runoff and removed from the system. UNSAT-H uses the Richards' equation for saturated and unsaturated water flow through soils (capillary pores). Soil water retention can be described using commonly used mathematical functions such as the Haverkamp function (Haverkamp et al. 1977), the van Genuchten function (van Genuchten 1980), and the Brooks-Corey function (Brooks-Corey 1964). Hysteresis in water retention function can be included in the van Genuchten function. Options for defining the unsaturated hydraulic conductivity functions include the Haverkamp model, the Mualem model, the Burdine model, and the Brooks-Corey model. Initial condition is defined by soil suction. Transpiration is simulated as a sink term in the Richard's equation. Evaporation is computed using Fick's law when heat flow is modeled and evaporation is a function of potential evaporation when heat flow is not modeled. Potential evapotranspiration is calculated using Penman type equation using daily relative humidity, net solar radiation, wind speed, and daily minimum and maximum air temperatures. UNSAT-H does not simulate snowmelt, freeze or thaw, and temperature dependence of soil properties (Fayer 2000).

UNSAT-H was used to simulate percolation due to micropore flow through the test section during the first three years of service. RZWQM predictions were compared with UNSAT-H predictions.

4.2 Root Zone Water Quality Model (RZWQM)

RZWQM (version 2.42) is a 1-D, two-domain, finite difference, soil water flow and chemical transport model that simulates saturated and unsaturated flow in vertical soil profiles (Ahuja et al. 2000). The model assumes that soil consist of two interacting domains: (1) micropore domain

representing micropores in the soil matrix; and (2) macropore domain representing cracks or other larger pores where flow occurs due to gravity only. A schematic showing how RZWQM computes the water balance is shown in Figure 4.1.

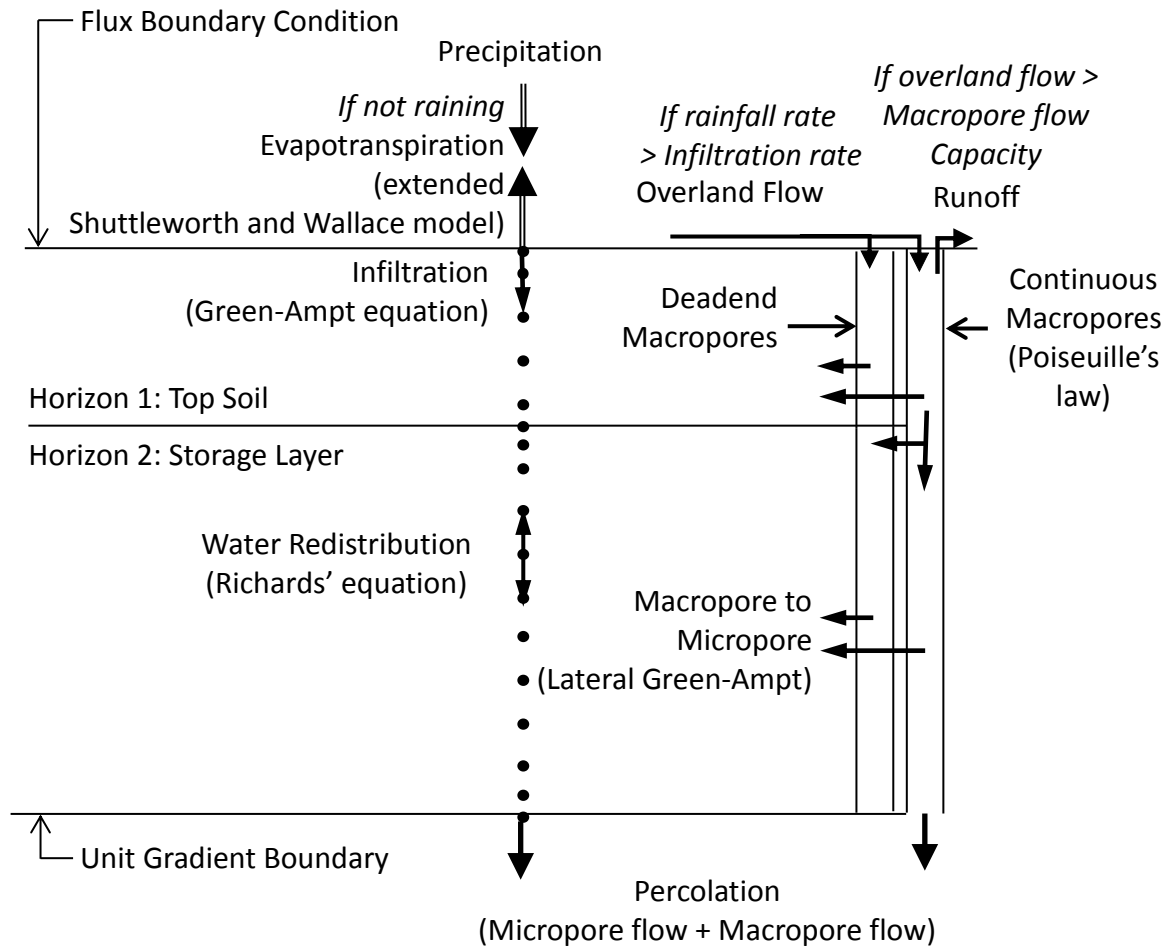


Figure 4.1: Schematic showing conceptual model for RZWQM

Three grid systems are used to simulate water flow in RZWQM: (1) horizons/layers for defining hydraulic properties, (2) layers for redistribution, and (3) 1 cm thick layers for infiltration. The Green-Ampt approach (Green and Ampt 1911) is used to model infiltration into the soil matrix (Eq. 4.1),

$$V = \overline{k_{sat}} \frac{h_c + H_0 + Z_{wf}}{Z_{wf}} \quad \text{Eq. 4.1}$$

where V = the infiltration rate at any given time (cm/hr.); $\overline{k_{sat}}$ = the effective saturated hydraulic conductivity of the wetting zone (cm/hr., a correction factor of 0.5 is used to account for the entrapped air and resulting viscous resistance); h_c = the suction head at the wetting front (cm) estimated from unsaturated hydraulic conductivity function; H_0 = the depth of surface ponding (cm); and Z_{wf} = the depth of the wetting front (cm).

Redistribution of water in the soil matrix following infiltration is simulated using the Richards' equation (Celia et al. 1990, Richards 1931) as follows,

$$\frac{\partial \theta}{\partial z} = \frac{\partial}{\partial z} \left[k(h, z) \frac{\partial h}{\partial z} - k(h, z) \right] - S_r(z, t) \quad \text{Eq. 4.2}$$

where θ = volumetric water content (cm³/cm³); t = time (hr.); z = soil depth (cm); h = soil-water pressure head (cm); k = unsaturated hydraulic conductivity (cm/hr.); and S_r = sink term for root water uptake and tile drainage rates (hr⁻¹). Soil hydraulic properties, SWCCs and unsaturated hydraulic conductivity functions, for each layer is described using modified Brooks-Corey function (Ahuja et. al. 2000). Initial condition can be defined by soil suction or water content for each horizon.

RZWQM does not simulate surface runoff or ponding infiltration. However, the difference between rainfall or irrigation rate and infiltration rate is resulted as overland flow when rainfall or irrigation rate is more than infiltration rate. If macropores are present then the overland flow re-routed into the macropores, and if the macropore flow capacity exceeds then the balance of overland flow results as surface runoff and removed from the system. The surface boundary

condition is modeled as specified flux boundary similar to UNSAT-H. Evapotranspiration is modeled as a function of potential evaporation until the soil dries to wilting point at which point the upper boundary condition becomes constant head. Potential evapotranspiration is computed using extended Shuttleworth and Wallace model (Farahani and Ahuja 1996). Water uptake by plants is simulated as a sink term in the Richards' equation using the approach of Nimah and Hanks (1973). The lower boundary can be unit gradient or constant flux when water table is present.

4.2.1 Macropore Flow Component

Overland flow generated at the soil surface flows into the macropores. The surface soil layer is assumed to have cylindrical macropores while the layers beneath the surface layer can have cylindrical or planar cracks. The Poiseuille law is used to calculate the macropore flow rate capacity assuming gravity flow (unit gradient) as presented in Eq. 4.3 and Eq. 4.4,

For cylindrical holes:

$$K_{mac} = \frac{N_p \rho g \pi R_p^4}{8\mu} \quad \text{Eq. 4.3}$$

For planar cracks:

$$K_{mac} = \frac{L_c \rho g w^3}{12\mu} \quad \text{Eq. 4.4}$$

where ρ = density of water (1.0017 g/cm³); g = the gravitational constant (1.27×10¹⁰ cm/hr²); R_p = the radius of cylindrical holes (cm); w = the width of planar cracks (cm); μ = the dynamic viscosity of water (36.072 g/hr/cm); N_p = the number of pores per unit area; and L_c = the total

length of planar cracks per unit area (cm). The number of macropores per unit area can be calculated from total macroporosity and the radius of the single cylindrical macropore (Malone et al. 2001),

$$N_p = \frac{P_{mac}}{\pi \times R_p^2} \quad \text{Eq. 4.5}$$

Similarly for planar cracks,

$$N_p = \frac{P_{mac}}{w \times L_c} \quad \text{Eq. 4.6}$$

where P_{mac} is the macroporosity.

Continuous macropores are idealized to be vertical and extends to a point below the depth of the soil profile modeled or to water table (if exists). However, horizontal macropores can be defined as deadend macropores that branch off from vertical macropores in each soil horizon and end within the soil horizons. However, the macropores are not physically modeled, only the amount of water flow through continuous macropores, the amount of water stored in deadend macropore, and the amount of water absorbed from continuous and deadend macropores to the soil matrix is calculated. Macropore flow capacity limits the flow of ponded water into the macropores. Macropore flow is sequentially routed downward through the continuous macropores in 1 cm depth increments for each time step. During each depth increment, macropore is allowed to absorb laterally by the soil matrix from deadend and continuous macropores. Lateral/radial absorption rate is calculated by lateral Green-Ampt type equation. A reduction factor is used to account for the influence of the compaction or an organic coating surrounding the walls of macropores in lateral absorption (Malone et al. 2001). However, water flow from the soil matrix to macropore is not considered in RZWQM.

4.3 Input Parameters

The input parameters used for water balance simulations using UNSAT-H and RZWQM are summarized in Tables 4.1 and 4.2. Detail discussion on how the input parameters were measured or estimated is presented in following subsections.

4.3.1 Field Measured Unsaturated Hydraulic Properties

In order to numerically model landfill earthen final covers, site-specific unsaturated hydraulic properties of cover soils are required. The hydrology of earthen cover is strongly influenced by hydraulic properties which include: saturated hydraulic conductivity, unsaturated hydraulic conductivity function (the relationship between unsaturated hydraulic conductivities and soil suction), and the soil water characteristics curve (SWCC) (the relationship between volumetric water content and soil suction). Because cover soil is generally unsaturated, the unsaturated hydraulic conductivity function and SWCC are required input for most water balance models. Khire et al. (1995) presented the importance of using site-specific unsaturated hydraulic conductivity function to simulate the hydrology of the earthen landfill final cover accurately. The hydraulic properties are measured using laboratory methods or field methods. Field method is recommended whenever possible because it is most representative of the field structure of the soil which is often not replicated in the lab tests (Benson and Gibb, 1997).

Table 4.1: Input parameters for water balance modeling using UNSAT-H and RZWQM

Parameter		Input Value	Reference	Model Application
Field Specifics				
Area (ha)		0.007	Measured	RZWQM
Elevation (m)		204	Google Earth	RZWQM; UNSAT-H
Aspect (deg.)		260	Google Earth	RZWQM
Latitude (deg.)		42 ⁰ N	Google Earth	RZWQM; UNSAT-H
Longitude (deg.)		-83.25	Google Earth	RZWQM
Slope (deg.)		10	Measured	RZWQM
Climate zone(rain>20 in/yr)		3	Measured	RZWQM
Soil Layer Description				
Soil type	Top Soil	Sandy Loam	Mijares et al. 2012	RZWQM
	Storage Layer	Clay Loam	Mijares et al. 2012	RZWQM
Depth (cm)	Top Soil	0-31	Design Values (Mijares et al. 2012)	RZWQM; UNSAT-H
	Storage Layer	32-182	Design Values (Mijares et al. 2012)	RZWQM; UNSAT-H
Soil Hydraulic Properties				
Brooks-Corey fitting parameters	Top Soil	Table 4.2	Lab Measured	RZWQM; UNSAT-H
Brooks-Corey fitting parameters	Storage Layer	Table 4.2	Saravanathiiban and Khire (2014b)	RZWQM; UNSAT-H
Meteorological and Hydrologic Data				
Precipitation, air temperature, solar radiation, wind speed		---	On-site measurement	RZWQM; UNSAT-H
Dew point , cloud cover		---	NOAA weather station	UNSAT-H
Relative humidity		---	On-site measurement	RZWQM

Table 4.1 (cont'd)

Albedo	0.20	Chudnovskii (1966)	UNSAT-H
Albedo of dry soil	0.30	Ma et al. (2011)	RZWQM
Albedo of wet soil	0.20	Ma et al. (2011)	RZWQM
Initial and boundary conditions			
Initial condition	Matric suction	Field Measured	UNSAT-H
	Water content	Field Measured	RZWQM
Upper boundary condition	Specified Flux	Measured Precipitation	RZWQM; UNSAT-H
Lower boundary condition	Unit gradient	Fayer et al. (2000); Khire et al. (1997)	RZWQM; UNSAT-H
Macropore Parameters			
Total macroporosity (cc/cc)	9.50E-08 – 1.37E-07	calibrated	RZWQM
Avg. radius of cylindrical macropores (cm)	0.15 – 0.18	calibrated	RZWQM
Fraction deadend macropores	0	Field observation	RZWQM
Sorptivity factor for lateral infiltration	1	calibrated	RZWQM

Table 4.2: Saturated and unsaturated hydraulic input parameters used for modeling.

Model	Soil Layer	Saturated VWC (θ_s)	Residual VWC (θ_r)	SWCC			Unsaturated conductivity function			
				h_e (cm)	B		k_{sat} (cm/s)	h_{bk} (cm)	B	l
UNSAT-H	Topsoil	0.41	0.00	63.1	3.33		1×10^{-2}	63.1	3.33	2
	Storage Layer	0.39	0.03	29.7	8.3		4.4×10^{-6}	12.0	-2.0	0.84
				h_e (cm)	A_1	A_2	k_{sat} (cm/s)	h_{bk} (cm)	N_1	N_2
RZWQM	Topsoil	0.41	0.00	63.1	0	0.30	1×10^{-2}	63.1	0.0	2.90
	Storage Layer	0.39	0.03	29.7	0	0.12	4.4×10^{-6}	12.0	0.0	1.08

Table 4.3: In-situ saturated and unsaturated hydraulic properties.

Storage Layer									
Function	Curve	Saturated VWC (θ_s)	Residual VWC (θ_r)	SWCC		Unsaturated conductivity function			
				α (1/cm)	n	k_{sat} (cm/s)	α_{κ} (1/cm)	n_k	l
van Genuchten	Lower	0.39	0.10	0.030	1.60	4.4×10^{-6}	----	---	---
	Average	0.39	0.11	0.015	1.22		0.02	1.9	-3.67
	Upper	0.39	0.10	0.007	1.14		----	---	---
				h_b (cm)	λ		h_{bk} (cm)	λ_k	
Brooks-Corey	Average	0.39	0.03	29.7	0.12		12	-0.31	---
Topsoil									
Brooks-Corey	----	0.41	0.00	63.1	0.30	1×10^{-2}	63.1	0.30	----

Note: Original Brooks-Corey parameters

In-situ water content and soil suction measured using co-located WCRs and HDMP sensors, respectively, as shown in Figure 4.2 were used to develop field unsaturated hydraulic properties (Saravanathiiban and Khire 2014b). A detail description on WCRs including the temperature depended calibration is presented in Section 3.2.

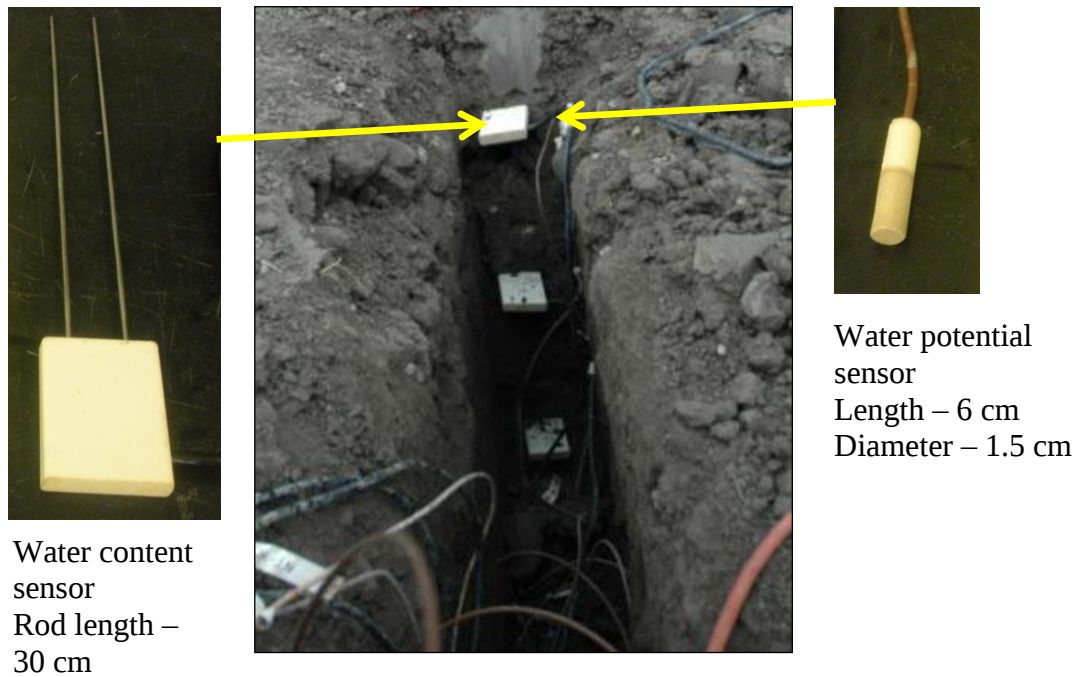


Figure 4.2: Co-located water content and water potential sensors

HDMP sensor (Figure 4.2) is made up of a cylindrical-shaped porous ceramic tip with heating element and a thermocouple inserted at its center. This sensor uses thermal conductivity of the ceramic tip to measure soil water potential, indirectly, using a built in sensor-specific calibration. When matric suction of the surrounding soil is in equilibrium with the ceramic tip, soil suction is determined using the correlation between thermal conductivity and water content of the ceramic tip that corresponds to matric suction. These sensors measure soil water potentials

ranging from -2,500 to -10 kPa. Because the air entry pressure of the ceramic tip is about -10 kPa, the sensors remain saturated until it reaches the air entry value. Hence, the sensor cannot measure matric suctions between -10 kPa to 0 kPa. The sensors were calibrated individually according to the procedure presented by Flint et al. (2002).

Field based SWCCs were developed using co-located water content and water potential sensors. The data sets of volumetric water content (VWC) and water potential from all three sensor nests measured at six depths in each nest were used. During the process of development of SWCCs, a time lag was noticed between the changes in water content and corresponding change in water potential. This time-lag is the result of unsaturated hydraulic conductivity of the porous tip which causes a finite amount of time for the sensor potential to equilibrate with the soil. Hence, the set of VWC and water potential data were manually chosen considering the time lag in water potential measurements (if any) after drying events. The data set of VWC and water potential from all three sensor nests is presented in Figure 4.3(a). The data shows some scatter. Therefore, three SWCC curves were generated for each test section using the van Genuchten fitting function (van Genuchten 1980) and the Brooks-Corey fitting function. The middle curve represents the average of field properties and the other two curves show the upper and lower bounds observed in the data. The van Genuchten fitting function is as follows,

$$\theta(h) = \theta_r + (\theta_s - \theta_r) \left\{ \frac{1}{1 + (\alpha h)^n} \right\}^m \quad \text{Eq.4.7}$$

and

$$m = 1 - \frac{1}{n} \text{ (for the Mualem model)}$$

where θ_r is the residual VWC; θ_s is the saturated VWC; h is the matric suction; θ is the VWC at suction h ; and α , n , and m are the curve fitting parameters.

And, the SWCC curve according to Brooks-Corey function,

$$\theta = \theta_s \quad \text{when } h < h_b$$

Eq. 4.8

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{h_b}{h} \right)^\lambda \quad \text{when } h \geq h_b$$

where h_b is the air entry pressure; and λ is the pore size distribution index. The fitting parameters are listed in Table 4.3.

Benson and Gribb (1997) recommended the instantaneous profile method (Watson 1966, Hillel et al. 1972, Khire et al. 1995, Meerdink et al. 1996) to measure unsaturated hydraulic conductivities of fine-grained soils because large volume of soil can be tested. Moreover, they recommend this method to measure the unsaturated hydraulic conductivities of landfill cover soils because the boundary conditions are reasonably well defined when a monotonic drying is observed in the field and percolation from the base of the cover being investigated is zero. Hence, the instantaneous profile method is used to develop the field unsaturated hydraulic conductivity functions using in-situ water content and soil suction. Data were selected for the calculation based on nearly monotonic decreasing water contents and increasing matric suctions noticed from in the data collected from the water content and water potential sensors, respectively. Percolation was zero during the periods when the data was selected for unsaturated hydraulic conductivity calculations. This ensured that the required key assumptions for the instantaneous profile method were met: (1) flow is 1-D; and (2) flow is unidirectional. The calculation was based on the assumptions that the flow was one-dimensionally orthogonal to the test section and water was removed via evaporation only (i.e., the effect of transpiration is negligible). Plant roots existed predominantly in the upper 30 cm thick vegetative layer and had

minimal penetration in the lower clay layer (more detail on plant roots is presented in Section 4.3.2). Hence, the assumption that evaporation was the key driver for the removal of water is reasonable. A detailed step by step procedure followed in the instantaneous profile method to calculate unsaturated hydraulic conductivity can be found in Khire et al. (1995) and Meerdink et al. (1996). The suction values to calculate the hydraulic gradient and average suction were inferred from the field based average SWCC (Figure 4.3). Preliminary numerical simulations of water balance of the test section using UNSAT-H indicated that when the average SWCC is input to the model, the water balance predictions are relatively accurate (Khire and Saravanathiiban 2013).

Figure 4.3(b) presents the estimated unsaturated hydraulic conductivities. Also, predicted and fitted unsaturated hydraulic conductivity curves using the van Genuchten-Mualem function (van Genuchten 1980) and the Brooks-Corey function (Brooks and Corey 1964) are presented in Figure 4.3(b) as a reference. The van Genuchten-Mualem conductivity function is as follows,

$$k(h) = \frac{\left\{1 - (\alpha h)^{nm} \left[1 + (\alpha h)^n\right]^{-m}\right\}^2}{\left[1 + (\alpha h)^n\right]^{ml}} K_{sat} \quad \text{Eq. 4.9}$$

where l is the pore interaction term. Similarly, the Brooks-Corey conductivity function,

$$k(h) = k_{sat} \quad \text{when } h < h_{bk} \quad \text{Eq. 4.10}$$

$$k(h) = k_{sat} \left(\frac{h_{bk}}{h} \right)^{\lambda_k} \quad \text{when } h \geq h_{bk}$$

where h_{bk} is the air entry pressure; and λ_k is the pore size distribution index for conductivity function.

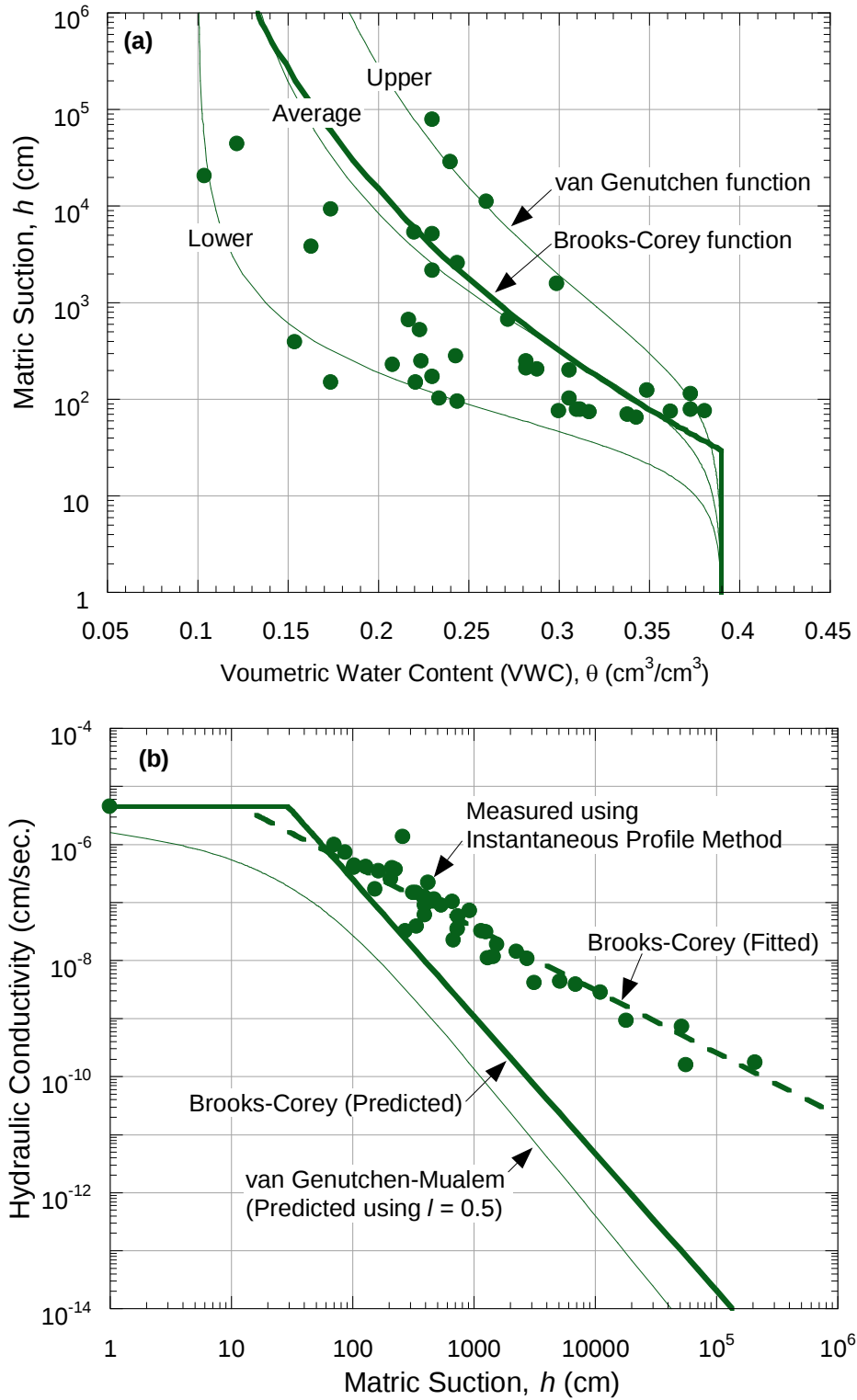


Figure 4.3: Estimated field-based SWCCs (a); and measured and predicted unsaturated hydraulic conductivities (b) for storage layer.

The Brooks-Corey functions are defined in slightly different formats in UNSAT-H and RZWQM. The SWCC curve according to UNSAT-H model:

$$\theta = \theta_s \quad \text{when } h < h_b$$

Eq. 4.11

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{h_b}{h} \right)^{1/B} \quad \text{when } h \geq h_b$$

where B is the inverse of the original Brooks-Corey parameter λ . And, conductivity function according to UNSAT-H model,

$$k(h) = k_{sat} \quad \text{when } h < h_{bk}$$

Eq. 4.12

$$k(h) = k_{sat} \left(\frac{h_{bk}}{h} \right)^{2+b'/B_k} \quad \text{when } h \geq h_{bk}$$

where B_k is the inverse of λ_k ; b' represents $1+l$ for Burdine conductivity model (Burdine 1953) where the exponent l is usually 2; and for Mualem model (Mualem 1976) b' represents $2+l$ and l is usually 0.5. The input parameters l , B , and B_k presented in Table 4.2 were calculated from the original Brooks-Corey fitting parameters presented in Table 4.3.

Modified form of the Brooks-Corey function is used in RZWQM (Ahuja et al. 2000). Eq. 4.13 and Eq. 4.14 presents SWCC and conductivity function used in RZWQM.

$$\theta = \theta_s - A_1(h) \quad \text{when } h < h_b$$

Eq. 4.13

$$\theta - \theta_r = B_1(h)^{-A_2} \quad \text{when } h \geq h_b$$

where A_1 and A_2 are fitting parameters, and $B_1 = (\theta_s - \theta_r - A_1 \times h_b) \times h_b^{A_2}$.

$$k(h) = k_{sat} (h)^{-N_1} \quad \text{when } h < h_{bk}$$

Eq. 4.14

$$k(h) = C_2 (h)^{-N_2} \quad \text{when } h \geq h_{bk}$$

where N_1 and N_2 are fitting parameters (slopes of the two segments of the log (k) - log (h) curve divided at air-entry pressure, h_{bk}); and $C_2 = k_{sat} \times h_{bk}^{N_2}$. When A_1 and N_1 approach to zero, Eq. 4.13 and Eq. 4.14 reduce to original Brooks-Corey equations (Eq. 4.8 and Eq. 4.10) and the parameters A_2 and N_2 are equal to λ and λ_k , respectively. The input parameters (B_1 , A_2 , and N_2) are presented in Table 4.2, which were calculated from the original Brooks-Corey fitting parameters presented in Table 4.3.

4.3.2 Vegetative Data

Input data relevant to transpiration modeling for UNSAT-H includes root-length density function, maximum root depth, and leaf area index (LAI), growing season, and percentage bare area. The root-length density function was measured using samples collected from the field test section. Two samples of 30 cm diameter and 50 cm deep were collected from two different locations of the test section. Figure 4.4 shows a sample excavated from the test section.

The samples were cut into 5 cm slices (Figure 4.5). The plant roots were washed and the weight of the plant roots from each slice was recorded. The average biomass at 2.5 cm and 50 cm depths were about 2 g/m² and 240 g/m². The normalized root-length density was calculated by dividing the biomass of each depth interval by total biomass for entire depth and is presented in

Figure 4.6. UNSAT-H uses the following equation for normalized root-length density (R) function,

$$R = ae^{-zb} + c \quad \text{Eq. 4.15}$$

where a , b , and c are the coefficients that fit the normalized root-length density data. The values of a , b , and c for the measured data are 1.43, 0.3, 0.018, respectively. The maximum root depth was used as 55 cm because negligible amount of roots were present at that depth.



Figure 4.4: Sample collected from the test section for root-length density measurement.

Healthy vegetation in the region can reach a maximum LAI of 4.0 to 4.5 according to Schroeder et al. (1994). However, a conservative value of 3.0 was used for the maximum LAI from visual observation. Average percentage bare area was set as 50% from visual observation during site visits.



Figure 4.5: Measurement of root-length density function.

RZWQM has a plant growth module that simulate above and below ground biomass. However, it requires calibration for specific plants. Hence, a simple known growth curve approach is added to the model to simulate only water and nutrient uptake. Quick Turf module is one of the growth curve approach modules in RZWQM that has Orchard grass built into it. However, the growing season cannot be input to the model for Quick Turf module. The turf can

undergo dormancy at the beginning of the year only (Bartling et al. 2012). The turf is simulated continuously according to planting and cutting dates. The initial plant height, plant height at cut, initial LAI, LAI at cut, maximum root depth, and planting and cutting dates are the input parameters relevant to water uptake for Quick Turf module. Planting and cutting dates were set as the growth season similar to UNSAT-H model input. LAI at cut was set to 3.0 and initial LAI was set to 0.1 to minimize the water uptake during early growing season. Preliminary simulation results from both UNSAT-H and RZWQM showed that including plant makes relatively small impact in simulated water balance, especially percolation. Hence, only results of water balance modeling without plants are presented in Sections 4.4 and 4.5.

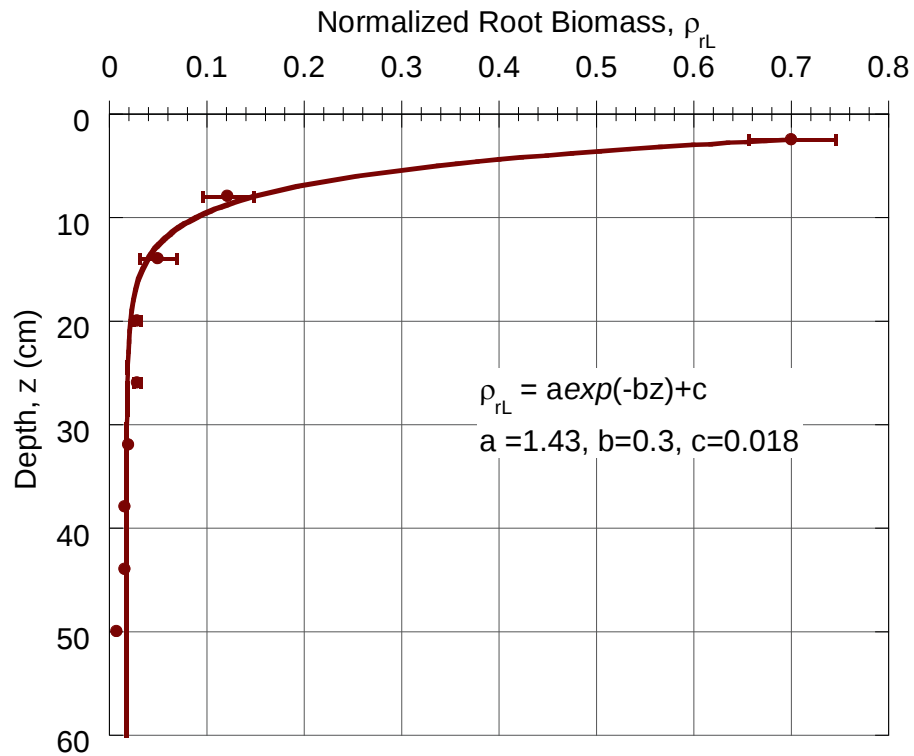


Figure 4.6: Measured normalized root-length density function.

4.3.3 Meteorological and Hydrologic Data

Meteorological data and soil albedo are used to calculate PET. Reflectance of total solar energy is quantified by the soil albedo. A soil surface albedo of 0.2 was used for UNSAT-H (Chudnovskii 1966; Khire et al. 1997). Meteorological data input to UNSAT-H includes daily and hourly precipitation, daily maximum and minimum air temperature, average daily dew point, daily total solar radiation, average daily wind speed, and average daily cloud cover. The data recorded on site were used as input. Daily dew point temperatures were obtained from NOAA weather station. Because net solar radiation was measured at the site, average cloud cover was assumed to be zero. Hourly precipitation was applied as it was recorded by the tipping bucket located at the site. However, the precipitation recorded at the site did not include snow. Hence, snow received during winter recorded by the NOAA weather station located about 5 km from the site was used as input. UNSAT-H does not simulate the snow melt. Hence, snow melting approach presented in Kustas et al. (1994) was used to melt the precipitation in the form of snow before supplied to the model. Estimated snow melt was applied as rainfall between 10:00 AM and 6:00 PM when the solar radiation is typically higher and snow melt is observed. This approach is consistent with the method used by Khire et al. (1997).

Hourly or daily meteorological data can be supplied to RZWQM. Hourly data of precipitation, average air temperature, solar radiation, average wind speed, and average relative humidity were supplied to RZWQM. RZWQM has snow module called PRMS (Precipitation Runoff Modeling System) (Leavesley et al. 1983) to estimate the snow depth and snow melt from the meteorological data. RZWQM requires albedo for wet and dry soil separately. The soil albedo was set as 0.2 and 0.3 for wet and dry soil, respectively, for RZWQM (Ma et al. 2011).

4.3.4 Initial and Boundary Condition

Initial conditions were defined using soil suction values assigned to each node in UNSAT-H and initial average water contents of each layer were specified in RZWQM. The simulations were carried out individual years for the first three years of service. Field measured water contents and soil suctions on October 31st 2009, October 31st 2010, and October 31st 2011 were used as the initial conditions for the simulation of Year 1, Year 2, and Year 3, respectively. The initial soil water storages for Year 1, Year 2, and Year 3 were 42.5 cm, 44 cm, and 58 cm, respectively.

The boundary conditions assigned in both the models were similar. The top boundary of the model was assigned as a flux boundary which considers infiltration and evapotranspiration as specified fluxes. The lower boundary was assigned as a unit gradient to simulate the vented lower boundary of the lysimeter (Khire et. al. 1997; Benson et al. 2010).

4.3.5 Macropore Flow Data

Macropore flow module of RZWQM requires total macroporosity, average radius of cylindrical macropore, fraction of dead end macropore, and sorptivity factor for lateral infiltration. One macropore was identified in the field test section within the lysimeter area (Section 3.7) and the flow rate was measured using irrigation tests (Section 3.5). Hence, the model was calibrated using one cylindrical macropore for the lysimeter area. The average radius of the macropore was calibrated to match the measured flow rate during the second irritation test. The fraction of dead end macropores was set to zero because non-active macropores were not identified within the

lysimeter area. Also, sorptivity factor for lateral infiltration was set to 1. The sorptivity factor of one allows lateral infiltration rate based on Green-Ampt equation without any reduction.

4.4 Evaluation of RZWQM for Water Balance Modeling of Earthen Landfill Cover

The simulations that considered only micropores were carried out using UNSAT-H and RZWQM to quantify the micropore flow through the test section. Input parameters listed in Table 4.1 and Table 4.2 were used for the simulations. Plants were not considered for these simulations because the influence of plants was negligible on deep percolation, and all plant related parameters were not measured except the root-length density function. Simulations were carried out on yearly basis which allowed providing initial conditions at the beginning of each year. From November 1st 2009 to October 31st 2010 was considered as Year 1. Similarly, November 1st 2010 to October 31st 2011, November 1st 2011 to October 31st 2012, and November 1st 2012 to October 31st 2013 were considered as Year 2, Year 3, and Year 4 respectively. However, numerical simulations were carried out only for the first three years because the test section was dismantled in Year 4. Irrigation tests carried out during Year 1 and Year 4 were simulated separately to obtain calibrated input parameters.

4.4.1 Simulations of Irrigation Tests

The first irrigation that was carried out during the first year after the test section was built. The water balance of this test was simulated for two weeks starting four days before the irrigation event. Measured and simulated cumulative percolation and cumulative precipitation and

irrigation are presented in Figure 4.7(a). The simulated percolation is relatively accurate. The measured and simulated SWSs of the test section during irrigation test-1 are presented in Figure 4.7(b). The simulated SWSs are relatively similar to each other and within about 1cm compared to the measured SWS.

Figure 4.8 presents simulated cumulative surface runoffs. Irrigation applied was about 21 cm and about 19 cm and 18 cm of the irrigation was resulted as surface runoff according to RZWQM and UNSAT-H, respectively.

Hence, both the models simulated the water balance of the earthen cover relatively accurately during the first irrigation test. The water balance predictions of both models are comparable to each other.

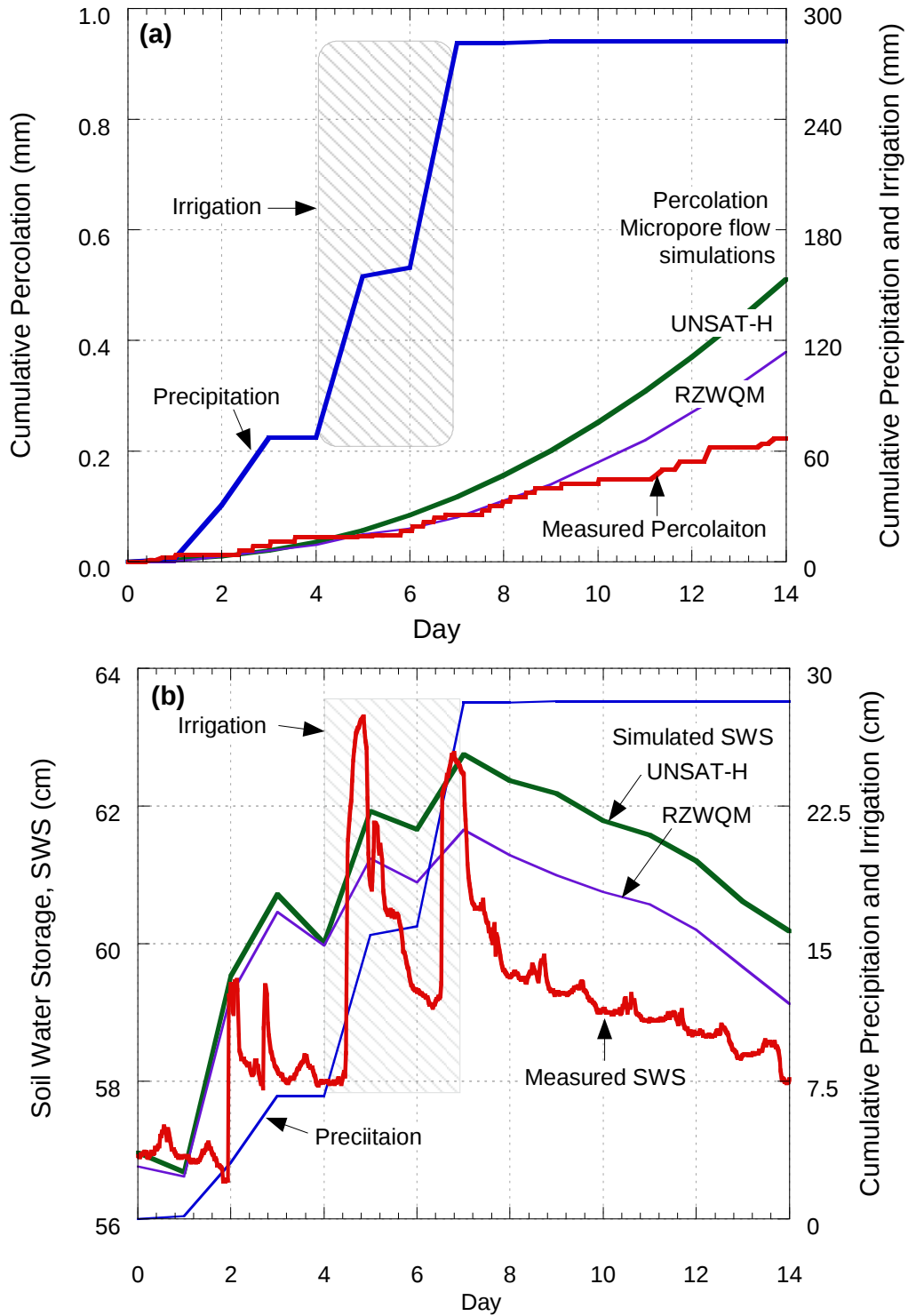


Figure 4.7: Measured and simulated cumulative percolation (a); and soil water storage (b) during the first irrigation test (2010).

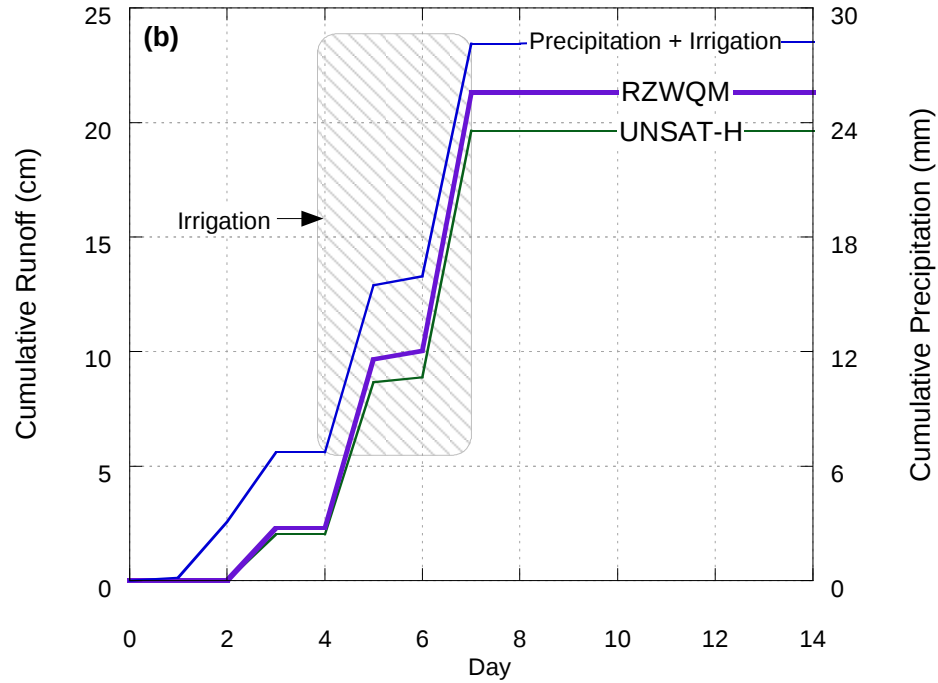


Figure 4.8: Simulated cumulative surface runoff during the first irrigation test (2010).

Similar to the first irrigation test, water balance of the test section during the second irrigation test was simulated for two weeks starting four days before the irrigation event. Measured and simulated cumulative percolations, and cumulative precipitation and irrigation are presented in Figure 4.9(a). The measured cumulative percolation was about 11 mm whereas the simulated cumulative percolation was about 1 mm. The percolation measured during the second irrigation test was influenced by macropore flow. UNSAT-H or RZWQM without macropore flow module cannot simulate the percolation dominated by macropore flow in the fourth year of service of the earthen cover. RZWQM simulations of water balance with macropore module are presented in Section 4.5. Measured and simulated SWSs of the test section during the second irrigation test are presented in Figure 4.9(b).

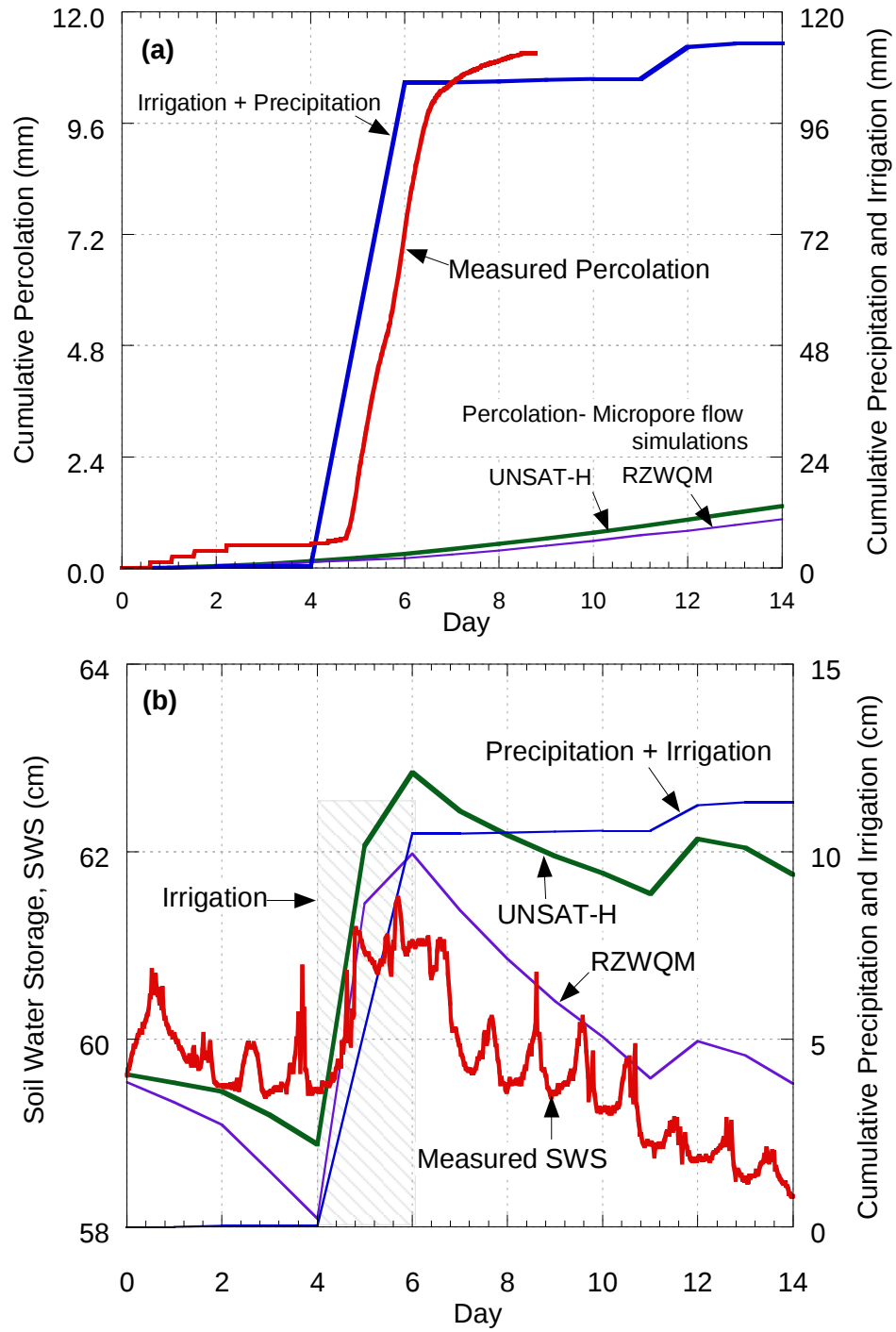


Figure 4.9: Measured and simulated cumulative percolation (a); and soil water storage (b) during the second irrigation test (2013).

Compare to UNSAT-H, RZWQM showed more drying, in other words more evaporation. However, the SWSs simulated by both the models follow the trend observed in measured SWS. Figure 4.10 presents simulated cumulative surface runoffs. UNSAT-H and RZWQM simulated relatively similar surface runoff. The simulated cumulative surface runoff was about 5 cm while cumulative precipitation and irrigation was 11 cm.

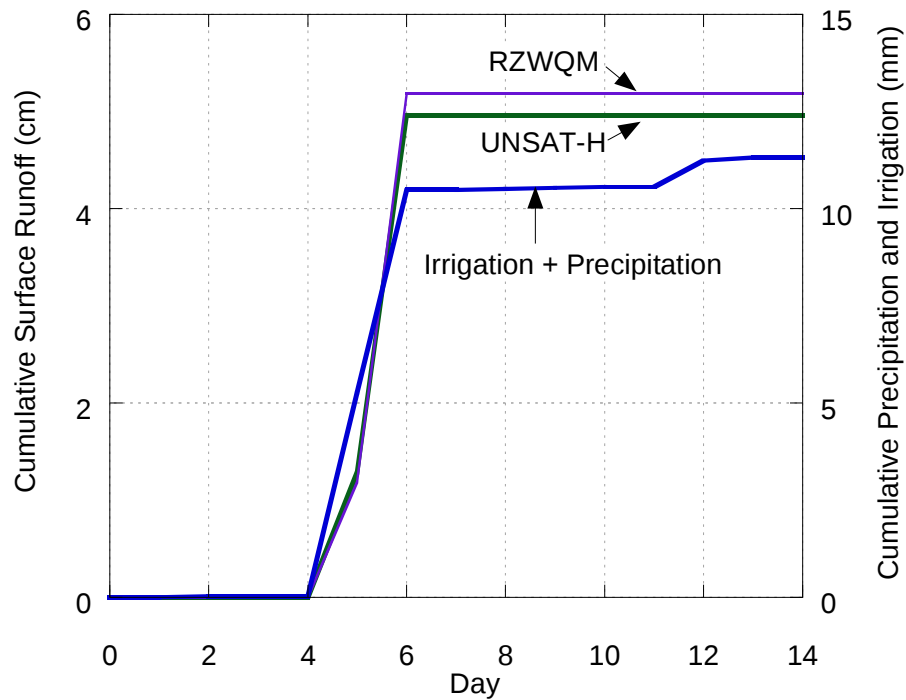


Figure 4.10: Simulated surface runoff during the second irrigation test (2013).

4.4.2 Simulations of Year 1

Figure 4.11(a) presents the measured and simulated cumulative percolation, and recorded cumulative precipitation and irrigation for the first year. During Year 1, cumulative water applied to the model was about 993 mm. The simulated cumulative percolation exceeded the

measured percolation only by a few mm. Flow was predominantly through micropores during the first year. Percolation simulated by UNSAT-H and RZWQM are comparable. Hence, both models predicted percolation reasonable well when the flow was predominantly through micropores. Figure 4.11(b) presents the measured and simulated SWSs of the test section. The simulated SWSs followed similar trend as observed in the measured SWS except during Spring 2010. The simulated SWSs showed more drying than the measured SWS during March to May 2010. The soil was frozen to 15 cm depth during Winter 2010. The temperature of the soil surface and the soil temperature at depth of 15 cm are presented in Figure 4.11(b). The models do not simulate freeze-thaw process and do not account for the effect of frozen ground surface. During Winter 2010, the model predictions were slightly different from each other because the snow melt were simulated differently. The precipitation during Winter 2010 was applied during early March 2010 for UNSAT-H model because the model does not have a snow melt algorithm. RZWQM has an in-built snow melt module. After May 2010, the simulated SWSs were identical.

Comparison of simulated cumulative surface runoff, and cumulative evaporation (E) and cumulative potential evaporation (PE) during Year 1 are presented in Figure 4.12. Both models produced runoff during the irrigation event only. Compared to UNSAT-H, RZWQM produced 2 cm of more runoff and 2 cm less infiltration during the irrigation event. Also, UNSAT-H simulated 2 cm of cumulative E more compared to RZWQM.

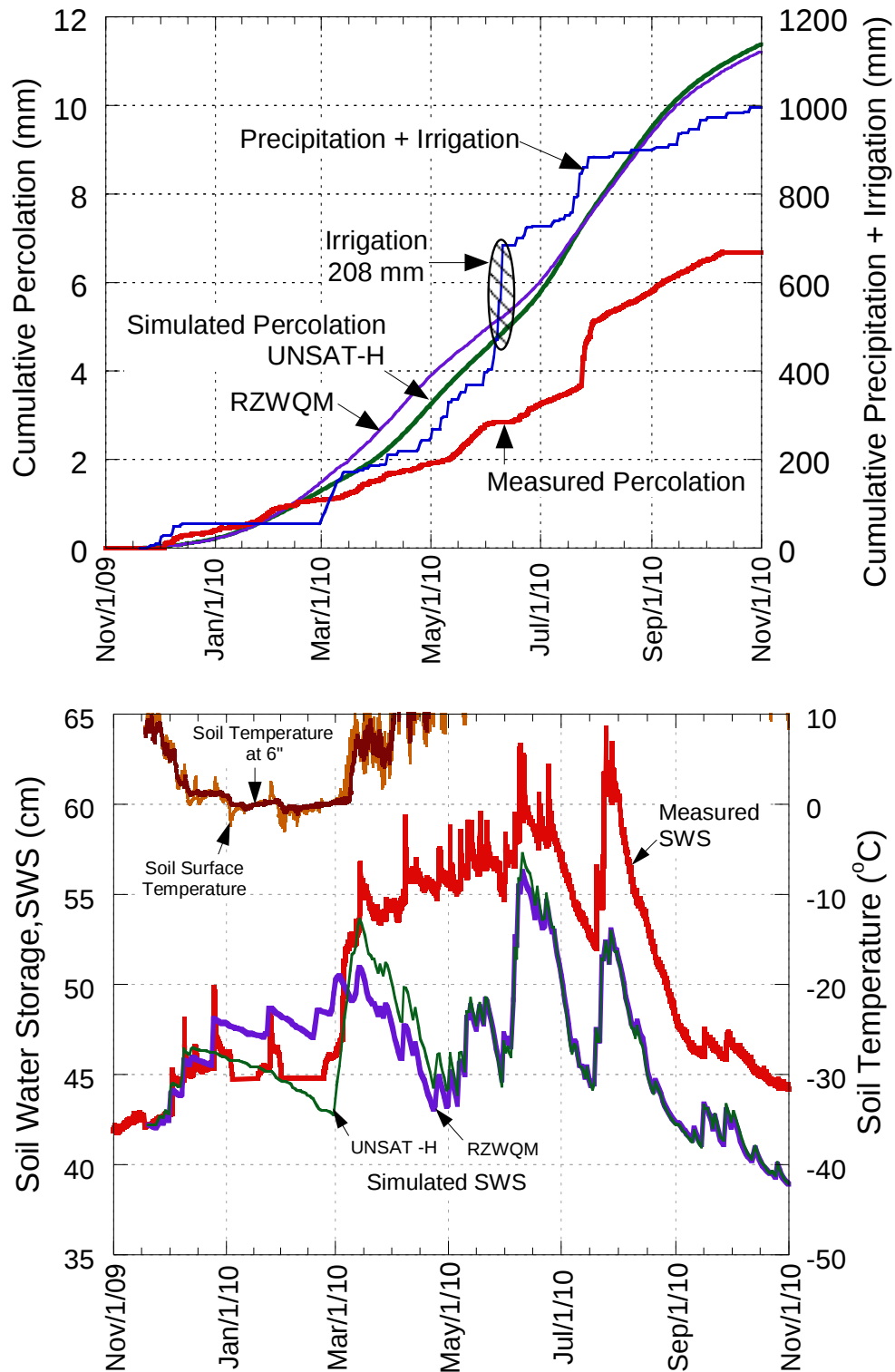


Figure 4.11: Measured and simulated cumulative percolation (a); and soil water storage (b)

during Year 1.

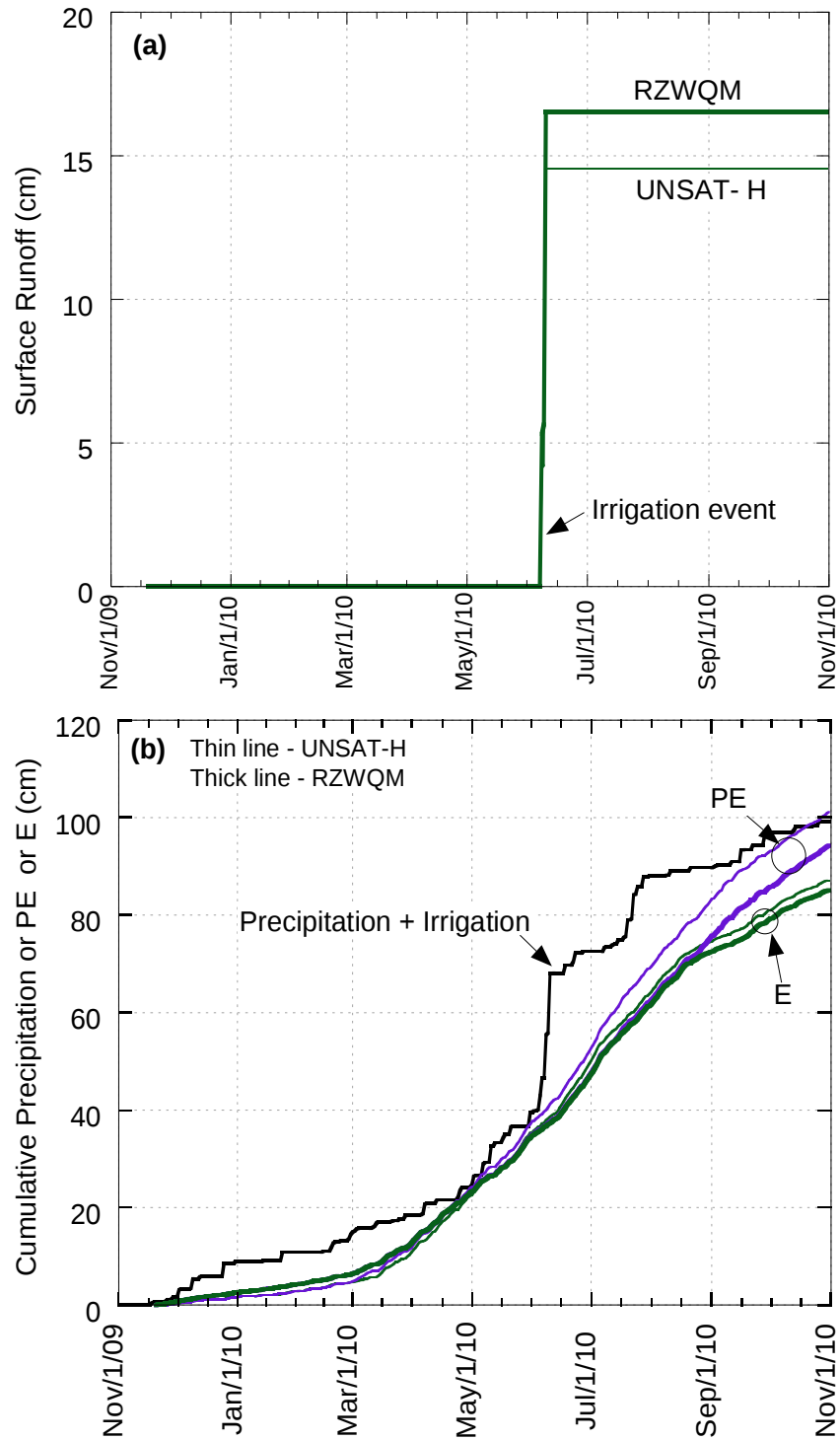


Figure 4.12: Simulated cumulative surface runoff (a); and cumulative evaporation (E) and cumulative potential evaporation (PE) (b) during Year 1.

4.4.3 Simulations of Year 2

Figure 4.13(a) presents the measured and simulated cumulative percolation for Year 2 together with measured cumulative precipitation. During Year 2, the total water applied to the model was about 1,038 mm and the measured percolation was 75 mm. Year 2 was the wettest year in 50 year history (Figure 3.10a) which partly contributed to greater percolation. UNSAT-H and RZWQM with only micropore flow simulated cumulative percolation of about 40 mm which was about half of the measured cumulative percolation. In addition, the slope of the field cumulative percolation was steeper than that simulated by UNSAT-H or RZWQM. Percolation measured during Year 2 was influenced by macropore flow. Hence, those models that are based on the Richard's equation alone underestimated percolation. The macropore flow simulations using RZWQM are presented in Section 4.5.

Figure 4.13(b) presents the measured and simulated SWSs of the test section. The simulated SWSs followed similar trend as the measured SWS. However, the simulated SWSs showed less storage than the measured SWS during Winter 2011. The soil temperature at 6 cm depth indicated frozen ground during the Winter of 2011. The soil temperature at soil surface and the soil temperature at depth of 15 cm are presented in Figure 4.13(b). Compared to Year 1, simulations of Year 2 yield better match with the measured SWS. Effect of frozen ground was less during Year 2 compared to Year 1. The frozen soil depth and duration were shorter during Year 2 compared to Year 1. During Winter 2011, UNSAT-H and RZWQM predictions were slightly different from each other because the snow melt were simulated differently. The snow melt approach presented by Kustas et al. (1994) was used to melt the precipitation that was snow before input to UNSAT-H whereas RZWQM used an in-built snow melt module PRSM

(Leavesley et al. 1983) to melt the snow according to the air temperature. After March 2011, the models predictions were relatively accurate. From March 2011 to September 2011, the model predictions of SWS were identical to each other. However, after September 2011, RZWQM predicted slightly less SWS and more E compared to UNSAT-H. The simulated cumulative E and PE are presented in Figure 4.14(a). Figure 4.14(b) presents the simulated cumulative surface runoff during Year 2. The simulated surface runoff events between the models showed few differences in Spring 2011 which could be because of the difference in snow melting approach and RZWQM uses Green-Ampt approach to model infiltration. However, cumulative simulated surface runoff at the end of Year 2 was similar to each other.

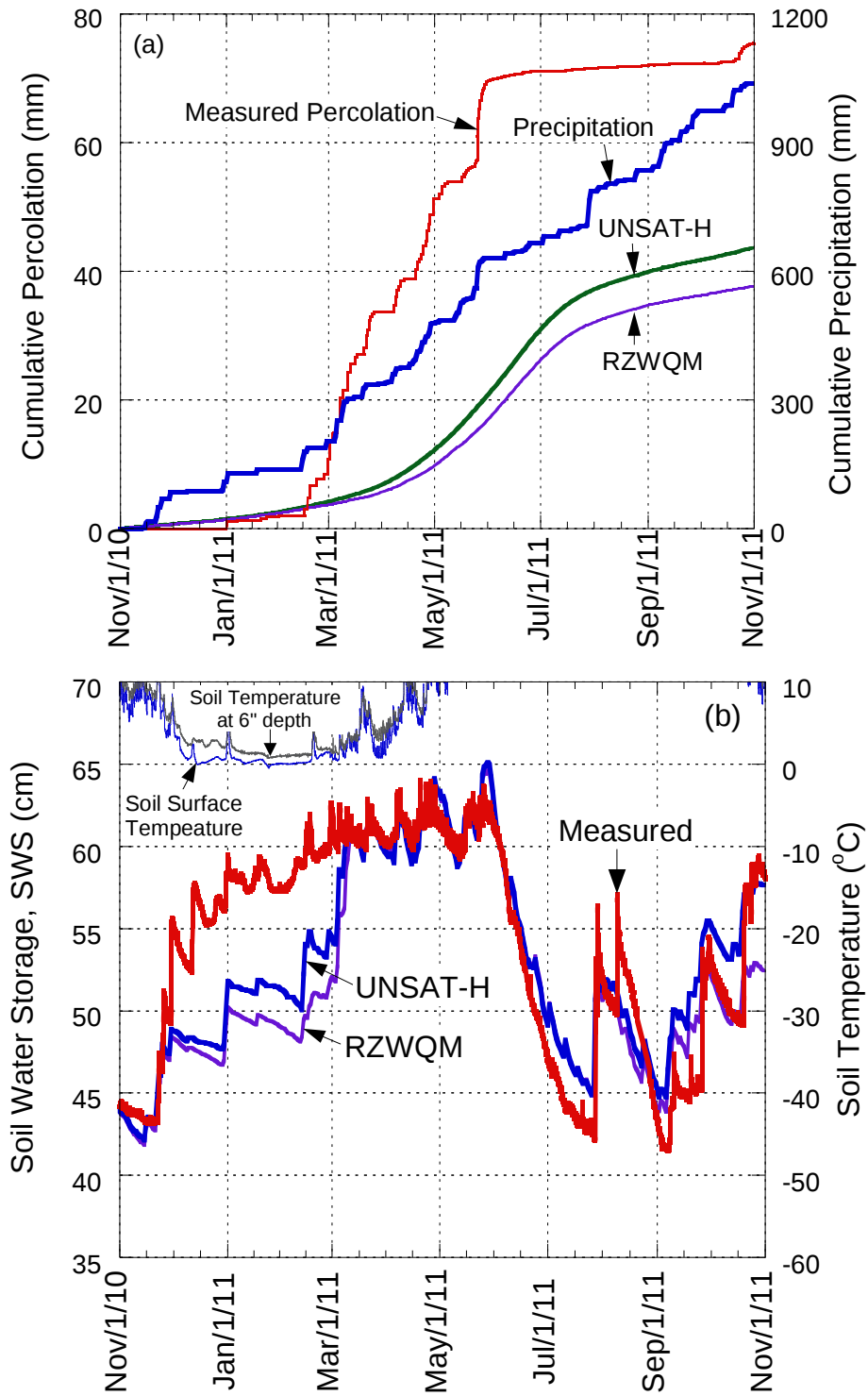


Figure 4.13: Measured and simulated cumulative percolation (a); and soil water storage (b)

during Year 2.

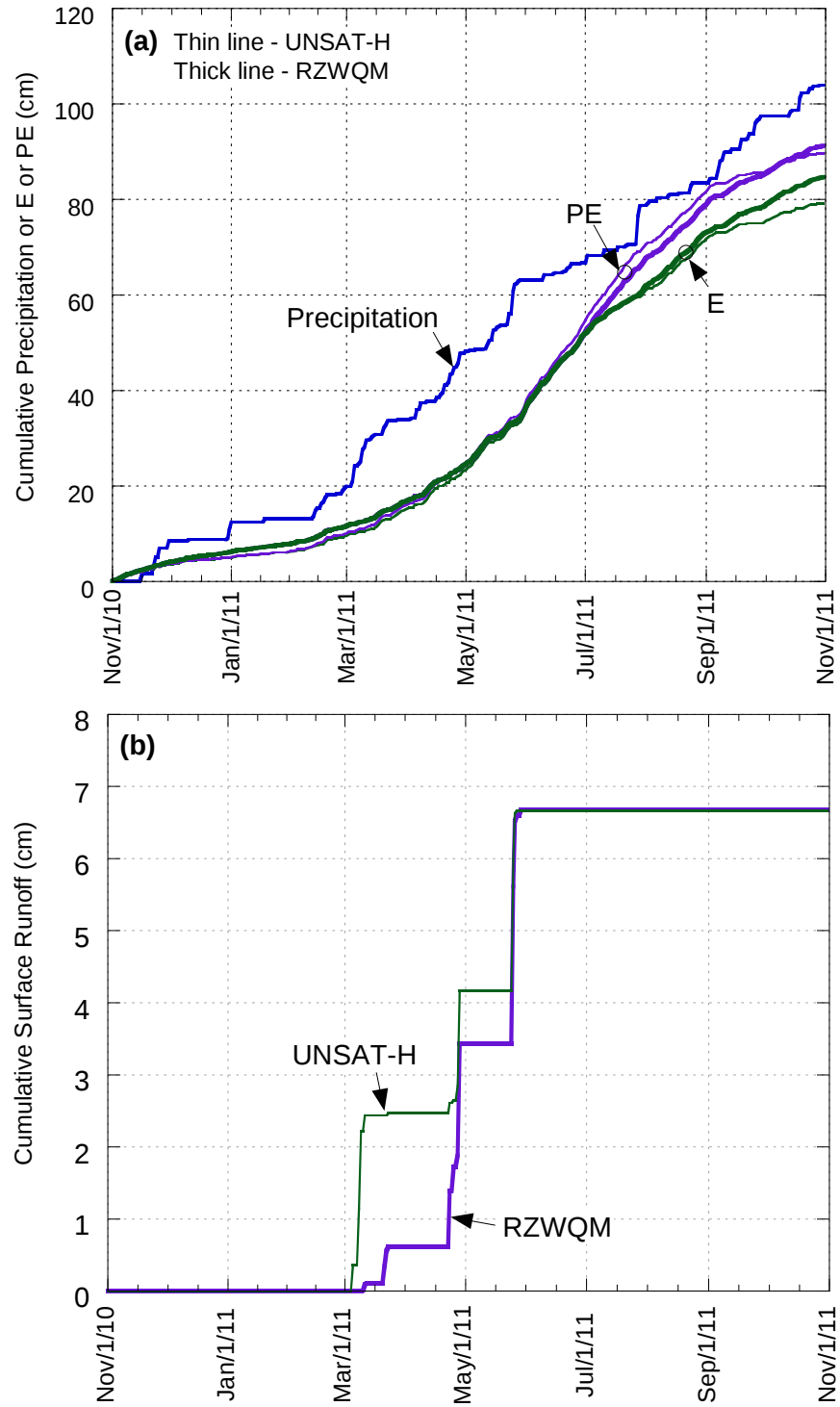


Figure 4.14: Simulated cumulative evaporation (E) and cumulative potential evaporation (ET)

(a); and cumulative surface runoff (b) during Year 2.

4.4.4 Simulations of Year 3

Figure 4.15(a) presents measured and simulated cumulative percolation for Year 3 together with recorded cumulative precipitation. During Year 3, total water applied to models was about 784 mm and measured percolation was 137 mm. About 60% of total precipitation occurred during Winter and Spring 2011/2012. Winter and spring precipitation can increase the percolation through earthen cover because ET is relatively small during winter and spring (Albright et al. 2010). Moreover, the test section was field saturated during Winter and Spring 2011/2012. Hence, initial saturated conditions, and higher precipitation during winter and spring can cause higher percolation during Year 3. However, the slope of the field cumulative percolation was steeper than that simulated by UNSAT-H or RZWQM indicating contribution from macropore flow. The micropore only flow simulations using UNSAT-H and RZWQM predicted cumulative percolation of about 12.5 cm and 9.5 cm, respectively, at the end of Year 3 which was about 90% and 70% of the measured cumulative percolation, respectively. However, the simulated cumulative percolation using UNSAT-H at Line A and Line B shown in Figure 4.15(a) (late January 2012 and late March 2012) were about 37% and 60% of the measured cumulative percolation, respectively. The simulated cumulative percolation using RZWQM was even lower compared to UNSAT-H at the Line A and the Line B shown in Figure 4.15(a). The time lag in simulated cumulative percolation compared to the measured cumulative percolation indicates the influence of macropore flow during Year 3.

Figure 4.15(b) presents the measured and simulated SWSs of the test section. Also, the temperature of the soil surface is presented in Figure 4.15(b). The simulated SWSs were slightly more during Winter and Spring 2011/2012 and slightly less during Summer 2012 compared to

the measured SWS. Unlike during Year 1 and Year 2, ground did not freeze during Year 3 and the simulated SWSs showed better match with the measured SWS. Also, the simulated SWSs using UNSAT-H and RZWQM were comparable.

Comparisons of simulated cumulative surface runoffs, and simulated cumulative evaporations and cumulative PEs during Year 3 are presented in Figure 4.16. Simulated cumulative surface runoff using UNSAT-H and RZWQM were relatively similar. The UNSAT-H simulated about 5 cm less cumulative evaporation compare to RZWQM.

4.5 Macropore Flow Simulations using RZWQM

RZWQM was used to simulate macropore flow that was observed in the field test section. The second irrigation test carried out during the fourth year of service indicated macropore flow through the test section. Percolation measured during the second irrigation test was used to calibrate the macropore flow component of RZWQM. The calibrated model parameters were then used to simulate percolation during Year 2 and Year 3.

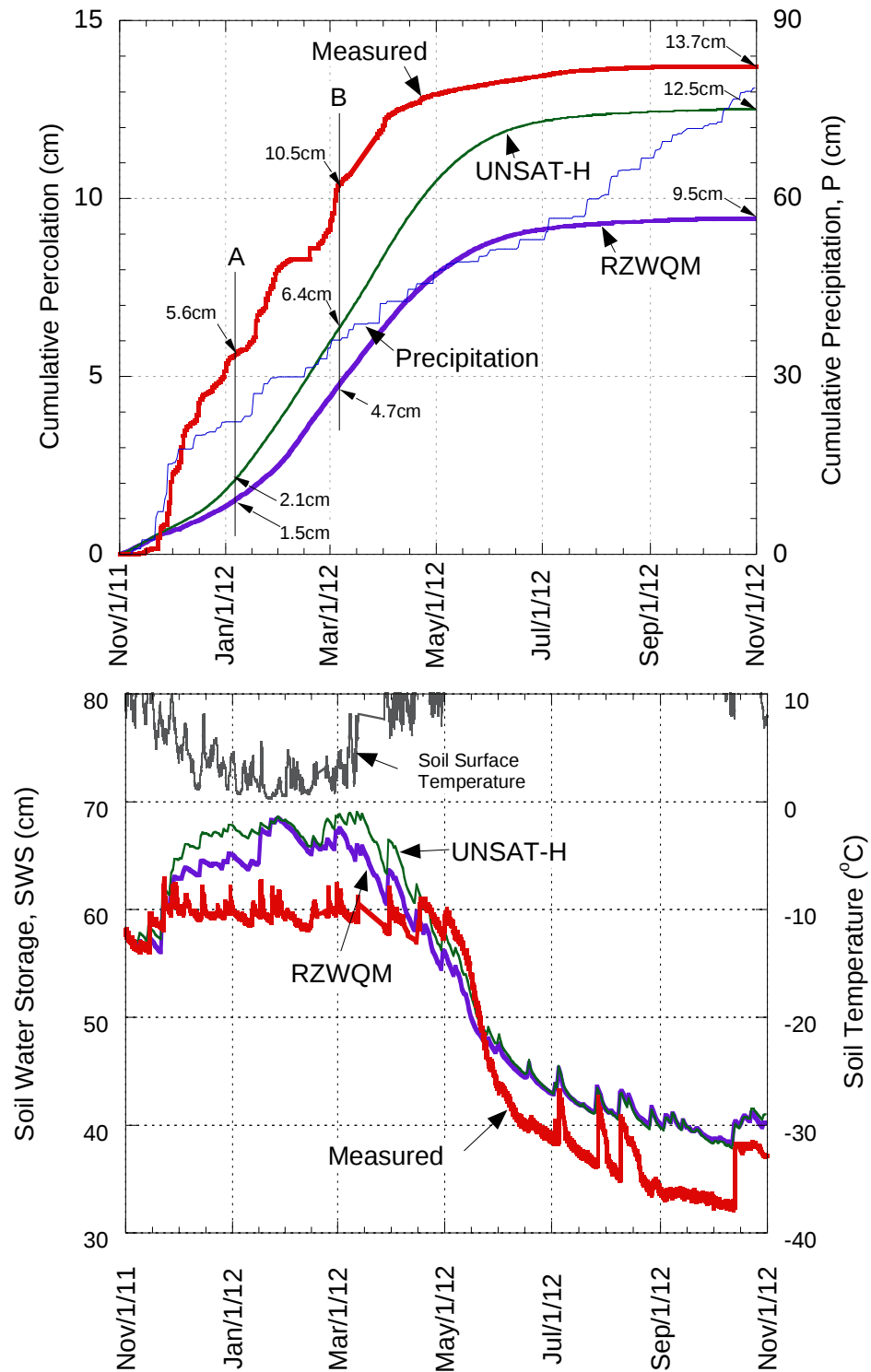


Figure 4.15: Measured and simulated cumulative percolation (a); and soil water storage (b) during Year 3.

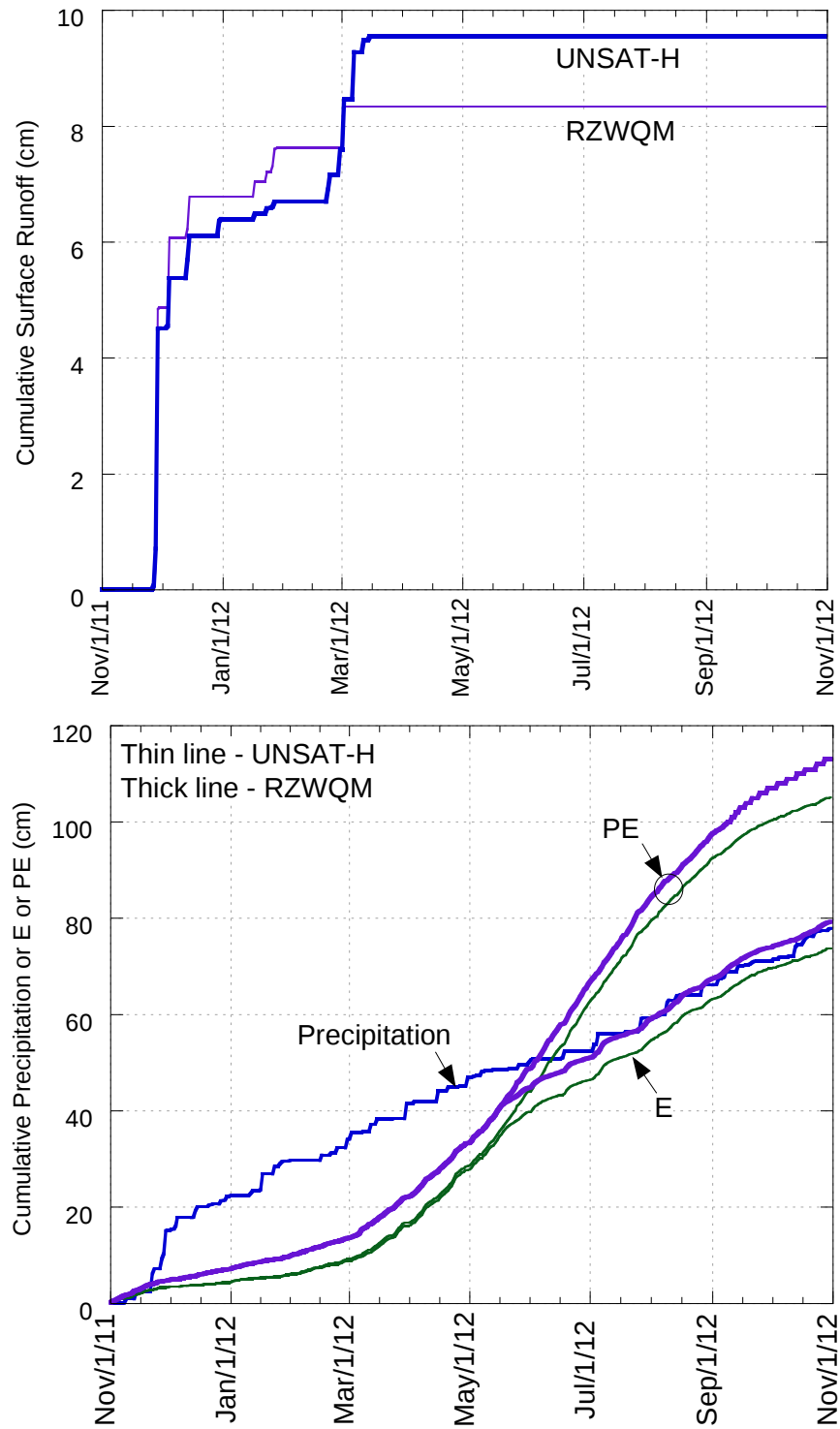


Figure 4.16: Simulated cumulative surface runoff (a); and cumulative evaporation (E) and cumulative potential evaporation (ET) (b) during Year 3.

4.5.1 Calibration of RZWQM for Macropore Flow

Cylindrical macropores were conceptualized in RZWQM and calibrated for their input parameters using field measured percolation during the second irrigation test carried out in the fourth year. The number of macropores per unit area for a given diameter of macropore can be calculated using Eq. 4.5. The spacing of macropores can be calculated using the number of macropore per unit area. Several combinations of diameter and spacing of macropores were able to simulate percolation during the irrigation test. Three sets of macropores used to simulate the percolation are presented in Figure 4.17. Figure 4.17(a) presents the simulated cumulative percolation with and without macropores and measured cumulative percolation. Diameter of cylindrical macropores 1 mm, 3 mm, and 5 mm with spacing of 0.86 m, 8.6 m, and 24 m, respectively were able to simulate the measured percolation relatively accurately. However, only one active macropore was identified within the lysimeter through CH₄ injection tests. Hence, the spacing of macropores was assigned equal to the linear dimension of the lysimeter of 8.5 m. 3 mm diameter macropore with 8.6 m spacing was able to simulate the percolation measured during the irrigation test.

Lateral infiltration from macropore to the soil matrix is fully allowed by setting the sorptivity factor for lateral infiltration to 1.0. The sorptivity factor 1.0 allows the lateral infiltration to occur according to the hydraulic gradient without any reduction. Also, a fraction of the deadend macropores was set to zero because non-active macropores were not identified within the lysimeter area during CH₄ injection tests. The measured and simulated SWSs with and without macropores are presented in Figure 4.17(b).

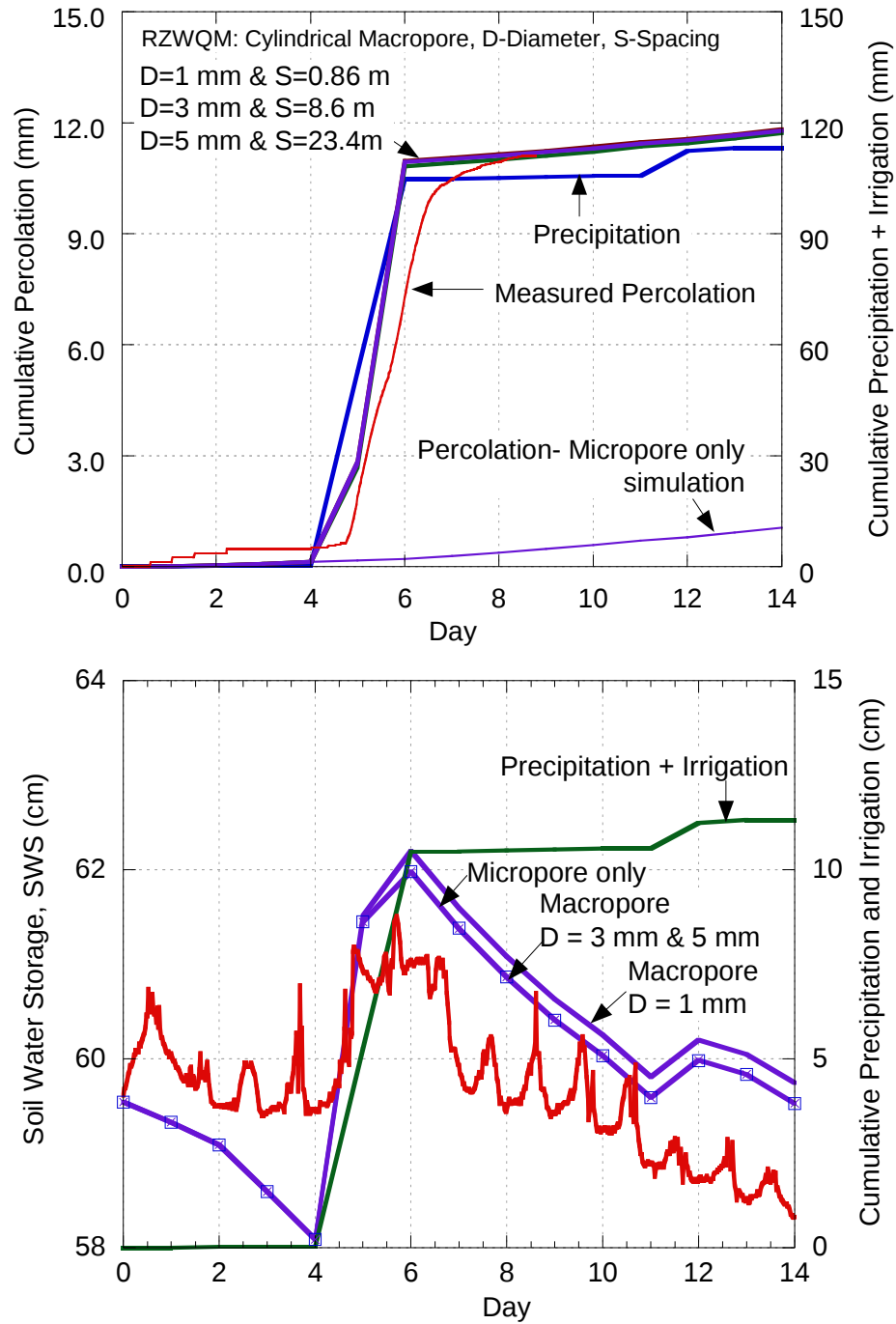


Figure 4.17: Measured and simulated percolation (a); and soil water storage (b) during the second irrigation test with micropores and macropores.

The simulated SWS using macropores having 3 mm and 5 mm diameter were similar. However, when the diameter of macropore was 1 mm it increases the SWS by few mm. The infiltration that enters macropores can be absorbed by the soil matrix depending on the degree of saturation of the soil and the balance releases profile as percolation. When the number of macropores is less and the diameter of the macropores large, percolation increases and relatively small amount of water is absorbed into the soil matrix. When the diameter and spacing of macropores decrease, the number of macropores increases. Hence, the total surface area of macropores walls increases and the amount of lateral infiltration increases which leads to increase in SWS. Figure 4.18 presents the simulated cumulative surface runoff with and without macropores. The simulated surface runoff with macropore is less than the surface runoff simulated without macropores. The cumulative surface runoff was reduced by about 1 cm compared to micropore only simulation which was re-routed into macropores. For simulation with macropores of diameter reduced to 1 mm, cumulative runoff was reduced further by few mm because greater macropores wall area results in greater absorption of infiltration.

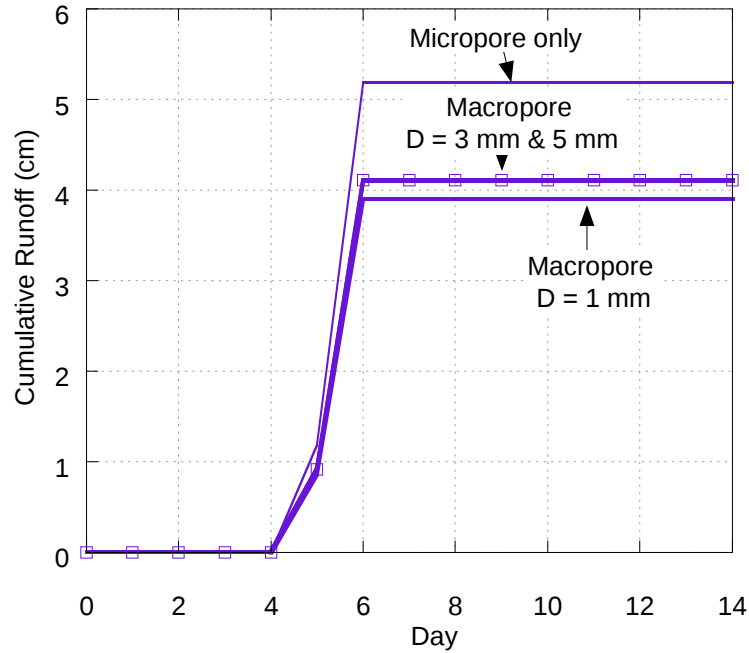


Figure 4.18: Simulated surface runoff during the second irrigation test with and without macropores.

4.5.2 Year 2 Simulation with Macropore Flow

The calibrated macropore parameters, 3 mm diameter cylindrical macropore at 8.6 m spacing, were used to simulate percolation during Year 2. Figure 4.19(a) presents recorded cumulative precipitation, and measured and simulated cumulative percolation for Year 2. Combined micropore and macropore simulation using the calibrated macropore parameters simulated cumulative percolation much better than micropore only simulation for Year 2. However, macropore simulation predicted about 1cm less cumulative percolation (about 13% less) compared to measured cumulative percolations. Year 2 was the wettest year in 50 years history of the site. The estimated k_{eff} based on the percolation measurement showed higher k_{eff} during Year 2 than during the second irrigation test (refer to Figure 3.14). Hence, macropore parameter needed to be reassigned. Larger macropore diameter was input to match the measured

cumulative percolation during Year 2. Macropore diameter of 3.6 mm with spacing of 8.6 m provided reasonably good prediction of cumulative percolation. The size of the macropore can change in the field due to swelling or shrinkage of clay, plant root penetration and death, and animal activity. Hence, calibration of macropore parameters needs to be done routinely to capture the macropore flow accurately.

The measured and simulated SWSs with and without macropores are presented in Figure 4.19(b). The simulated SWS with macropores was comparable to the simulated SWS without macropores.

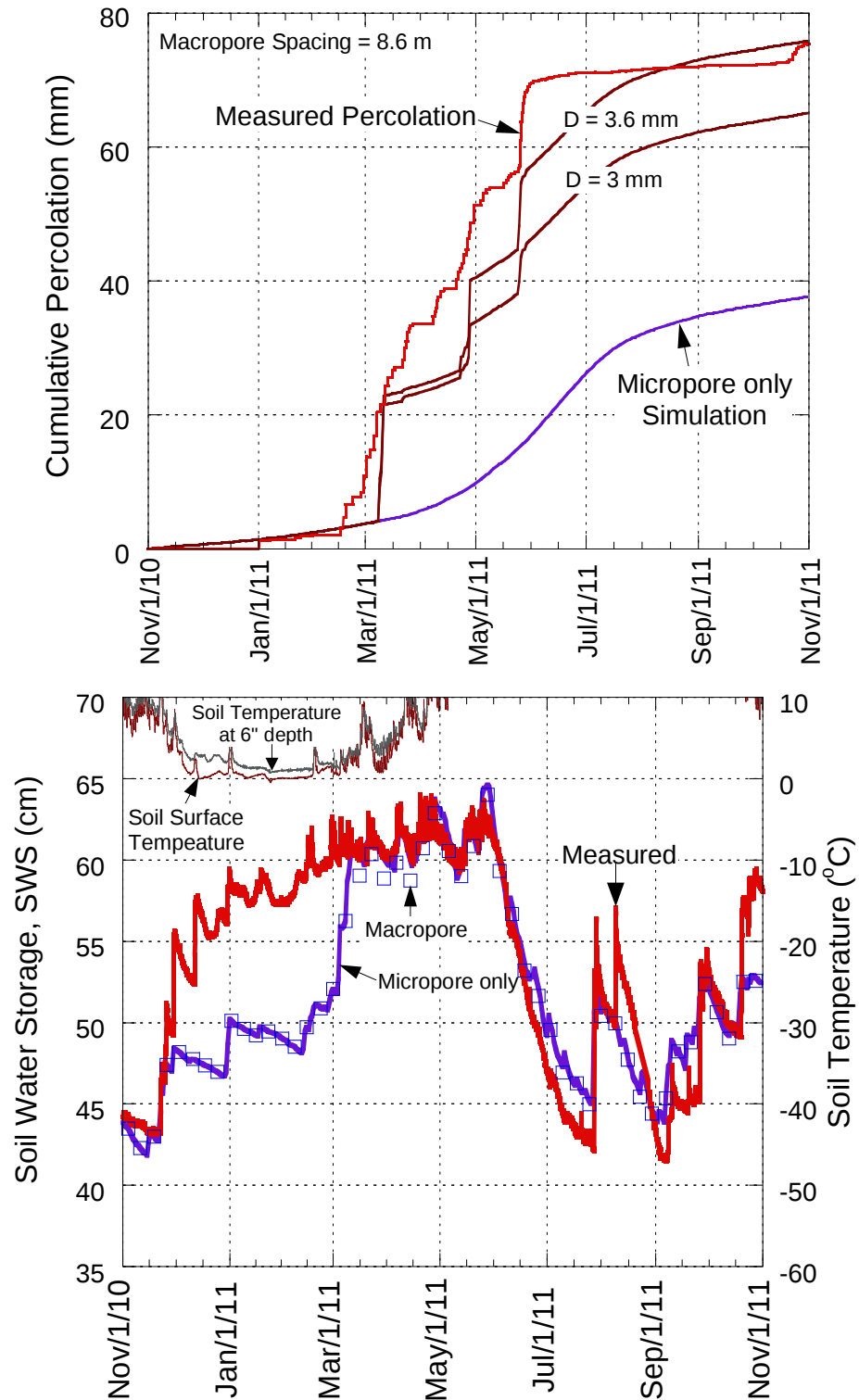


Figure 4.19: Measured and simulated percolation (a); and soil water storage (b) during Year 2 with and without macropores.

Simulated surface runoff during Year 2 with and without macropores is presented in Figure 4.20. As expected, macropores reduced simulated cumulative surface runoff compared to micropore only simulation. The reduction in surface runoff due to macropores was very close to the increase in simulated percolation. This shows that the model simulates all infiltration that enters the macropores is either absorbed by the matrix or is routed as percolations.

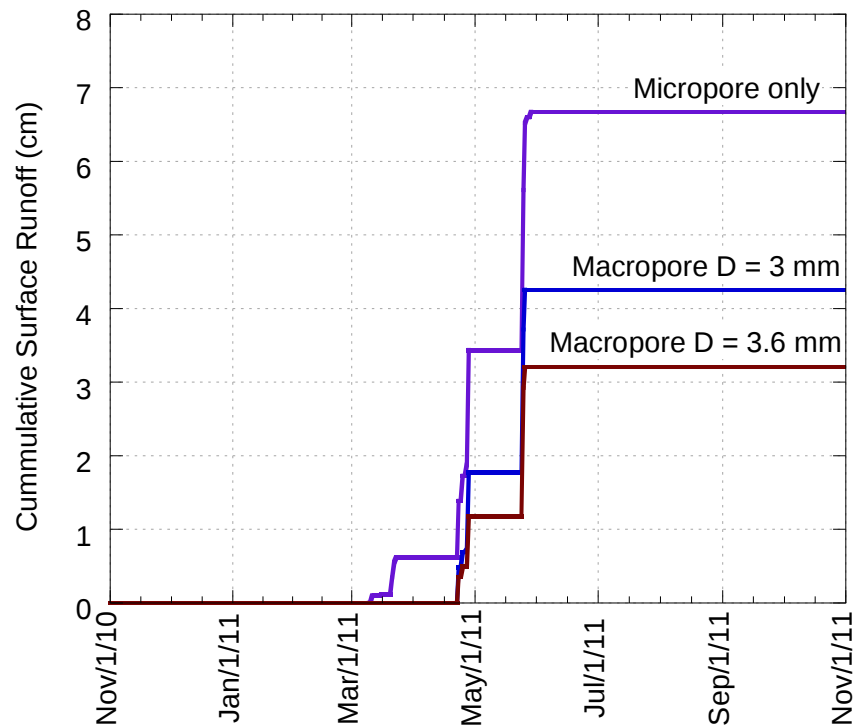


Figure 4.20: Simulated cumulative surface runoff during Year 2 with and without macropores.

4.5.3 Year 3 Simulation with Macropore Flow

Unlike the simulation of Year 2 with macropores where using the irrigation test data calibrated macropore parameters underestimated cumulative percolation, simulation of year 3 with calibrated macropore parameters provided excellent match with measured percolation. Figure 4.21(a) presents the measured and simulated cumulative percolation of Year 3. The estimated maximum k_{eff} during Year 3 and Year 4 were comparable. During the winter and spring of the Year 3 and Year 4, the test section was close to saturated compared to Year 2. When clay is saturated, swelling can reduce the macropore cross section area. Hence, the calibrated size simulated Year 3 better but not Year 2. Also, because the macropore size can be larger during Year 2, Year 2 required larger macropore diameter than the calibrated value. These results show that macropore geometries do change during service.

The measured and simulated SWSs with and without macropores are presented in Figure 4.21(b). The simulated SWSs with and without macropores were comparable. Figure 4.22 presents the simulated cumulative surface runoff during Year 3 with and without macropores. Macropores reduced the cumulative surface runoff which is consistent with simulation for Year 2.

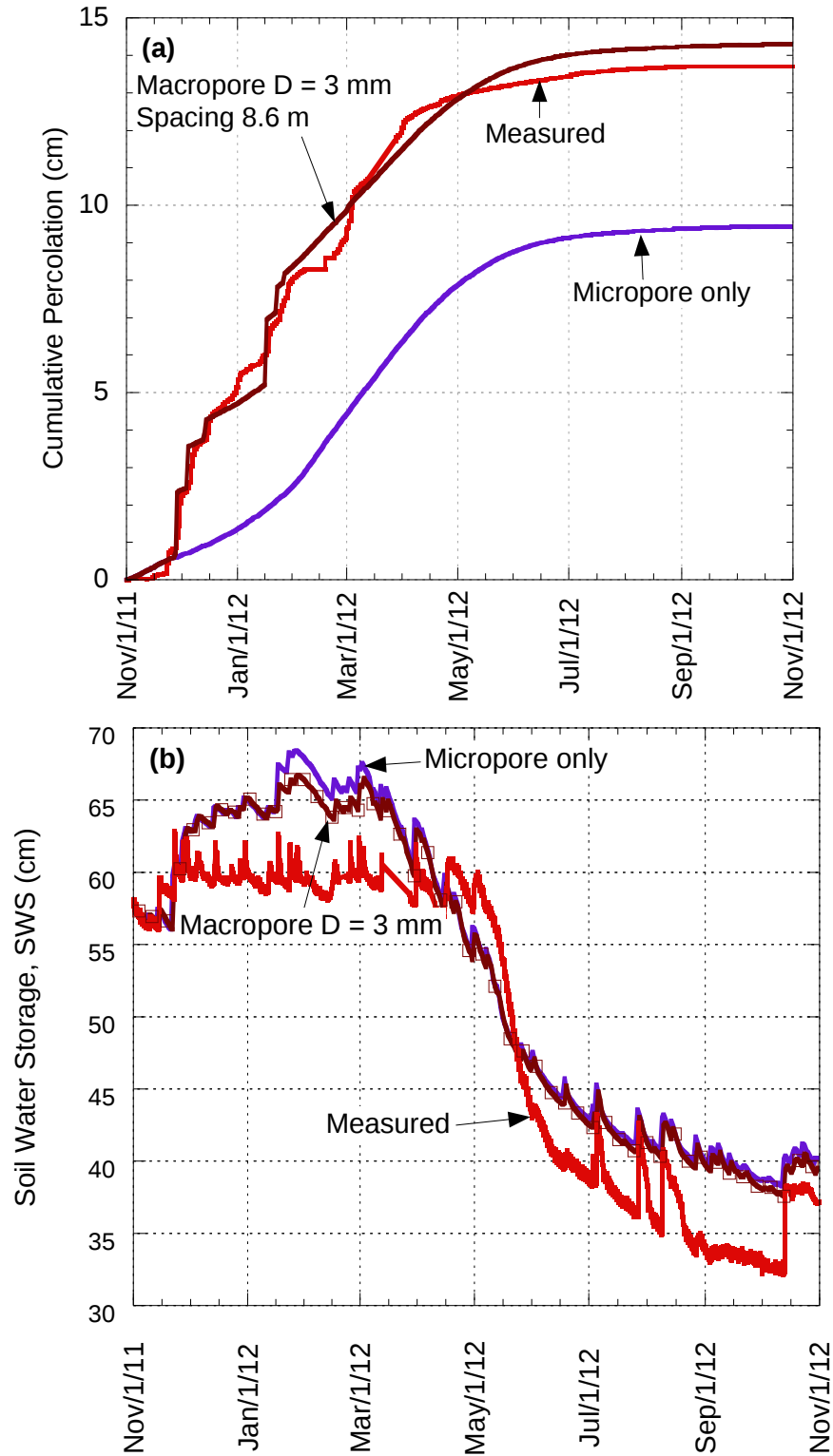


Figure 4.21: Measured and simulated cumulative percolation (a); and soil water storage (b) during Year 3 with and without macropores.

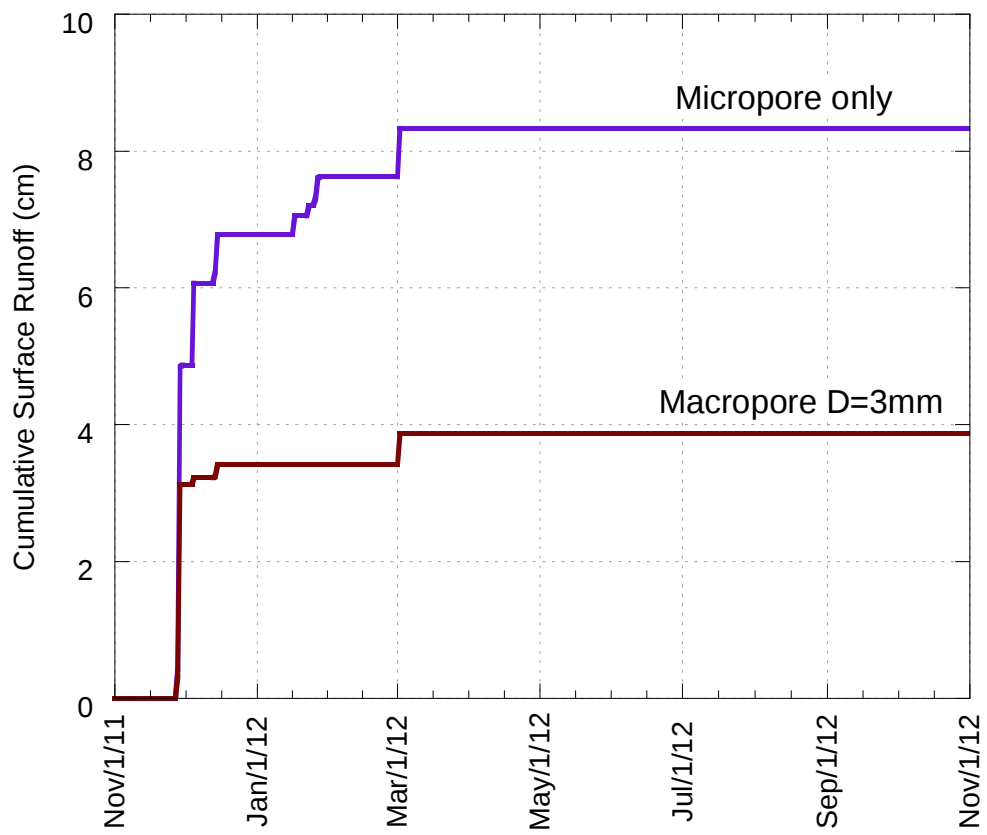


Figure 4.22: Simulated cumulative surface runoff during Year 3 with and without macropores.

CHAPTER 5: LABORATORY TESTING OF MACROPOROUS COMPACTED CLAY SAMPLES

Testing macropore flow through cracks in fine-grained soil in laboratory is a challenging task due to the self-healing nature of cracks. Increase effective stress, erosion of particles from macropore wall clogging the cracks, and swelling of clay are attributed as major causes of this self-healing nature of cracks (Eigenbrod 2003; Wang et al. 2013; Kim and Daniel 1992; Othman and Benson 1993). Self-healing mitigates the macropore flow by partially closing the cracks. However, evaluation of macropore flow in laboratory is needed to improve our understanding of macropore flow phenomena in clay. Ahuja et al. (1995) used quick-setting cement to prevent the closure of macropores during laboratory test in their experimental setup. A new technique was developed in this study to create macropores in the lab. Crystal sugar supported by a thin highly permeable insect mesh was inserted within the clay specimen during compaction. The sugar dissolved during permeation and formed macropores where sugar once occupied the space. Control tests were carried out to test the effect of sugar in the permeant on permeability of compacted clay specimen. Double ring rigid wall permeameter was used to measure the hydraulic conductivity of the compacted specimens. High resolution X-Ray CT scans were performed on compacted clay specimens to develop 3D morphology of the macropores. Macroporosity and morphology of macropores were analyzed using X-ray CT images. Also, the X-ray CT images were used as direct input to LBM which is described in Chapter 6.

5.1 Self-healing of Cracks in Compacted Clay Soil

The self-healing behavior of clay used to construct the field test section (Section 3.1) was evaluated. Particle size distribution of the specimen is presented in Figure 5.1(a). The uniformity coefficient and coefficient of curvature of the clay are 70 and 0.7, respectively. Percentage of fines in the clay soil is about 78%. The SP compaction test results are shown in Figure 5.1(b). The optimum water content and maximum dry unit weight of the clay for SP effort was 13.4% and 18.5 kN/m^3 , respectively. The LL and PI of the clay is 29 and 13, respectively. The SL of the clay as predicted using the LL and the PI based on a procedure presented in Holtz and Kovacs (2010) is 13.25. The clay is classified as CL according to USCS.

The first specimen, 30 cm diameter and 30 cm tall, to evaluate the self-healing behavior was compacted at 4% dry of optimum water content in 6 cm thick lifts. Achieved dry unit weight was about 98% of the maximum dry unit weight. The compaction criteria were similar to the field compaction of the test section. The specimen was initially saturated and then dried for about three months. Cracks were formed but the cracks were mostly shallow. Figure 5.2(a) presents the picture of the cracked clay specimen. The specimen was wetted by gradual spraying. The cracks partially self-healed and closed as shown in Figure 5.2(b). Similar observation was reported by Greve et al. (2010).

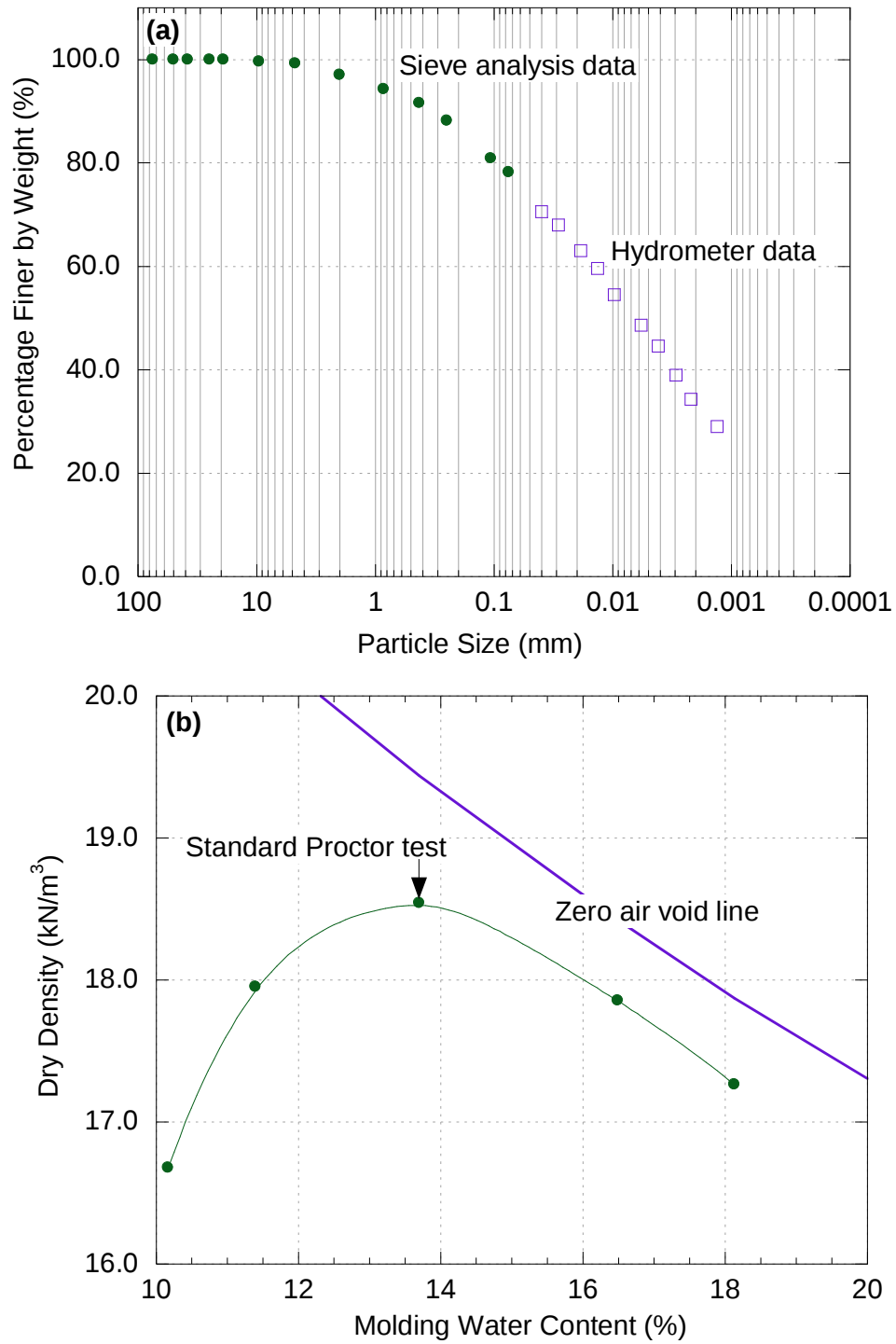


Figure 5.1: Particle size distribution (a); and compaction curve (b) of the clay used for macroporous specimens.

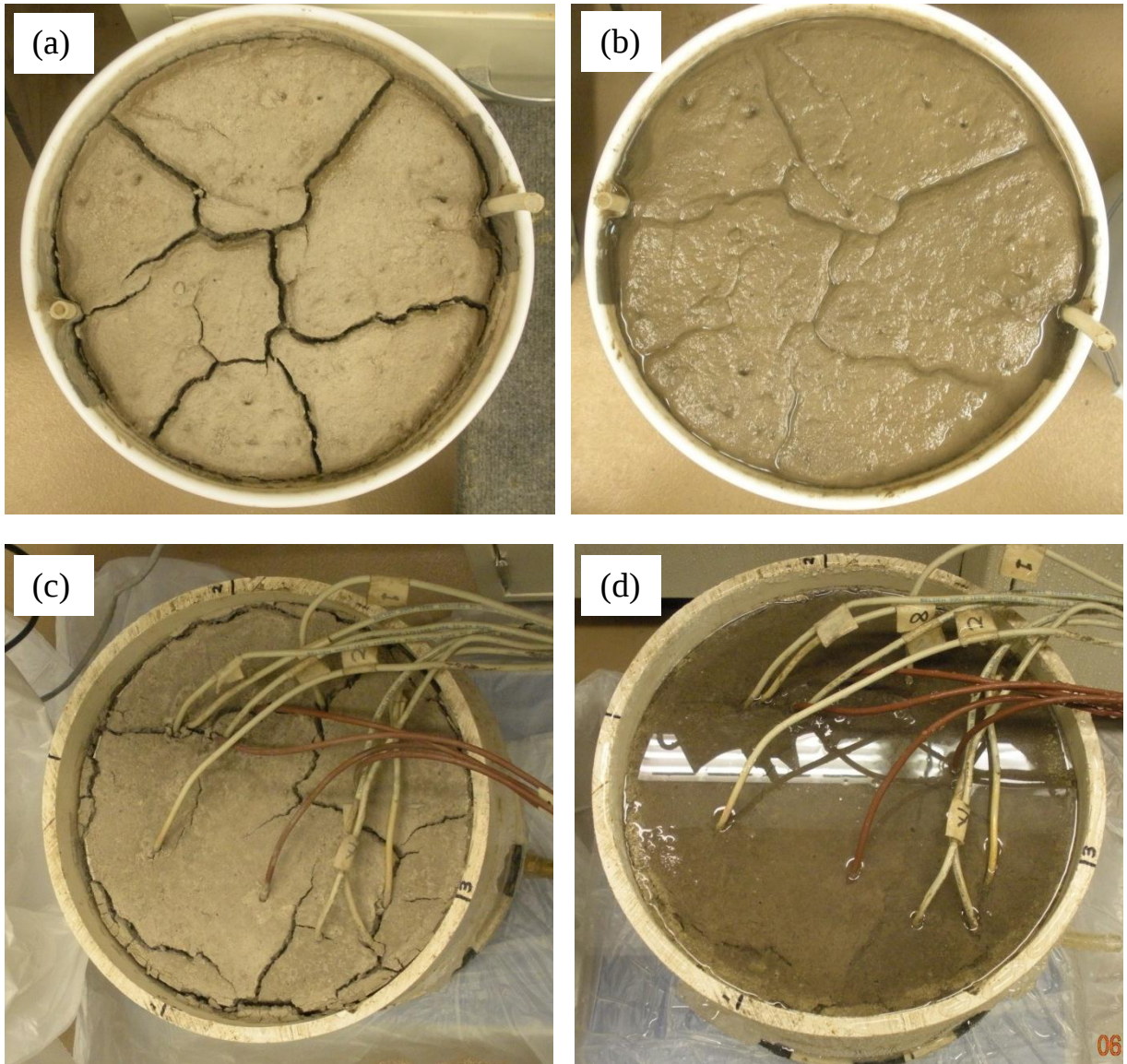


Figure 5.2: Cracked (a); and self-healed (b) sample-1; and cracked (c); and self-healed (d) sample-2.

The second specimen was compacted in four lifts and two water content and water potential sensors were placed in between each lifts. The specimen was compacted in a PVC specimen holder. Compaction criteria used for the first specimen was followed. The specimen was initially saturated with about 2 cm head of water ponded on the specimen and then the water level was increased to about 90 cm to increase the gradient. Measured water contents indicated that the specimen reached saturation in about a month. Measured water content is presented in Figure 5.3. The saturated specimen was dried for about a month. Cracks formed in the specimen as shown in Figure 5.2(c). The specimen wetted by ponding of water. Initially ponding height was about 2 cm and then the water level was increased to 90 cm. The measured water contents increased suddenly after the water was ponded indicating the cracks were developed to at least 21 cm depth. The water contents dropped to a steady-state level in about a day indicating the self-healing of cracks.

5.2 Macroporous Specimen Preparation

The specimens were compacted in 10 cm diameter Proctor compaction mold. Standard procedure for SP compaction test was followed (ASTM 2007). However, food grade crystal sugar packed in an insect mesh was placed within specimen at each lift as shown in Figure 5.4. The specimen was compacted. The continuity of sugar column was maintained between lifts. Within a lift the shape of the sugar packed space was straight or tortuous. Three macroporous specimens were prepared namely S1, S2, and S3. S1 with two vertical columns of sugar, S2 with one vertical column of sugar, and S3 with one tortuous column of sugar were prepared. After compaction the specimens were retrieved using a hydraulic extruder.

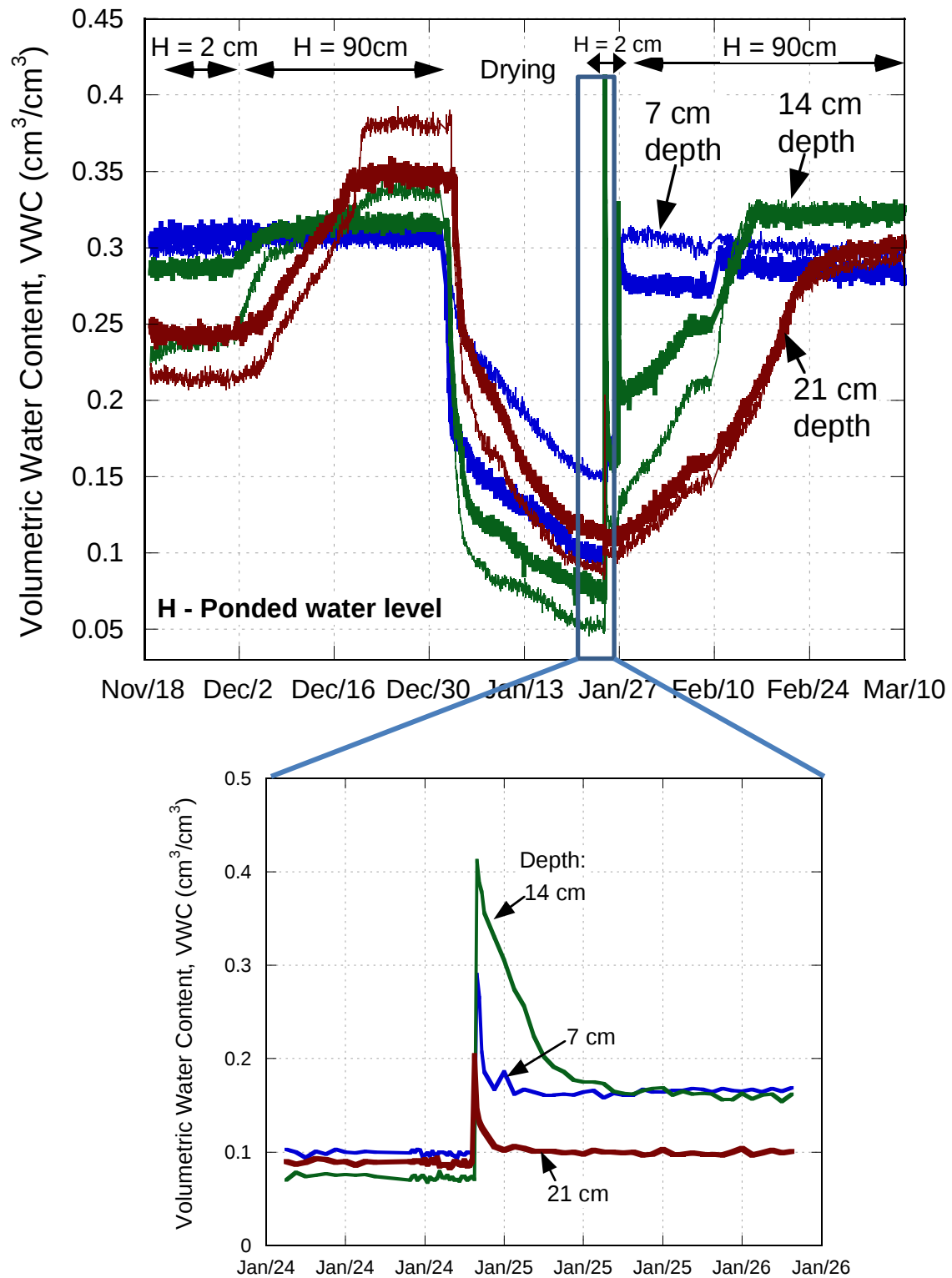


Figure 5.3: Measured water content of Sample 2 during drying and wetting.

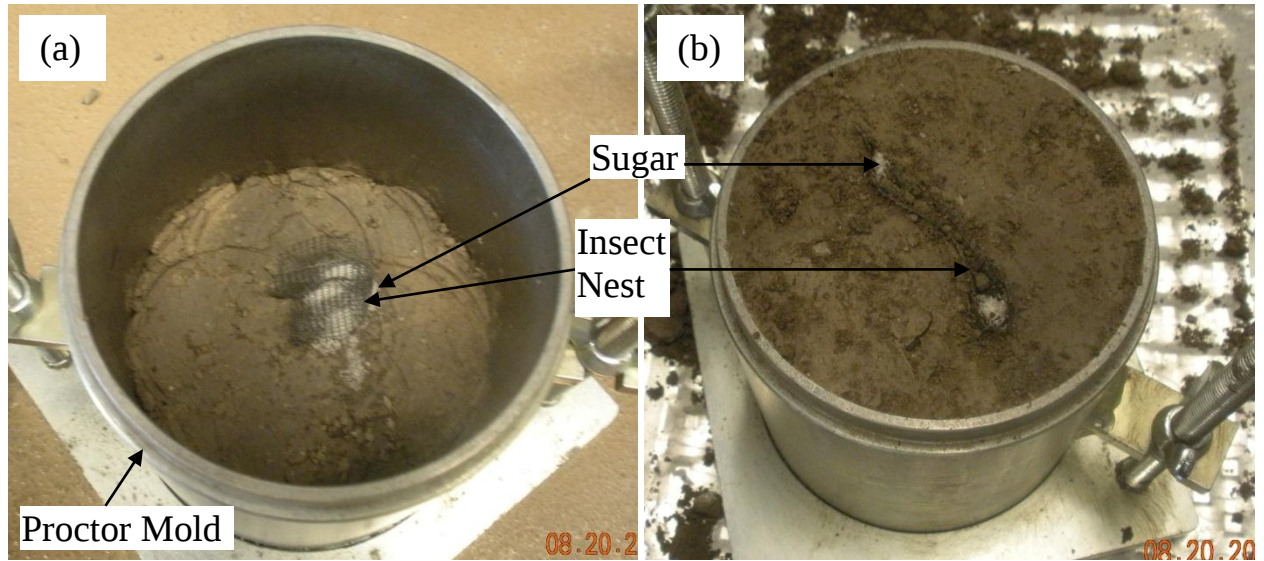


Figure 5.4: Macroporous specimen preparation: at the end of the first lift (a); and at the end of compaction (b).

The specimens were tested in flexible wall permeameter (ASTM 2010a). Two control tests were carried out on intact specimens using only DI water and DI water with dissolved sugar as the permeant to test the effect of sugar on hydraulic conductivity of the clay specimens. The concentration of sugar in the permeant (20 g/L) was decided based on the amount of sugar added to and the pore volume of the macroporous specimens. Flexible wall permeameter results are presented in Figures 5.5 and 5.6. The k_{sat} of specimens without macropores (control) were 1×10^{-6} cm/s. and 5×10^{-7} cm/s. Ratio of outflow to inflow reached about one when one pore volume of flow had passed. The cumulative volume change [Figure 5.6(b)] of the specimen shows shrinkage at pore volume equal to 1.6 due to increase in confining pressure. The hydraulic conductivity decreased when sugar solution was used as the permeant and the tests needed to be stopped before they reached steady state due to time limitations. Also, detailed analysis on how

sugar water influences the permeability of clay soil is not considered in this study. However, the tests confirmed that the sugar solution decreases the hydraulic conductivity. Hence, increase in hydraulic conductivity of macroporous specimens would be due to the macropores and not due to the sugar in the permeant.

Hydraulic conductivity of macroporous specimens were measured using flexible wall permeameter. The influent, effluent, and confining pressures were maintained at 13.8 kPa, 3.4 kPa, and 20.7 kPa, respectively, for specimens S1 and S2. The confining pressure of specimen S2 was increased to 27.6 kPa after the pore volume reached about 2.6 to study the effect of confining pressure on macropores. For specimen S3, the influent, effluent, and confining pressures were maintained at 3.4 kPa, 0.0 kPa, and 6.9 kPa, respectively. The sugar used to create the macropores was flushed out once the influent was permeated. Figure 5.7(a) presents the measured k_{sat} of macroporous specimens using flexible wall permeameter. Measured k_{sat} of all three macroporous specimens was about 1×10^{-3} cm/s which is the permeability of the flexible wall permeameter. Hence, the k_{sat} of macroporous specimens can be $\geq 1 \times 10^{-3}$ cm/s. The k_{sat} of macroporous specimens were measured using double ring rigid wall permeameter (discussed in Section 5.3). The effect of increase in confining stress tested in S2 is presented in Figure 5.7(b). Increase in confining pressure reduces k_{sat} because increase in effective stress closes the crack (Kim and Daniel 1992). The decrease in volume as the confining stress increased shown in Figure 5.7(b) is an indication of healing of crack. Similar finding on natural macropores were presented by Kim and Daniel (1992), Othman and Benson (1993), and Eigenbrod (2003). Hence, the artificial macropores developed in this study behave similar to natural cracks when effective stress increases.

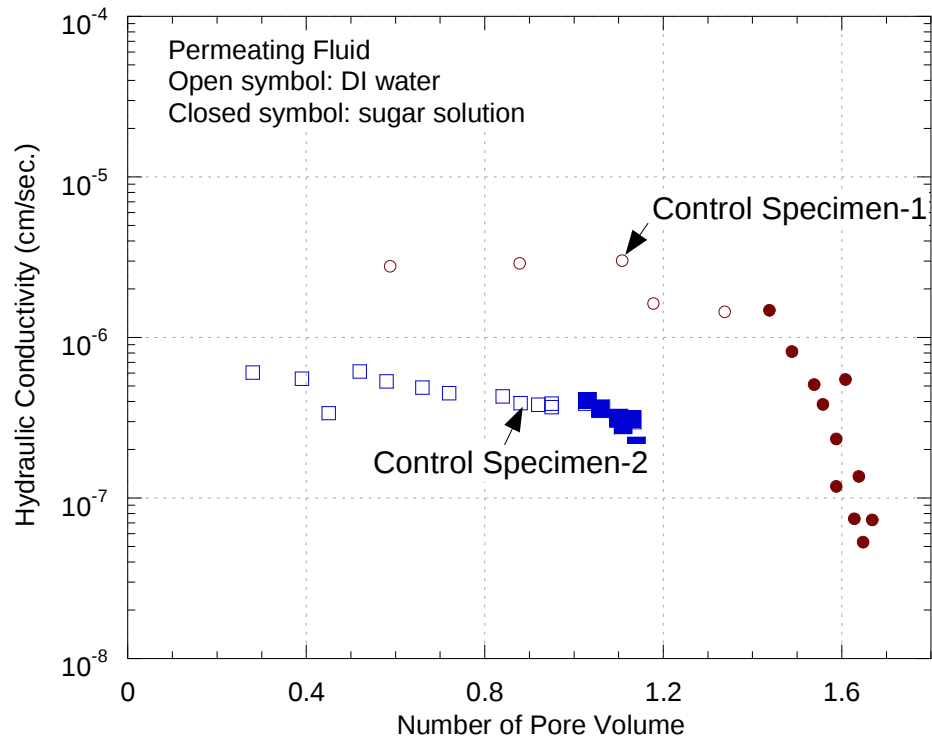
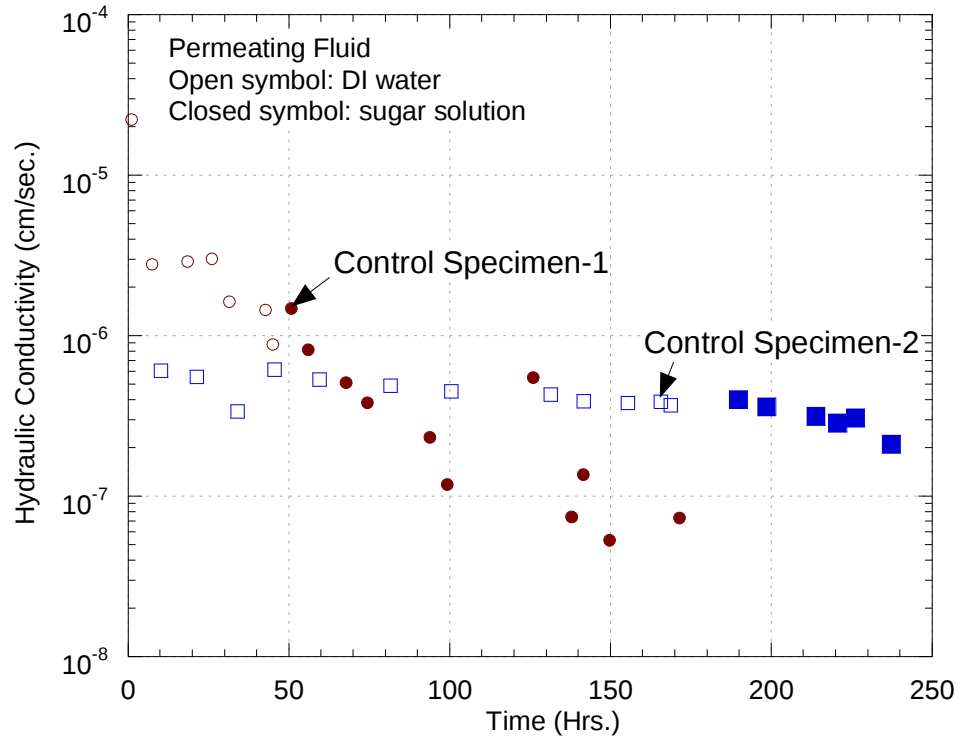


Figure 5.5: Measured hydraulic conductivity of compacted clay intact samples with time (a); and with number of pore volume (b).

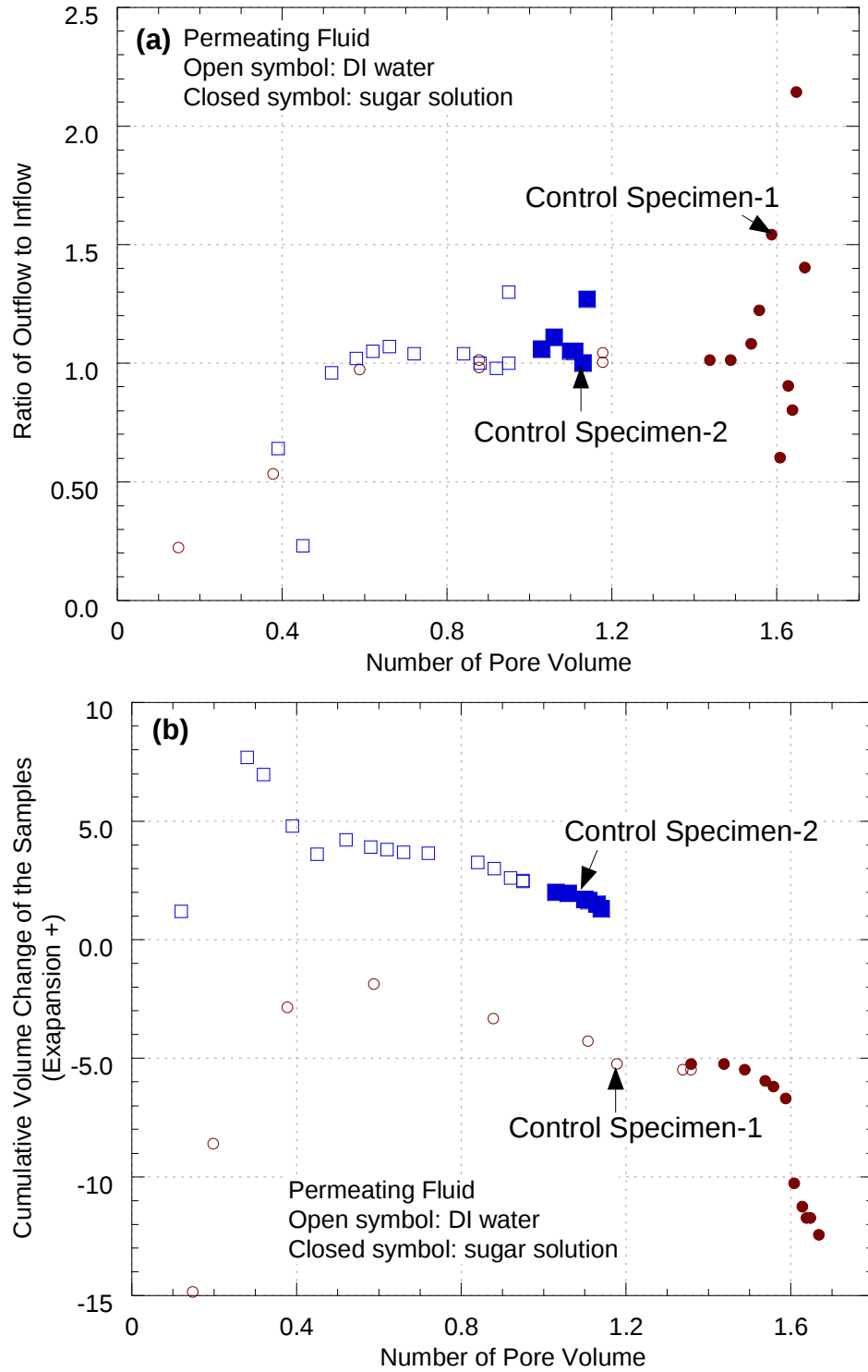


Figure 5.6: Ratio of outflow to inflow (a); and cumulative volume change of the specimens (b) during flexible wall permeability test.

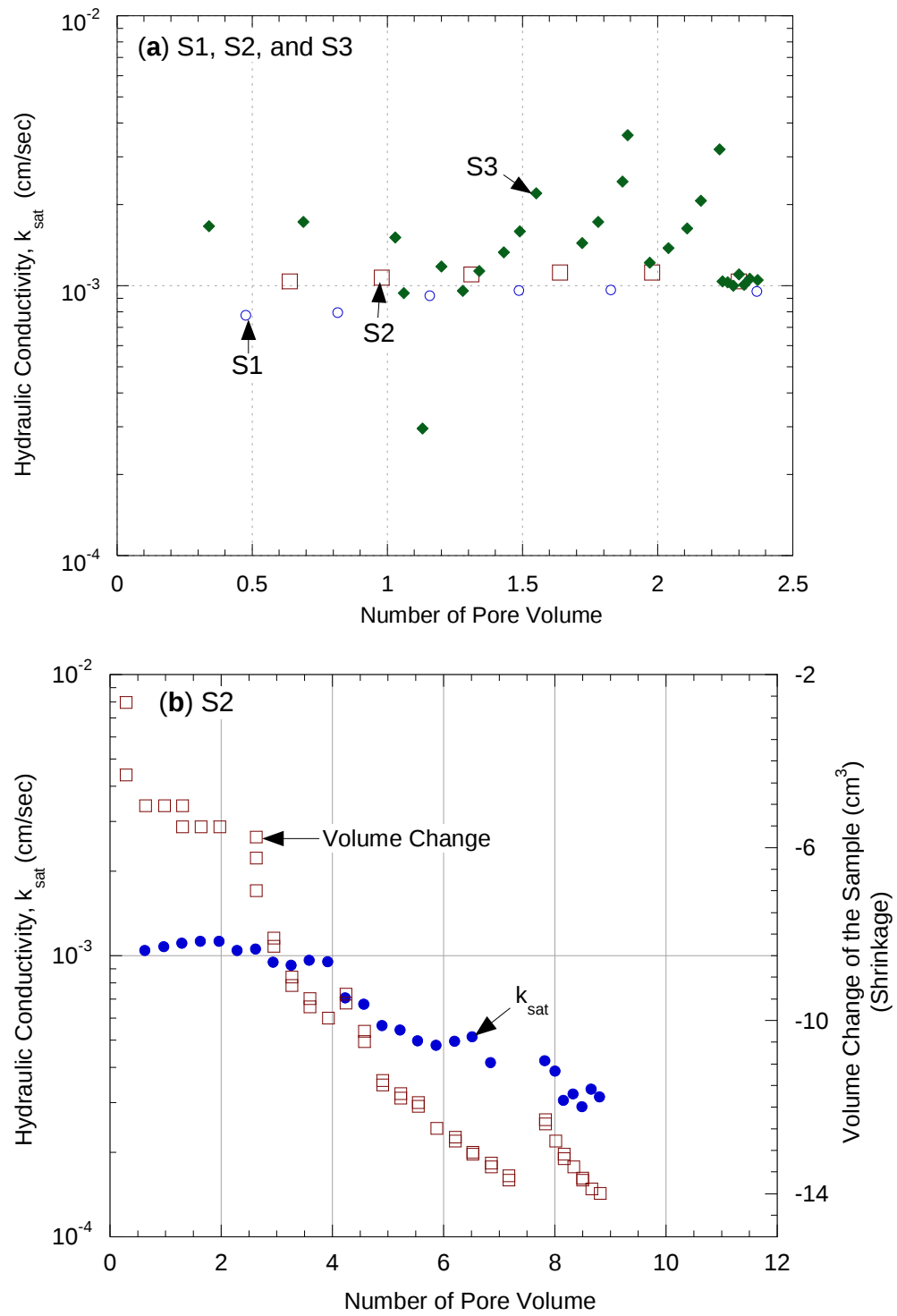


Figure 5.7: Measured hydraulic conductivity of macroporous specimen using flexible wall permeameter.

5.3 Measurement of Macropore Flow

Because flexible wall permeameter with higher k_{sat} measurement capability was not available, a double ring rigid wall permeameter (DRRP) was used to measure k_{sat} of the macroporous specimens. Figure 5.8 shows the DRRP setup. Common issue with rigid wall permeameter on measuring k_{sat} of fine grain soil is side wall leakage (Boynton and Daniel 1985). The DRRP has two rings on the bottom plate such that the areas enclosed by both the rings have the same area as shown in Figure 5.8(a). The purpose of the outer ring is to collect water through the area of specimen within the outer ring and evaluate side wall leakage (if any). Hence, water collected from inner ring is not affected by the side wall leakage. The DRRP setup could hold standard compaction specimens having 10.16 cm (4 inches) diameter and 11.64 cm (4.58 inches) height (Figure 5.8(b)). Diameter of the inner ring is 7.18 cm. Geotextile was placed at the bottom within the rings and at the top of the specimen. The specimens were pushed through the inner ring divider as shown in Figure 5.8(c).

Constant head tests were conducted on macroporous specimens as shown in Figure 5.8(d). The hydraulic gradient was maintained at about one. The specimens exhibited swelling during permeation. Figure 5.9 shows the specimen before and after the test. Before the test, few mm of spacing can be noticed between specimen perimeter and rigid wall cell. However, after the test, the gap between the specimen perimeter and the rigid wall of the perimeter was closed or reduced due to swelling of the clay during saturation. The permeability of the inner and outer rings was measured separately. The macropores were within the inner ring on all three specimens. The measured k_{sat} for all three specimens are presented in Table 5.1. The measured flow through the outer ring indicated some degree of side wall leakage except for specimen S1.

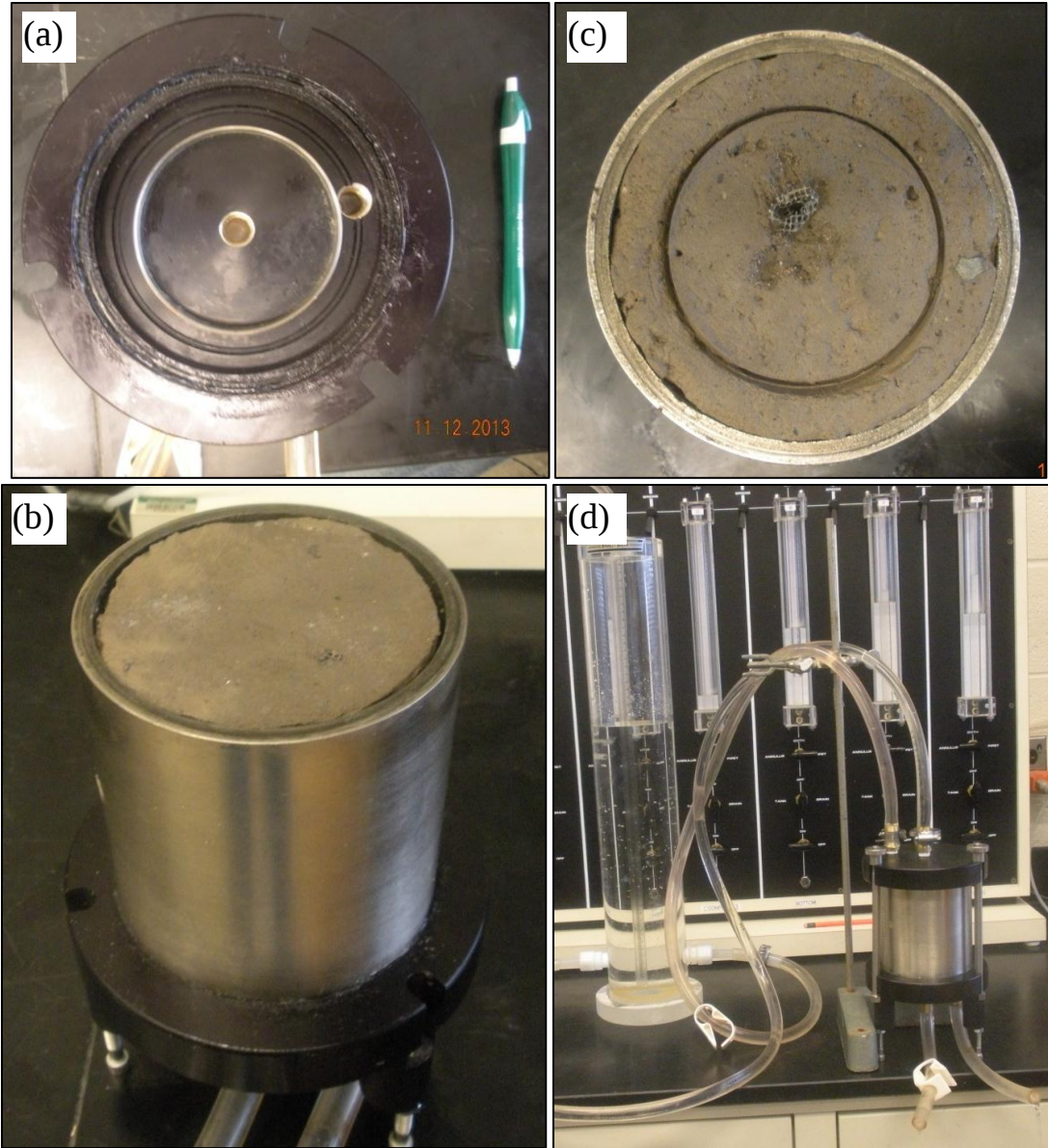


Figure 5.8: Double ring rigid wall permeameter (DRRP) setup: bottom plate (a); specimen inside the rigid wall cell (b); bottom of specimen (c); and test setup (d).

The overall k_{sat} of specimens were 0.06 cm/s, 0.05 cm/s, and 0.02 cm/s for S1, S2, and S3, respectively. However, conductivity of the setup is 0.17 cm/s. Generally the conductivity of the setup needs to be at least an order of magnitude higher than the conductivity of the specimen to

measure the conductivity accurately. Hence, except S1, the k_{sat} of S2 and S3 could be greater than listed in Table 5.1.



Figure 5.9: Macroporous specimen before test (a); and after test (b).

Table 5.1: Measured k_{sat} of macroporous specimens

Specimen ID	k_{sat} (cm/s)		
	Inner ring (macropore)	Outer ring	Overall
S1	0.12	0.0000	0.06
S2	0.10	0.0060	0.05
S3	0.03	0.0007	0.02

5.4 High-Resolution X-Ray CT Images

High resolution X-Ray CT scans of the compacted clay specimens were used to develop 3D morphology of the macropore. The X-Ray CT facility at the Texas Transportation Institute, Texas A&M University performed the X-Ray CT scans. Individual scan images are called slices. An individual slice is shown in Figure 5.10(a). The vertical resolution (Δz) of the greyscale images was 1.0 mm that means the vertical distance between two slices is 1.0 mm. The horizontal resolutions (Δx and Δy) can be calculated directly from the specimen diameter and the pixel of the scan images. The horizontal resolution was 0.1688 mm/pixel in both directions. The original grayscale image was converted to binary images using specific threshold where black color was assigned for soil matrix and white color was assigned to macropores. The threshold was selected based on the average value of variation of threshold along the macropore. Figure 5.10(b) presents the binary image developed using average threshold (50) and Figure 5.10(c) presents variation of threshold along the cross section Line A-A' shown in Figure 5.10(a). However, the upper limit of threshold slightly varied depending on the orientation of the Line A-A' [Figure 5.10(a)]. Hence, sensitivity analysis was carried out to understand the effect of threshold value on macropore parameter. The average threshold value used for images of specimens S1, S2, and S3 were 55, 50, and 54, respectively.

XCAT image analysis software developed by Kutay et al. (2010) was used to develop 3-D structure of the macropores within the specimens. The binary images developed were used as input to XCAT software. The 3-D structures of macropores are presented in Figure 5.11. The long continuous macropores that can be identified in the Figure 5.11 are the artificial macropores. Isolated small macropores visible in Figure 5.11 are inter-clod voids.

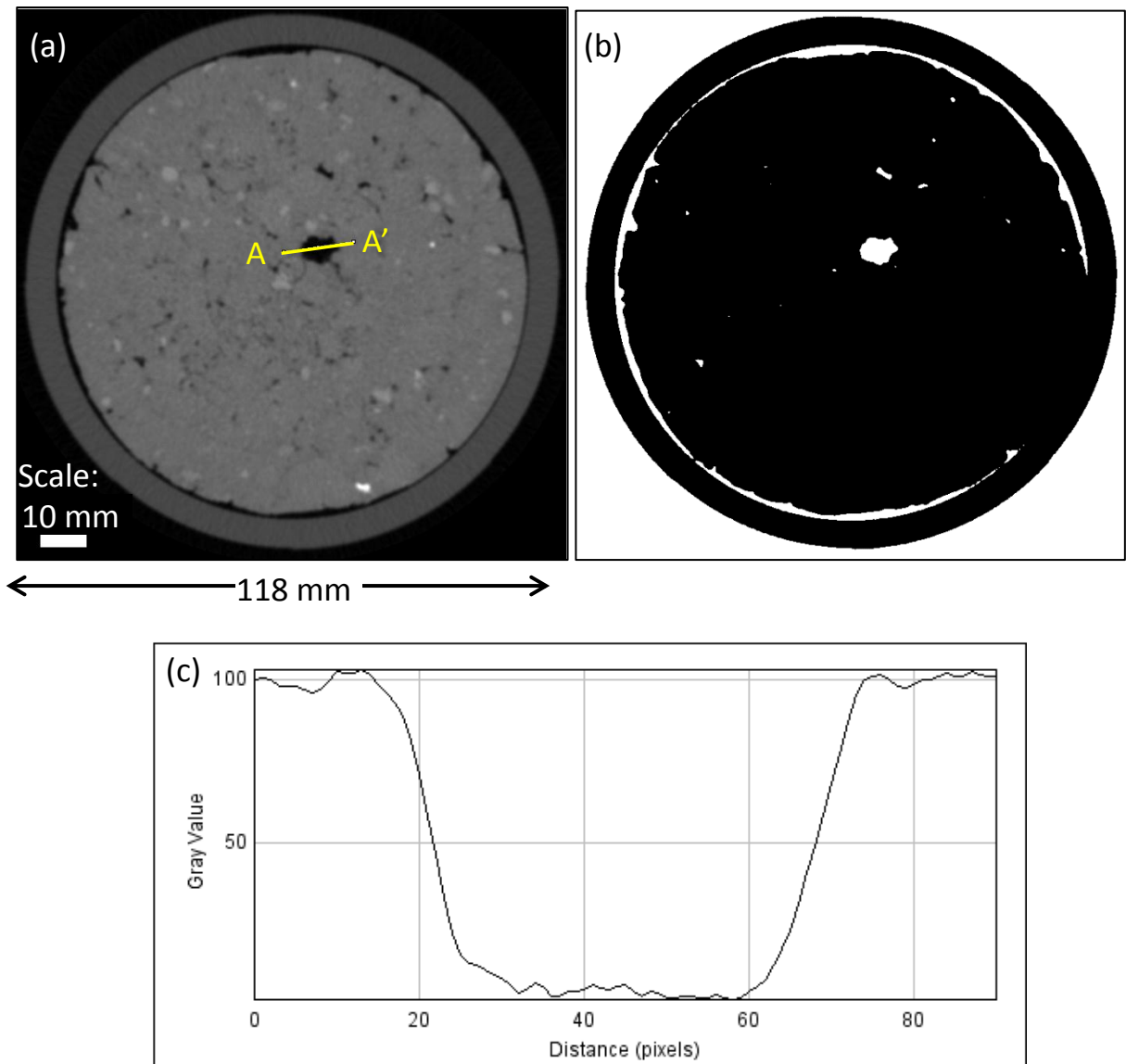


Figure 5.10: X-ray CT scan image: original greyscale image (a); binary image (b); and variation of threshold along the Line A-A' (c).

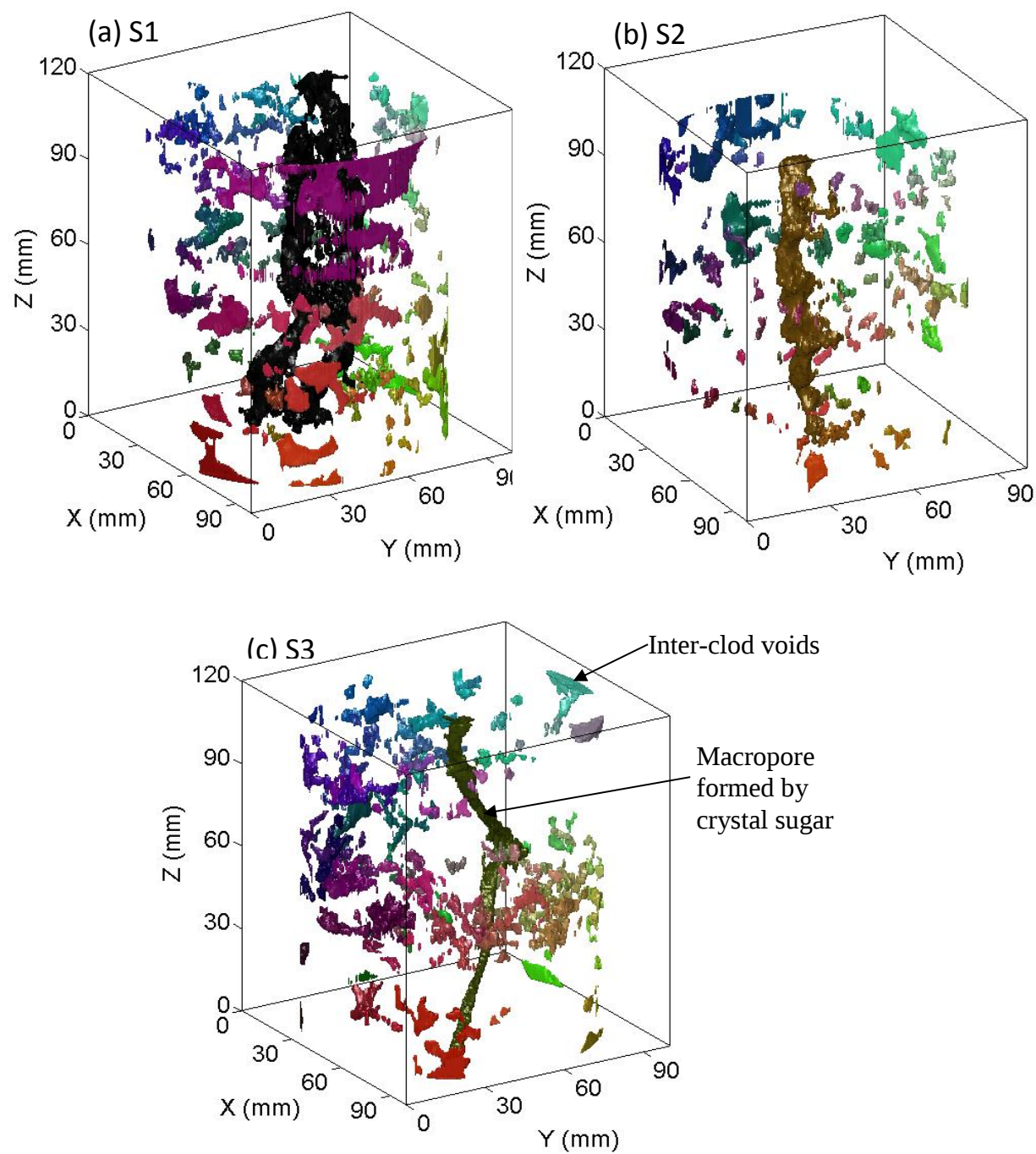


Figure 5.11: 3D structure of macropores: S1 (a); S2 (b); and S3 (c).

5.5 Macroporosity and Characterization of Macropores

The characterization of macropores consisted of measurement of the average diameter, minimum width, and maximum width. High resolution X-ray CT scan images were used to characterize the macropores and to measure the Macroporosity. The formed macropore was isolated from inter-clod voids [Figure 5.11(c)] in order to characterize the formed macropore. Areas showing formed macropore and soil matrix on each slice were calculated by summing up the white color pixels and black color pixels, respectively, on each slice. The micropores within the soil matrix were not identified separately from soil matrix and hence not included in the macroporosity. The total macroporosities of each specimen were estimated by adding the macropore areas from each slice and dividing by the total area of all slices. However, the resolution of the slices along the vertical direction is larger than the resolution in the horizontal direction. Hence, the macropore areas on each slice were multiplied by three in order to achieve similar resolution in all three dimensions. Further details on construction of 3-D image structure with uniform resolution are explained in Section 6.4. Estimated macroporosities are presented in Table 5.2. The specimen S1 had the maximum macroporosity of 6.84% followed by specimen S2 and S1 which had macroporosity of 0.51% and 0.28%, respectively.

The equivalent radii were estimated assuming the macropore is cylindrical and having the same cross sectional area as the estimated formed macropore area for each slice. The equivalent radius for specimen S1 was calculated using the area of the only one continuous macropore. The other macropores dead-ended and hence was not included in the analysis. Figure 5.12 presents the frequency count of equivalent radii of macropores for each specimen. The minimum, mean, mode, and maximum radius of macropores are tabulated in Table 5.2. The maximum equivalent

radius for specimen S1, S2, and S3 were 6.36 mm, 5.83 mm, and 5.01 mm, respectively. Similarly, the minimum equivalent radius for specimen S1, S2, and S3 were 3.340 mm, 1.973 mm, and 1.966 mm, respectively.

Table 5.2: Characteristics of formed macropore and estimated macroporosity

Specimen ID	Macroporosity (%)	Radius (mm)			
		Min.	Mean	Mode	Max.
S1	6.84	3.340	4.610	4.096	6.365
S2	0.51	1.973	3.605	3.488	5.834
S3	0.28	1.966	2.604	2.574	5.010

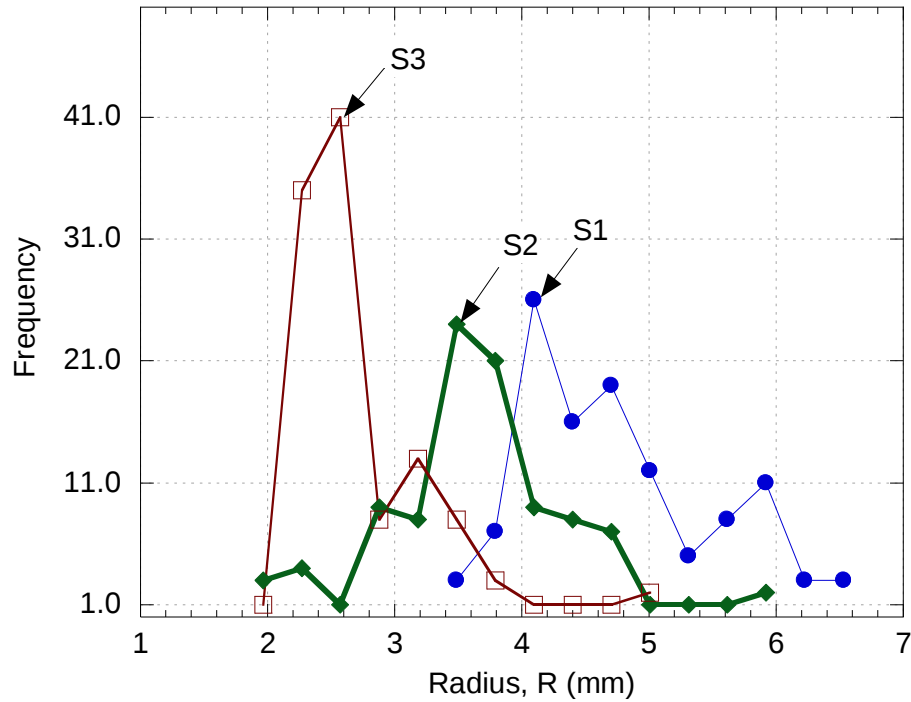


Figure 5.12: Frequency distribution of equivalent radius of the formed macropore.

CHAPTER 6: LATTICE BOLTZMANN MODELS

Typically, the fluid flow simulations start from Navier-Stokes (NS) equations, which are nonlinear partial differential equations for the conservation of mass and momentum. The NS equations are discretized by finite differences, finite volumes, and finite elements, or spectral methods and solved by common numerical methods. This approach is called ‘top-bottom’ approach (Wolf-Gladrow, 2000). The LBM follows a so-called ‘bottom-up’ approach, where it starts from a discrete lattice model and reaches to the solution of NS equations as it evolves in lattice space (Wolf-Gladrow, 2000). This chapter presents the LBM algorithms used for this study. LBM algorithms developed in this study were first verified using analytical solutions, and then validated using X-ray CT images of macroporous (cracked) clay specimens and k_{sat} measured in laboratory. A systematic analysis of morphology and tortuosity of macropores on macropore flow rate was conducted. An equation was formulated to predict flow rate through arbitrary shape and tortuous macropores using the flow rate of straight and vertical cylindrical macropore which has equivalent sectional area. In addition, multiphase LBM was tried to model unsaturated flow through macropores.

6.1 Saturated (single phase) LBM

In the LBM, the fluid phase is discretized according to the conservation of macroscopic properties and the necessary symmetries required by NS equations (He and Luo, 1997). The average movement of fluid particles are represented by distribution function, $f_i(x)$, which is

defined for each lattice vector e_i (microscopic velocity in i^{th} direction) at each site x . D2Q9 and D3Q19 are two lattice models of D x Q y series proposed by Qian et al. (1992), where x is the space dimension and y is the number of discrete velocity vectors in the model. The microscopic velocities for the lattice models D2Q9 and D3Q19 are illustrated in Figure 6.1.

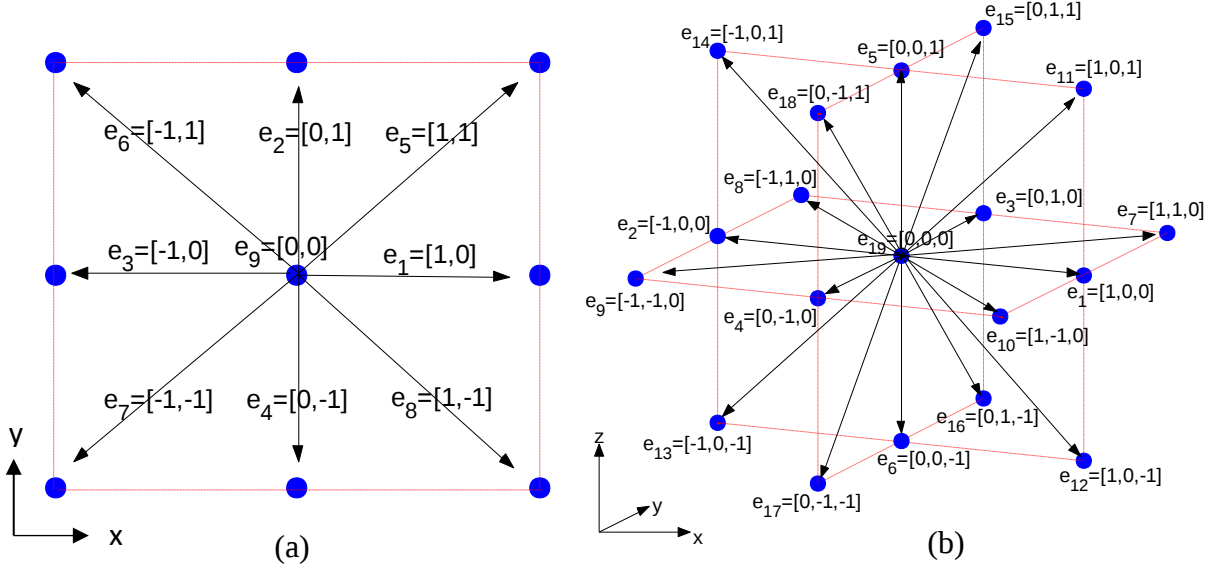


Figure 6.1: Microscopic velocity directions of D2Q9 model (a); and D3Q19 model (b).

Similar to the implementation by Sukop and Thorne (2006), uniform unit particle mass (1 mu) is assumed, therefore the microscopic velocities and momenta are always equivalent. The evolution of distribution function is done in two steps for each time step t : (i) one is advection and (ii) the other one is collision. The advection of the distribution function occurs along the microscopic velocity vectors and it can be represented as:

$$f_i^{\text{in}}(x, t) = f_i^{\text{out}}(x - e_i, t - 1) \quad \text{Eq. 6.1}$$

where f_i^{in} is the incoming distribution function from the neighboring nodes to the current node x at time t ; and f_i^{out} is the outgoing distribution function at the neighboring node $x - e_i$ at the previous

time step $t-1$. After the advection, a new distribution function, called equilibrium distribution function (f_i^{eq}), is determined at each site to represent the effect of collision. The collision step includes the ongoing collisions between particles by weighting the distribution function at a site with its f_i^{eq} . The equilibrium distribution function depends on the fluid macroscopic velocity (u) and density (ρ) at a node x , which can be computed as:

$$\rho(x) = \sum_i f_i^{in}(x) \quad \text{Eq. 6.2}$$

$$u = \frac{\sum_i f_i^{in} e_i}{\rho} \quad \text{Eq. 6.3}$$

f_i^{eq} for models D2Q9 and D3Q19 is:

$$f_i^{eq} = \rho W_i \left[1 + 3(e_i \cdot u) + \frac{9}{2}(e_i \cdot u)^2 - \frac{3}{2}(u \cdot u) \right] \quad \text{Eq. 6.4}$$

where W_i is weight factor in i^{th} direction. The weight factors differ based on the lattice models. The weight factors of D2Q9 are: $W_i = 1/9$ for $i = 1$ to 4 (face-connected particles); $W_i = 1/36$ for $i = 5$ to 8 (edge-connected particles); and $W_i = 4/9$ for $i = 9$ (rest particles). Similarly, the weight factors of D3Q19 are: $W_i = 1/18$ for $i = 1$ to 6 (face-connected particles); $W_i = 1/36$ for $i = 5$ to 8 (edge-connected particles); and $W_i = 4/9$ for $i = 9$ (rest particle). The numbering of the i^{th} direction is similar to the microscopic velocity numbering in Figure 6.1. More details on the derivation of the weight factors can be found in Wolf-Gladrow (2000). Using the linear relaxation presented by Bhatnagar et al. (1954), also known as BGK approximation, the collision step can be written as:

$$f_i^{out}(x,t) = f_i^{in}(x,t) - \frac{f_i^{in}(x,t) - f_i^{eq}(x,t)}{\tau} \quad \text{Eq. 6.5}$$

where τ is the relaxation time which controls the rate at which particle distribution relaxes to equilibrium. The relaxation time relates to the kinematic viscosity of the fluid (ν) with $\nu = c_s^2(\tau - 0.5)$ in lattice units. The c_s is the speed of sound in lattice units, which is equal to $1/\sqrt{3}$ for D2Q9 and D3Q19 LB models.

The body force (BF) is applied to the system by adding the force term to the collision step (Eq. 6.5) in the following form (Martys et al. 1998):

$$BF_i = -\frac{W_i}{c_s^2} \rho(e_i \cdot g) \quad \text{Eq. 6.6}$$

where g is the gravitational acceleration; and ρ is density. In LBM used in this study, the following form of the equation of state (EOS) defines the pressure (P) as follows:

$$P = c_s^2 \rho \quad \text{Eq. 6.7}$$

Hence, pressure boundary is simulated by setting the boundary densities according to Eq. 6.7.

6.1.1 Real-numbered Solid Density Micropore and Macropore Flow Model

The permeable solid (i.e., the clay soil medium in this study) is implemented using the partial-bounceback model proposed by Walsh et al. (2009). The partial-bounceback is implemented as a secondary collision step in standard LBM as follows:

$$f_i^{out}(x,t) = (1 - n_s) f_i^{out}(x,t) + n_s f_i^{in}(x,t) \quad \text{Eq. 6.8}$$

where $\bar{t}$ indicates the opposite direction vector; and n_s is the damping parameter related to solid fraction. The value of n_s ranges from 0 to 1. When n_s is equal to 0, the model recovers the standard LB model (i.e., equations Eq. 6.1 to Eq. 6.5). When n_s is equal to 1, Eq. 6.8 reduces to full-bounceback condition, i.e., the no-slip boundary condition.

6.2 Theoretical Verification of the D2Q9 and the D3Q19 Model

The D2Q9 permeable solid model was first verified using Poiseuille flow through a slit between two parallel plates. The velocity at the plate boundaries are zero and follow a parabolic velocity distribution between the plates. The velocity distribution between two parallel plates which is $2a$ distance apart is given by,

$$u_y = \frac{\nabla P_y}{2\mu} (a^2 - x^2) \quad \text{Eq. 6.9}$$

where u_y is the velocity in y direction; ∇P_y is the pressure gradient; μ is the dynamic viscosity of the fluid; and x is the distance from centerline between parallel plates. Numerical simulations were performed in a 50×50 lattice domain representing 5 mm each side. The relaxation time and the density of the fluid were set to 0.8 and 1 in lattice units, respectively. No slip boundary condition was applied at the wall boundaries using full-bounceback.

Pressure gradient ∇P_y of $4 \times 10^{-3} \text{ g/mm}^2\text{s}^2$ was applied between top and bottom boundary. Unknown distribution function components at the top and bottom boundaries were calculated using the formulation given in Kutay et al. (2006). LBM simulation and analytical

solution are plotted in Figure 6.2 and the LBM simulation matches very well with the analytical solutions.

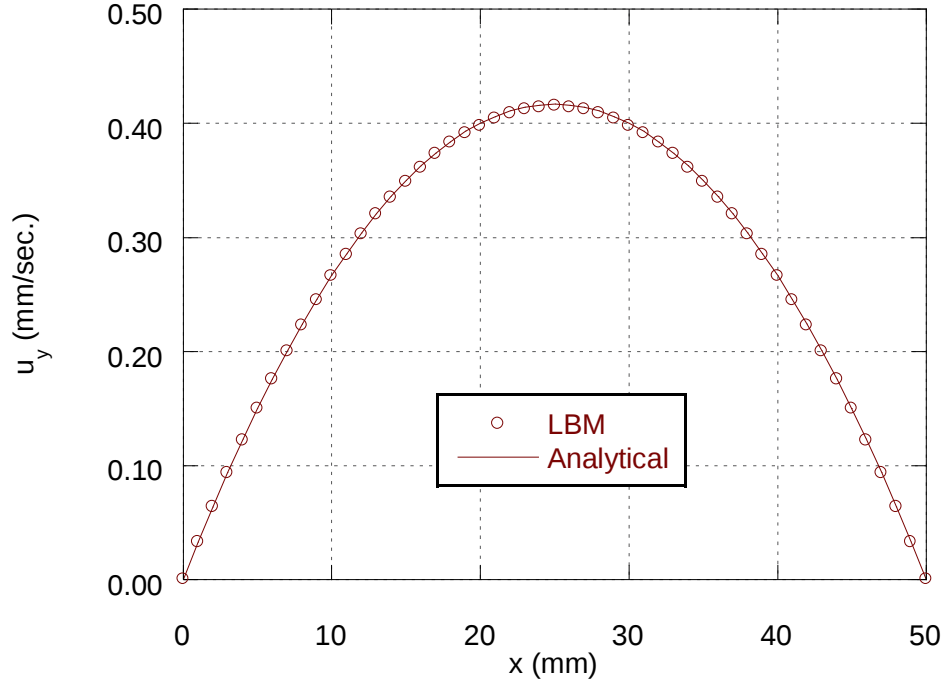


Figure 6.2: Verification of D2Q9 permeable solid model using Poiseuille flow simulation between two parallel plates.

D3Q19 permeable solid model was verified by simulating flow through a cylindrical void and comparing the velocity profile with the velocity profile given by the analytical solution (i.e., Poiseuille Law). A cylindrical cavity with a diameter (D) of 50 mm was utilized. Pixel resolution (dx) and time step (ts) used were 1.0 mm/pixel and 0.1 sec/ts, respectively. No slip boundary condition was applied at the boundary of the solid wall/water interface by assigning $n_s = 1$ for solids located outside the cylinder. Pressure gradient (∇P_z) of $1.67 \times 10^{-3} \text{ g/mm}^2\text{s}^2$ was applied between the inlet and outlet boundaries. Unknown distribution function components at

the inlet and outlet boundaries were calculated using formulations given in Kutay et al. (2006). The relaxation time and the density of the fluid were set to 0.8 and 1 in lattice units, respectively. The Poiseuille's analytical solution of velocity distribution of laminar flow through a cylinder is:

$$u_z = \frac{\nabla P_z}{\mu} \left(\frac{D^2}{16} - \frac{r^2}{4} \right) \quad \text{Eq. 6.10}$$

where u_z is the velocity in the z-direction; and r is the distance from the centerline of the cylinder in radial direction. Figure 6.3 shows the comparison of analytical solution and LB simulation results where an excellent match is visible.

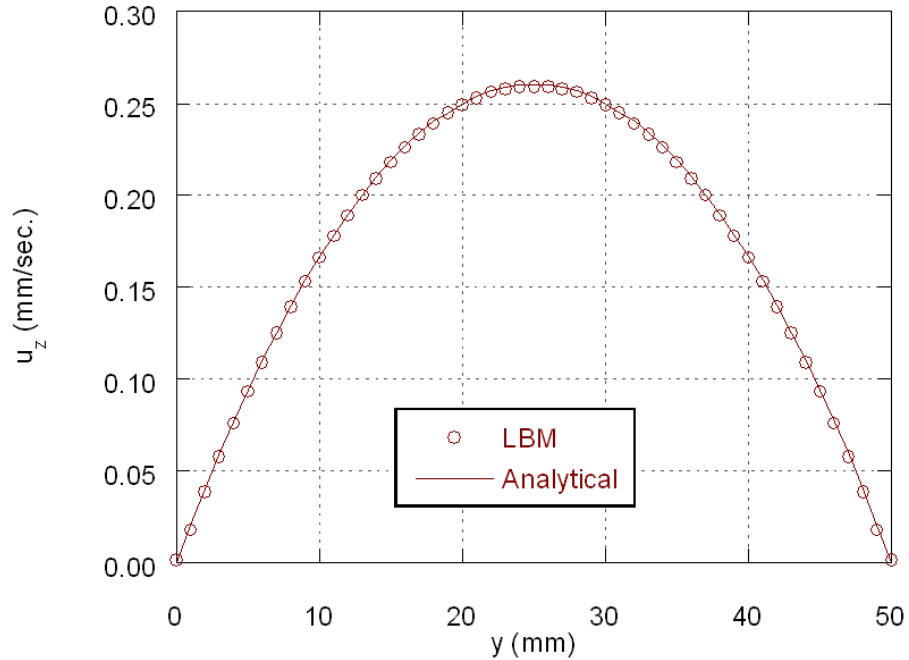


Figure 6.3: Verification of D3Q19 model using Poiseuille flow simulation through a cylindrical pipe.

Dardis and McCloskey (1998) presented analytical solution for velocity distribution in y direction (u_y) between parallel plates filled with solid scatters as follows:

$$u_y = -\frac{\nabla P_z}{\alpha\rho} \left(1 - \frac{\cosh[R(x-a)]}{\cosh(Ra)} \right) \quad \text{Eq. 6.11}$$

Where $\alpha = 2n_s$; n_s = damping parameter related to solid fraction (see Eq. 6.8); $R = \sqrt{\alpha/\nu}$; ν =kinematic viscosity; a = half of the gap between the plates; and x = distance from the centerline. The derivation of this solution (Eq. 6.12) from the Navier-Stokes equations is presented in Dardis and McCloskey (1998). Numerical simulations were performed in a 50×50 lattice domain representing 50 mm each side. Time step used was 0.1 sec/ts. Pressure gradient (∇P_z) of $1.33 \times 10^{-3} \text{ g/mm}^2\text{s}^2$ was applied between the inlet and outlet boundaries. Different values of solid fraction were simulated. No-slip boundary condition was applied at the wall boundaries using full-bounceback. Comparison of LBM simulation results and analytical solution is shown in Figure 6.4 where an excellent match is visible.

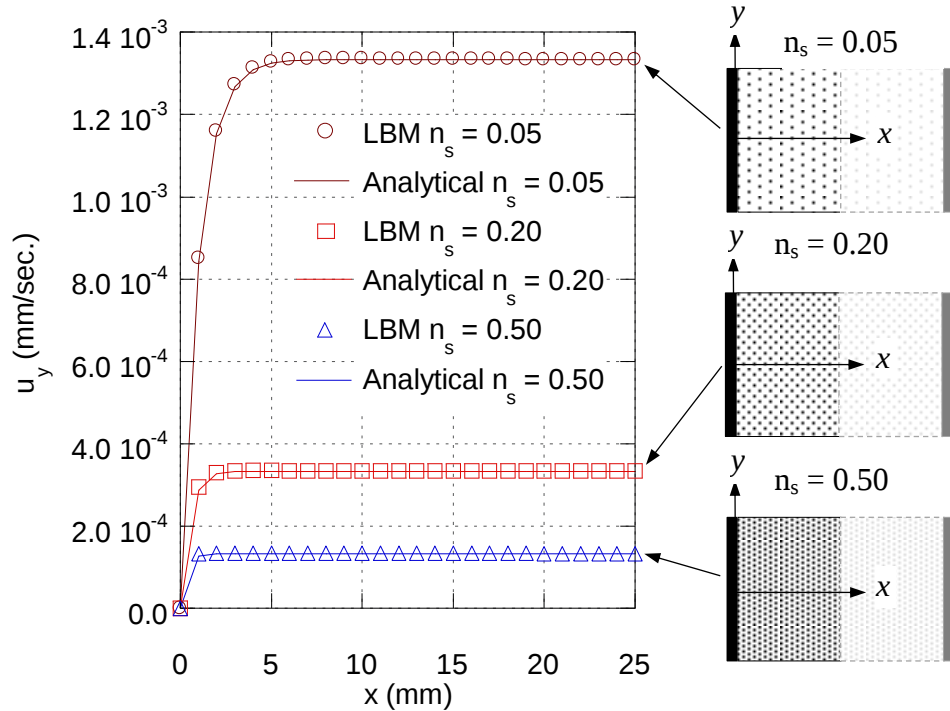


Figure 6.4: Velocity profiles between two parallel plates for different n_s values

Since typically the hydraulic conductivity (k) is used to represent the permeability of the soils, a relation between the n_s used in the LB formulations and the k is needed. The analytical expression that relates the intrinsic permeability (K) to n_s was derived by Walsh et al. (2009) as follows:

$$K = \frac{(1-n_s)v}{2n_s} \quad \text{Eq. 6.12}$$

where v =kinematic viscosity. Using the relationship between the intrinsic permeability and the hydraulic conductivity k ,

$$k = \frac{Kg}{v} \quad \text{Eq. 6.13}$$

following equation can be derived,

$$k = \frac{(1-n_s)g}{2n_s} \quad \text{Eq. 6.14}$$

In order to verify this formulation and the accuracy of the LB algorithm, LB simulations were conducted in a 3D domain of $50 \times 50 \times 50$ (corresponding to a $0.5\text{mm} \times 0.5\text{mm} \times 0.5\text{mm}$ domain) that is assumed to have n_s values ranging from 0.01 to 0.99. Time step used for simulations was 1.0×10^{-5} sec/ts. Periodic boundary condition was applied to all the boundaries. A gravitational body force was applied in the z-direction and resulting average velocity (v_{avg}) in the direction of gravity was used in Darcy's formulation to compute the hydraulic conductivity (i.e., $k = \frac{v_{avg}}{i}$, where i = hydraulic gradient = 1 because of gravity driven flow). Then this LB-based k is compared with the k computed using the Eq. 6.14 for different n_s values. As shown in Figure 6.5, LB-based k and k computed using Eq. 6.14 match very well, verifying the algorithm implementation as well as the formulation given by Walsh et al. 2009.

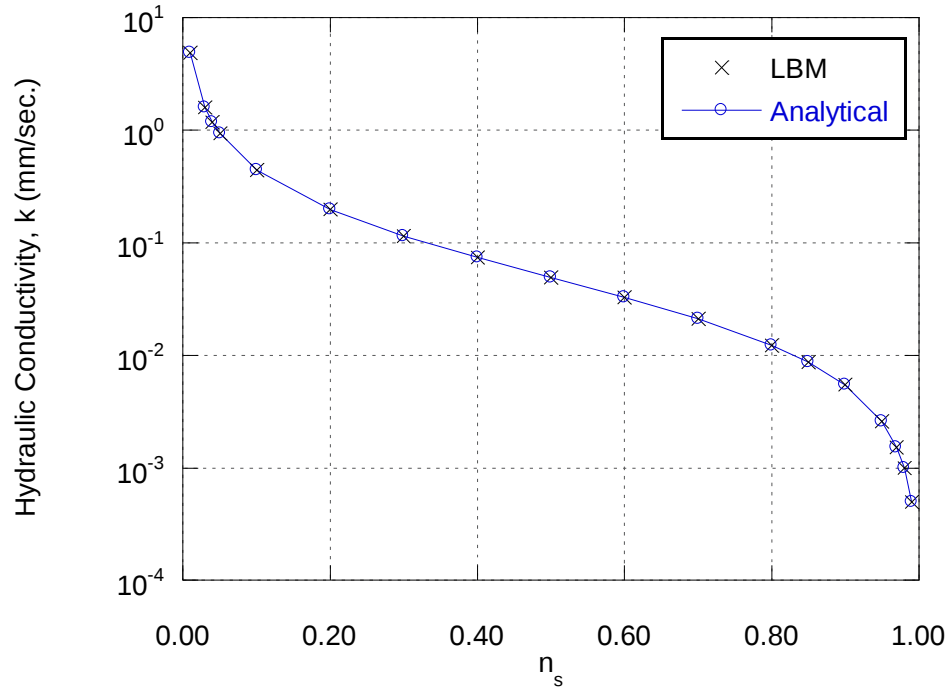


Figure 6.5: Hydraulic conductivity curve under gravity driven flow using analytical solution by Walsh et al. (2009) and LB model prediction.

6.3 Laboratory Validation of the LBM

The laboratory measurement of k_{sat} of macroporous specimens and X-ray CT scan images of those specimens were used to validate the LBM. More detail on laboratory tests and X-ray CT scan images can be found in Chapter 5. The binary images developed from X-ray CT scan images were used as direct input to the LBM. The binary images were stacked to reconstruct the 3-D structure of the Specimens. However, the resolutions (scaling relation from LBM to physical unit) of the images along the vertical and horizontal directions were not similar. Also, the original horizontal resolution of 0.1688 mm/pixel would take longer computer time and memory

to simulate. Hence, the horizontal resolution of 0.3375 was achieved by resizing the image slices using bilinear interpolation. Moreover, to achieve a uniform resolution in vertical and horizontal directions, each slice were repeated three times while stacking to construct the 3-D structure of the specimen as depicted in Figure 6.6. By repeating three times each slide, the original spacing between slices was divided in to three times which results in a new spacing of about 0.3333 mm ($1/3$ mm). The new spacing between slices is very close to the horizontal pixel spacing of 0.3375 mm. Similar approach to achieve a uniform resolution in all three directions of X-ray CT images was followed by Sukop et al. (2013).

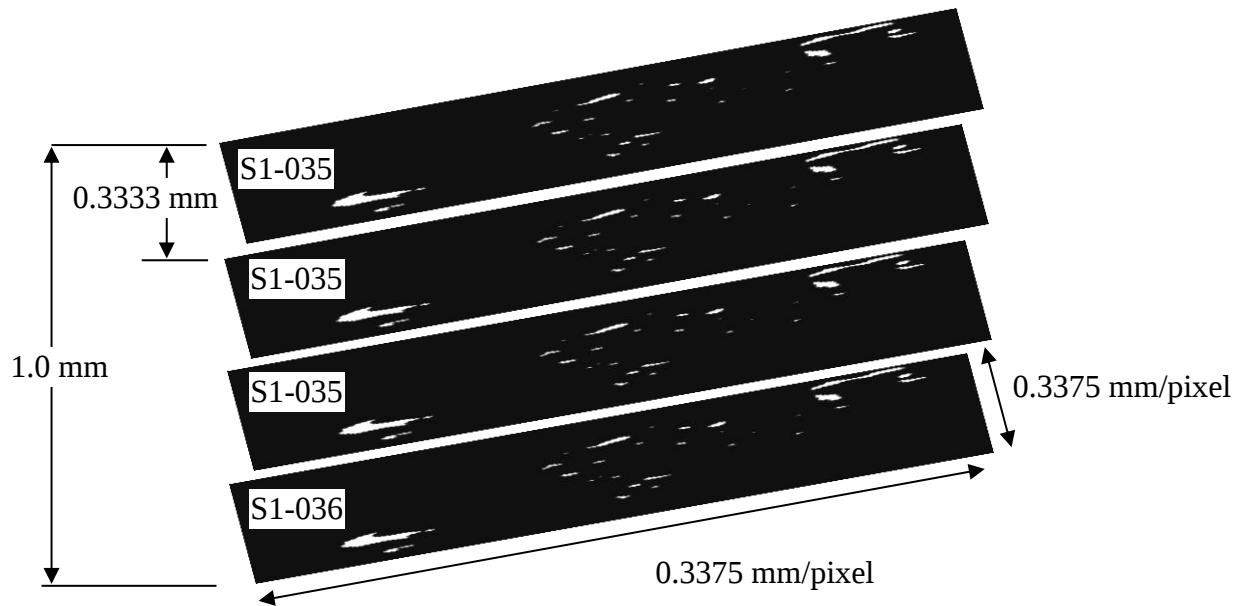


Figure 6.6: Construction of 3-D structure of the specimen using image slices. Two image slices of specimen S1 namely S1-035 and S1-035, and interpolation based on three repetitions of slice S1-035.

The relaxation parameter (τ) was set to 1.0 for all the simulations, which results in time step of 0.019 sec/ts. The n_s was set to zero which means soil matrix is impermeable. Assuming impermeable soil matrix is reasonable since the flow through soil matrix is very small (k_{sat} is 1×10^{-5} mm/sec.) compare to the flow through macropores. Pressure gradient was applied between top and bottom boundary. The flux was calculated as sum of the velocities of all the nodes on a slice. The difference in inflow and outflow of fluid mass was monitored. The difference between inflow and outflow reaches zero when the system reaches steady-state. The intrinsic permeability (K in pixel²) was calculated using Darcy's law,

$$K = q\rho\nu \frac{L}{\Delta P} \quad \text{Eq. 6.15}$$

where q is the Darcy flux (i.e., the flow rate per area in pixel/ts); and L is the length (in pixel) between inlet and outlet of the domain. Since the pressure gradient was applied using density of fluid at inflow and outflow, the average density (in mu.pixel³) was used for the intrinsic permeability calculations. ΔP (in mu.lu⁻¹.ts⁻²) can be calculated using the equation Eq. 6.7. The intrinsic permeability calculated in LB units can be converted to physical unit (in mm²) using the

scaling relation which is the resolution of the images. That is $K_{\text{physical}} = K_{\text{LB}} \times \left(\frac{L_{\text{physical}}}{L_{\text{LB}}} \right)^2$ where

$\left(\frac{L_{\text{physical}}}{L_{\text{LB}}} \right)$ is equal to the resolution of the image (0.3375 mm/pixel). The k_{sat} can be calculated

using Eq. 6.13. Figure 6.7 presents the calculated k_{sat} using LBM and measured k_{sat} in laboratory. The calculated k_{sat} is at least one order of magnitude higher than the measured k_{sat} . And the difference increase with the increasing k_{sat} . The measured k_{sat} of specimen S1 and S2 can be limited by the apparatus since the conductivity of the apparatus is very close to the measured k_{sat} .

However, measured k_{sat} of specimen S3 is about an order of magnitude lower than the conductivity of the apparatus.

The occurrence of non-Darcy flow can reduce the k_{sat} at higher hydraulic gradient (Sukop et al. 2013). The laboratory measurement of k_{sat} was carried out using about unit hydraulic gradient. However, applying hydraulic gradient above 1×10^{-4} is not feasible in LBM on large domains. Sukop et al. (2013) showed considerable reduction in k_{sat} due to non-Darcy flow above hydraulic gradient of 1×10^{-6} . Effect of hydraulic gradient on calculated k_{sat} of specimen S2 and S3 was studied by varying hydraulic gradient from 1×10^{-9} to 1×10^{-4} . Figure 6.8 presents the calculated k_{sat} for different hydraulic gradients. The calculated k_{sat} did not show difference with varying hydraulic gradient. The observation of calculated k_{sat} insensitive to hydraulic gradient is consistent for both specimens. Also, a simulation with lower resolution (0.1688 mm/pixel) was carried out on specimen S3 to verify the effect of resolution on calculated k_{sat} and presented in Figure 6.8. The effect of resolution on calculated k_{sat} was negligibly small.

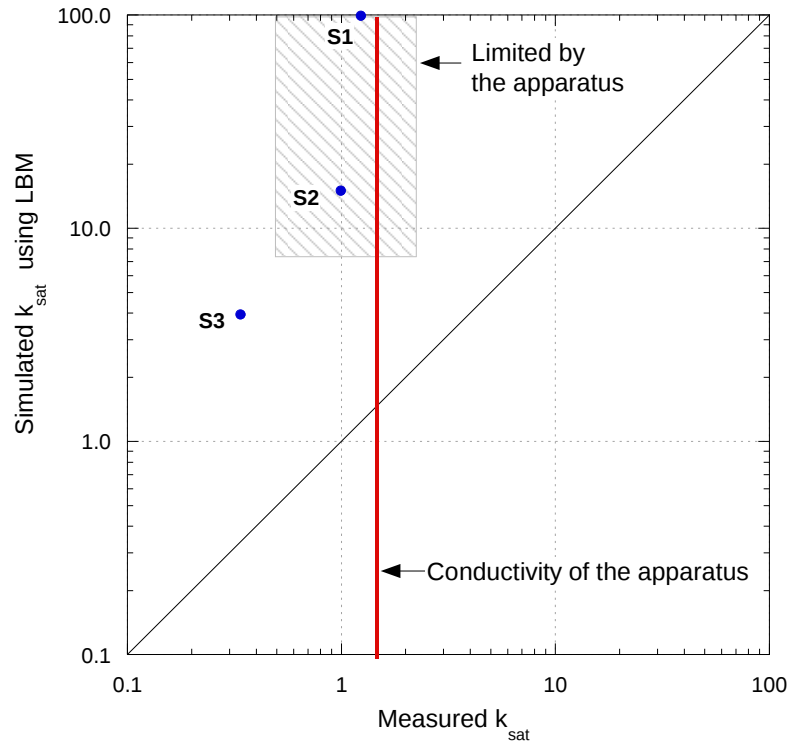


Figure 6.7: Measured and calculated k_{sat} of macroporous specimens.

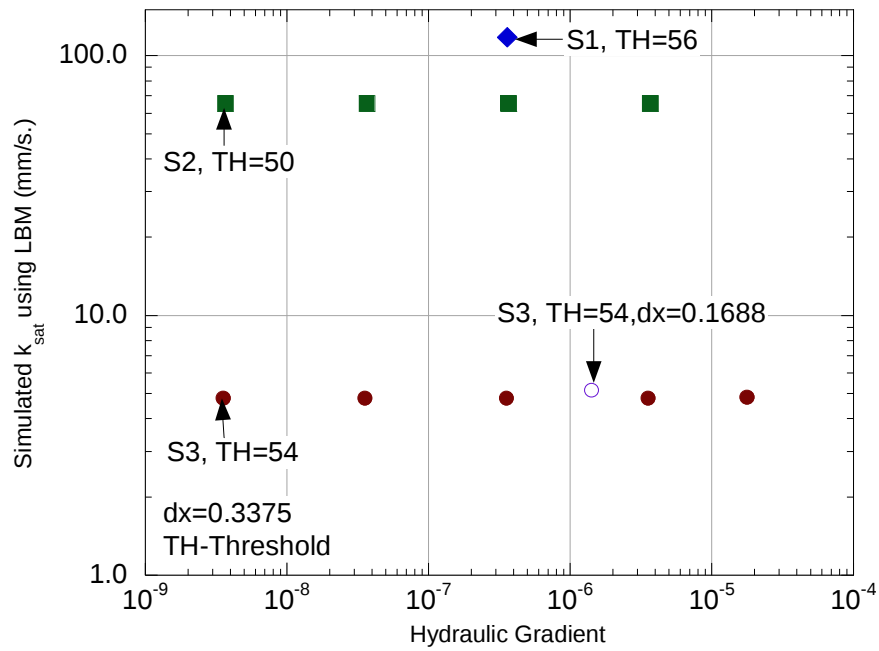


Figure 6.8: Effect of hydraulic gradient and resolution on calculated k_{sat} of macroporous specimens using LBM.

Also, the effect of threshold was tested. The average number of variation of threshold along the macropore was selected for each specimen (explained in section 5.4). However, the average number can vary slightly. Hence, the k_{sat} of specimen S3 was calculated using threshold of 49, 54, and 59 where 54 was the average threshold. The calculated k_{sat} is presented in Figure 6.9. The difference between the selected average threshold and 5 threshold upper or lower produced only about $\pm 15\%$ of calculated k_{sat} using selected average threshold.

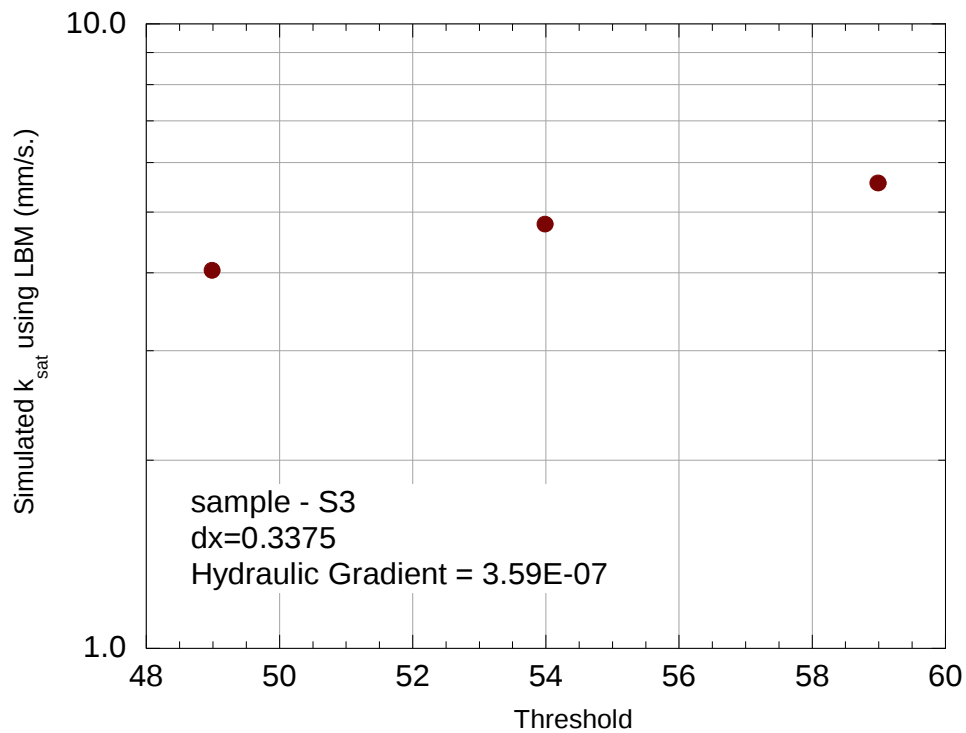


Figure 6.9: Effect of selected threshold on calculated k_{sat} of macroporous specimens using LBM.

Unlike macroporous rock (Sukop et al. 2013) or compacted aggregate (Kutay et al. 2006), the size of macropores within compacted clay can change due to swelling of clay particles. The

specimens were relatively dry when the specimens were received from X-ray CT scan facility. The swelling of the specimens during laboratory tests after the X-ray CT is presented in Figure 5.9 and discussed in section 5.3. The decrease in macropore size due to swelling of clay can affect the comparison between measured vs. calculated k_{sat} . Hence, the effect of swelling on calculated k_{sat} of macroporous specimens was studied through simulation flow through different sizes of artificial vertical macropore. The shape of the artificial macropore was roughly vertical cylinder. The difference between the sizes was in the increment of one pixel in radial direction of artificial macropore. The resolution was assigned as 0.3375 mm/pixel and hydraulic gradient of 3.59×10^{-7} was applied which is similar to the typical simulations of the macroporous specimens. Figure 6.10 presents the calculated k_{sat} with varying diagonal distance of macropore. The calculated k_{sat} shows considerable decrease when a circle of pixels (shown in black color in Figure 6.10) removed from the macropore (shown in gray color in Figure 6.10). This kind of reduction in macropore area can occur due to swelling during laboratory measurement of k_{sat} , the due to the effect of X-ray CT scan resolution, and due to damage of specimen during transportation from X-ray CT scan facility to laboratory to measure the k_{sat} .

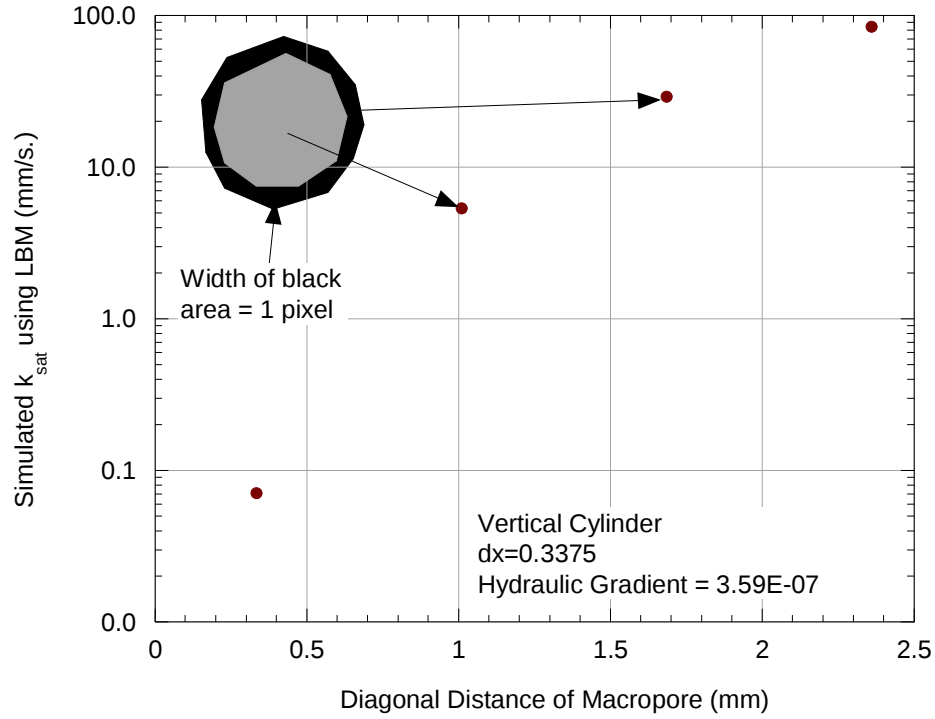


Figure 6.10: Effect of decrease or increase in macropore width in one pixel increment.

6.4 Effect of Morphology and Tortuosity of Macropore on Macropore Flow

In order to study the effect of macropore morphology on the overall flow regime in cracked clays, several artificial macropore shapes were created in 3D domain. Synthetic 3D images were developed using four different macropore cross sectional shapes: circle, diamond, ellipse, and rectangle (see Figure 6.11 which shows the x-y plane), and three tortuosity levels in x-z plane (see Figure 6.12). These shapes were created such that all the shapes have the same cross sectional area. Two different set of shapes were used with different cross sectional areas: (i) MP1= Macropore-1 and (ii) MP2= Macropore-2. The MP1 had an area of 0.784 mm^2 and macropore volume percentage of 23.9% (with respect to the overall domain size) and the MP2

had an area of 0.018 mm^2 and macropore volume percentage of 5.2%. For each set of shapes, the simulation domain area and volume were maintained constant for all the simulations.

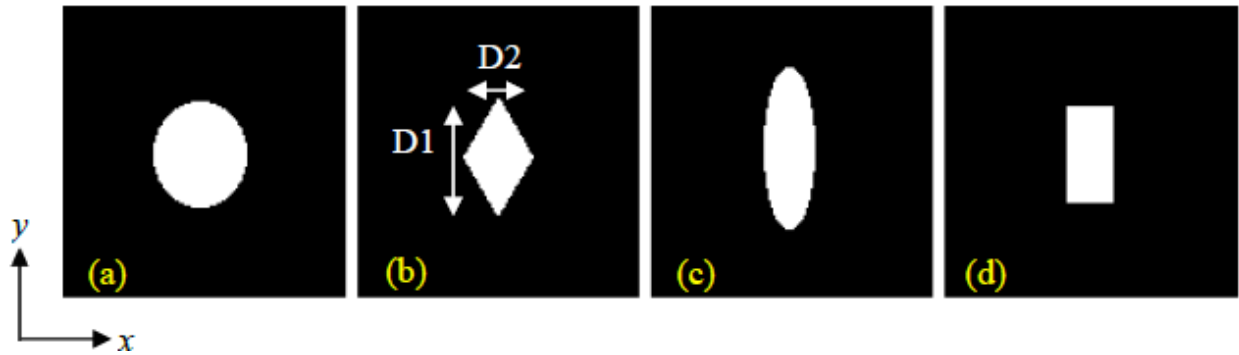


Figure 6.11: Sectional shapes of macropores used to generate 3D image: Circle (a); diamond (b); ellipse (c); and rectangle (d).

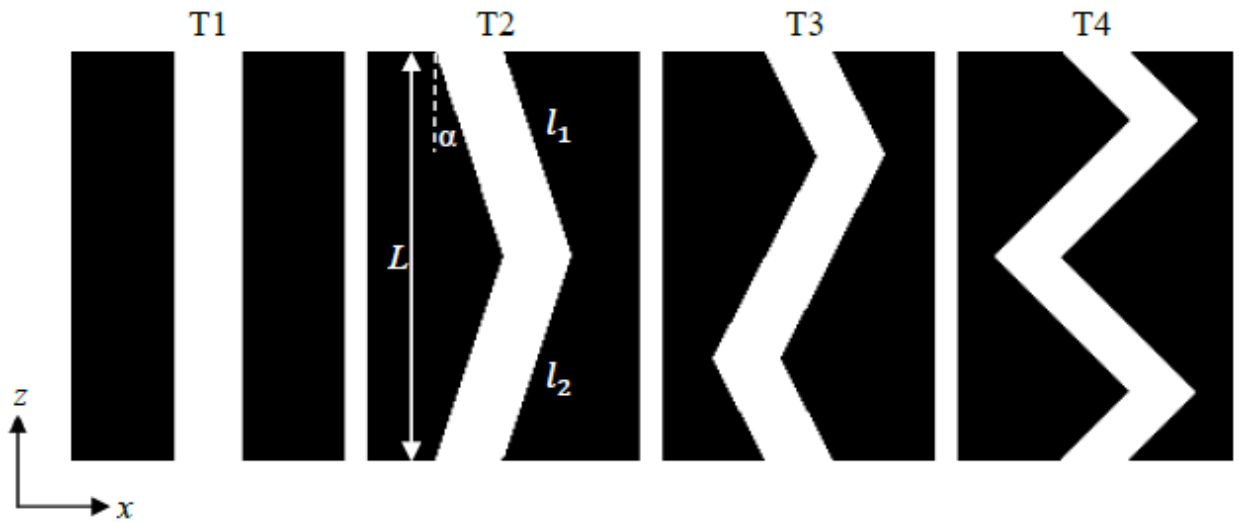


Figure 6.12: Tortuosity parameters and different tortuosity in same size of domain

Tortuosity is typically defined as the total length of the flow path divided by the shortest distance between inlet and outlet as follows (see Figure 6.12):

$$T = \frac{\sum_{i=1}^n l_i}{L} = \frac{L_e}{L} \quad \text{Eq. 6.16}$$

where L is the z-direction (vertical) distance between two macropore ends; l_i is the length of the i^{th} segment of the macropore; n is the number of segment between the ends of the macropore; and L_e (effective distance) is the summation of l_i . Macropores with different tortuosity and the tortuosity parameters are shown in Figure 6.12. The angle of macropore segment α was varied from 18.4° to 45° . The increase in T has two important consequences: (1) the hydraulic gradient on fluid decreases due to increase in effective distance, (2) change in the velocity direction from the direction of gradient. The combined influence in flow due to these two effects is represented by a tortuosity factor T^2 in capillary tube models (Carman 1977; Bear 2013; Corey 1977). Since gravity flow (unit gradient) is simulated in this study, increase in vertical distance alone will not make change in flow rate. Hence, numerical simulations were carried out with inclined (angle α from vertical) straight macropores and inclined bended macropores to study the effect of inclination and multiple bends on macropore flow rates. Macropore shape and tortuosity were varied systematically to investigate the influence of shape, perimeter of shape, aspect ratio of shape, and tortuosity in macropore flow.

Table 6.1 presents macropore parameters such as dimensions of the shape ($D1$ and $D2$), perimeter of the shape, aspect ratio ($D1/D2$), angle of macropore segment (α), tortuosity, and macropore area used for numerical simulations. Pixel resolution (dx) and time step (ts) used for MP1 simulations were 1.0×10^{-2} mm/pixel and 1.0×10^{-5} sec/ts, respectively. Similarly, for MP2 simulations the dx and ts were set to 5.0×10^{-3} mm/pixel and 2.5×10^{-6} sec/ts, respectively. For MP1 and MP2 simulations the n_s was set to 0.9 and 0.69, respectively. The n_s was set such that both the set of simulations give same micropore hydraulic conductivity of 5.45×10^{-3} mm/sec in

physical units. Gravity force of 9.81 m/s^2 was applied. Periodic boundary condition was implemented in all the boundaries. Relaxation parameter was set to 0.8 for all the simulations. The MP2 simulation series from T2 to T4 were repeated with straight inclined macropores in order to quantify the influence of inclined flow paths on macropore flow without the effect of bends. During the steady gravity flow (fully developed laminar flow) the length of inclined macropore does not influence the flow rate. Only the angle of inclination causes change in hydraulic gradient on flow through inclined direction for gravity flow. Simulations were carried out on high performance computing center (HPCC) of Michigan State University (MSU). A typical simulation took about 10 hours of computer time using single processor.

Macropore flow was not affected significantly by incorporating micropore flow because the simulations were carried out with a very small micropore hydraulic conductivity ($5.45 \times 10^{-3} \text{ mm/sec}$). The smaller micropore hydraulic conductivity was selected in order to represent clay soil. The increase in maximum velocity and macropore flow rate for cylindrical macropore due to incorporating micropore flow was only 0.1% and 1%, respectively. However, incorporating micropore flow allowed to simulate the actual physics at the boundary of micropore and macropore region and to quantify the influence of the flow through micropore matrix compare to macropore flow.

Table 6.1: Macropore parameters investigated

Simulation ID	Macropore Sectional Shape	D1 (mm)	D2 (mm)	Aspect Ratio	Perimeter (mm)	α	Tortuosity (T)	Macropore Area (mm ²)
MP1_C1_T1	Circle	1.00	1.00	1.00	3.280	0	1.00	0.784
MP1_D1_T1	Diamond	1.50	1.04	1.44	3.825	0	1.00	0.784
MP1_E1_T1	Ellipse	1.50	0.66	2.27	3.691	0	1.00	0.784
MP1_R1_T1	Rectangle	1.00	0.78	1.28	3.517	0	1.00	0.784
MP2_C2_T1	Circle	0.15	0.15	1.00	0.497	0	1.00	0.018
MP2_D2_T1	Diamond	0.23	0.15	1.53	0.587	0	1.00	0.018
MP2_E2_T1	Ellipse	0.25	0.09	2.78	0.598	0	1.00	0.018
MP2_R2_T1	Rectangle	0.15	0.12	1.25	0.528	0	1.00	0.018
MP2_C2_T2	Circle	0.15	0.15	1.00	0.497	18.4°	1.05	0.018
MP2_D2_T2	Diamond	0.23	0.15	1.53	0.587	18.4°	1.05	0.018
MP2_E2_T2	Ellipse	0.25	0.09	2.78	0.598	18.4°	1.05	0.018
MP2_R2_T2	Rectangle	0.15	0.12	1.25	0.528	18.4°	1.05	0.018
MP2_C2_T3	Circle	0.15	0.15	1.00	0.497	26.6°	1.12	0.018
MP2_D2_T3	Diamond	0.23	0.15	1.53	0.587	26.6°	1.12	0.018
MP2_E2_T3	Ellipse	0.25	0.09	2.78	0.598	26.6°	1.12	0.018
MP2_R2_T3	Rectangle	0.15	0.12	1.25	0.528	26.6°	1.12	0.018
MP2_C2_T4	Circle	0.15	0.15	1.00	0.497	45.0°	1.41	0.018
MP2_D2_T4	Diamond	0.23	0.15	1.53	0.587	45.0°	1.41	0.018
MP2_E2_T4	Ellipse	0.25	0.09	2.78	0.598	45.0°	1.41	0.018
MP2_R2_T4	Rectangle	0.15	0.12	1.25	0.528	45.0°	1.41	0.018

6.4.1 Effect of Macropore Shape and Shape Parameters

In order to compare the magnitudes of flow rate through the micropores and macropores, total flow rates through each zone was divided by their respective cross sectional area. In other words, flow rate through the ‘white’ area in Figure 6.11 was divided by the cross sectional area of the ‘white’ area to come up with a ‘normalized’ flow rate for macropore flow. Similarly, flow rate through the ‘black’ area in Figure 6.11 was divided by the cross sectional areas of the ‘black’ portion of the overall cross section. Figure 6.13 shows the comparison of macropore flow rate (per white area) to micropore flow rate (per black area) for two sets of macropores simulated. As shown, the ratio of macropore flow rate per area to micropore flow rate per area (RQ) varied from about 9800 to 13000 for MP1 macropores and it varied from 750 to 1100 for MP2 macropores. In both cases the lowest ratio was relevant to the ellipse shape, which has the highest aspect ratio.

Equivalent hydraulic conductivities (k_{eq}) were calculated using Darcy’s law by dividing the total flow rate at the bottom of the domain (flow rate through micropores + macropores) by the total cross sectional area perpendicular to the gravity. Then, the ratios of equivalent hydraulic conductivities were defined as:

$$R_{k_{eq}} = \frac{k_{eq} \text{ of section}}{k_{eq} \text{ of section with circle shape macropore}} \quad \text{Eq. 6.17}$$

where $R_{k_{eq}}$ is the equivalent hydraulic conductivity ratio.

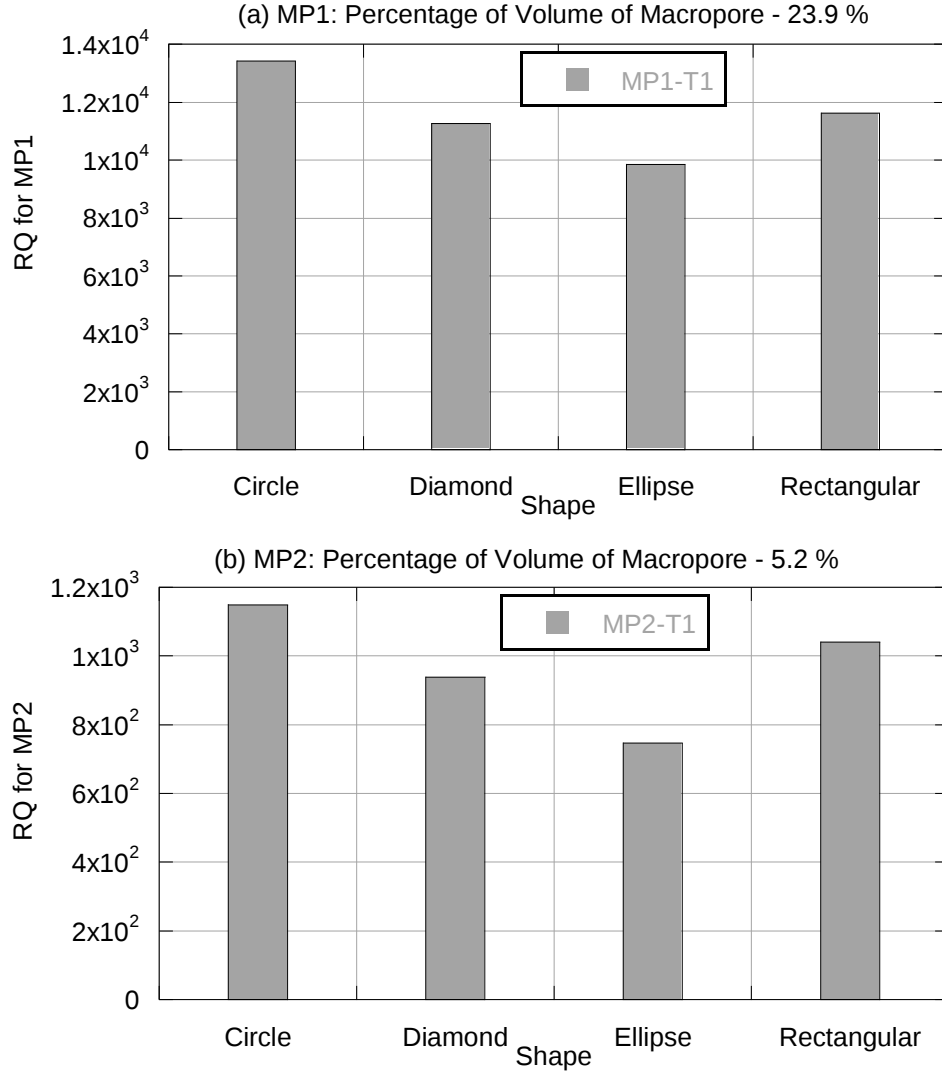


Figure 6.13: Ratio of macropore flow rate per area to micropore flow rate per area of different shape of macropores: MP1 (a); and MP2 (b).

Figure 6.14 presents $R_{k_{eq}}$ of two set of macropore flow simulated. All the shapes show reduction in k_{eq} as compared to circular shape and follow similar pattern for both the set of macropore sectional areas (MP1 and MP2). Maximum reduction in k_{eq} is about 35% for ellipse shape of MP2. Minimum reduction in k_{eq} is about 10% for rectangular shape of MP2. This

shows that the assumption of circular crack alone (not including other factors such as the tortuosity) leads to errors between 10% and 35%. It should be noted that the shapes analyzed in this paper (ellipse, diamond, rectangle) are simpler than the actual crack morphology in the field. Therefore, more error should be expected because of complex angular cross section of the cracks.

In order to analyze the influence of macropore parameters on the flow rate, ratios of macropore flow rate were plotted against perimeter and aspect ratio of a given macropore cross section. Ratio of macropore flow rate and ratio of perimeter were defined as:

$$R_Q = \frac{\text{Macropore flow rate}}{\text{Flow rate of circular section macropore}} \quad \text{Eq. 6.18}$$

$$R_P = \frac{\text{Perimeter of macropore of section}}{\text{Perimeter of circle macropore}} \quad \text{Eq. 6.19}$$

where R_Q is the flow rate ratio and R_P is the perimeter ratio. Figure 6.15 presents the variation of ratio of macropore flow rate with ratio of perimeter. Ellipse shape shows maximum reduction of 26% and 35% in flow rate for MP1 and MP2, respectively.

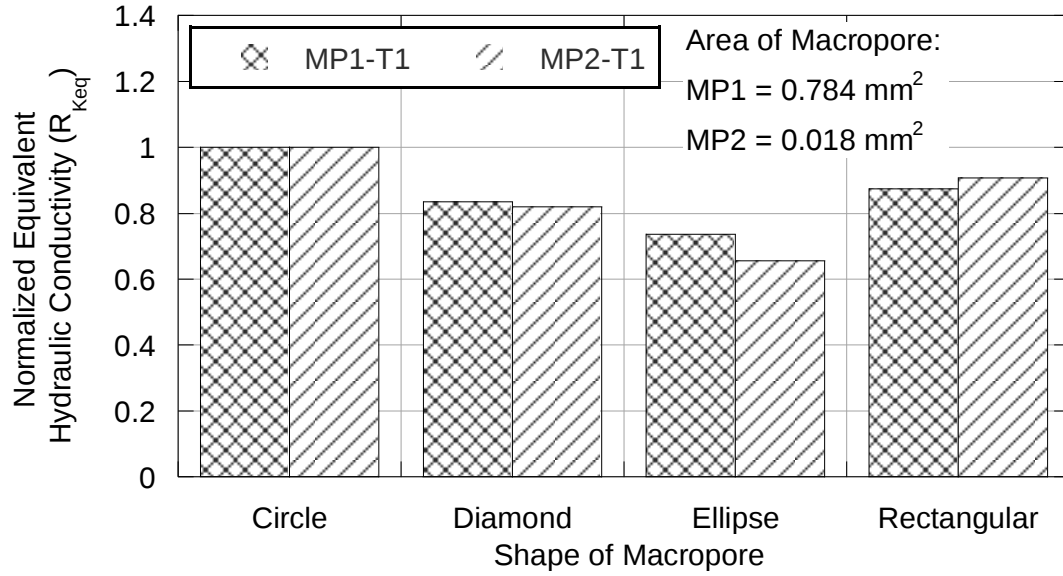


Figure 6.14: Effect of macropore shape on the equivalent hydraulic conductivity

Generally there is a trend between R_Q and R_P , except for the diamond shape. Increase in perimeter imply the increase in wall surface area, hence increase in wall friction. The reason for higher flow rate of diamond shape compare to ellipse (even though perimeter length of diamond is more than the perimeter length of ellipse) is that the diamond shape has larger eccentricity (i.e., distance from its centroid to closest macropore wall is larger) than the ellipse shape. The eccentricity (from the macropore wall) can be linked to the aspect ratio (see the D1 and D2 parameters in Table 6.1). The smaller aspect ratio represents larger eccentricity for the shapes and shape parameters used in this study. The effect of viscous drag increases with decreasing eccentricity (Panton 2006). In other words, as the centroid of the cross sectional area gets closer to the wall, viscous drag increases, decreasing the overall flow rate (Panton 2006).

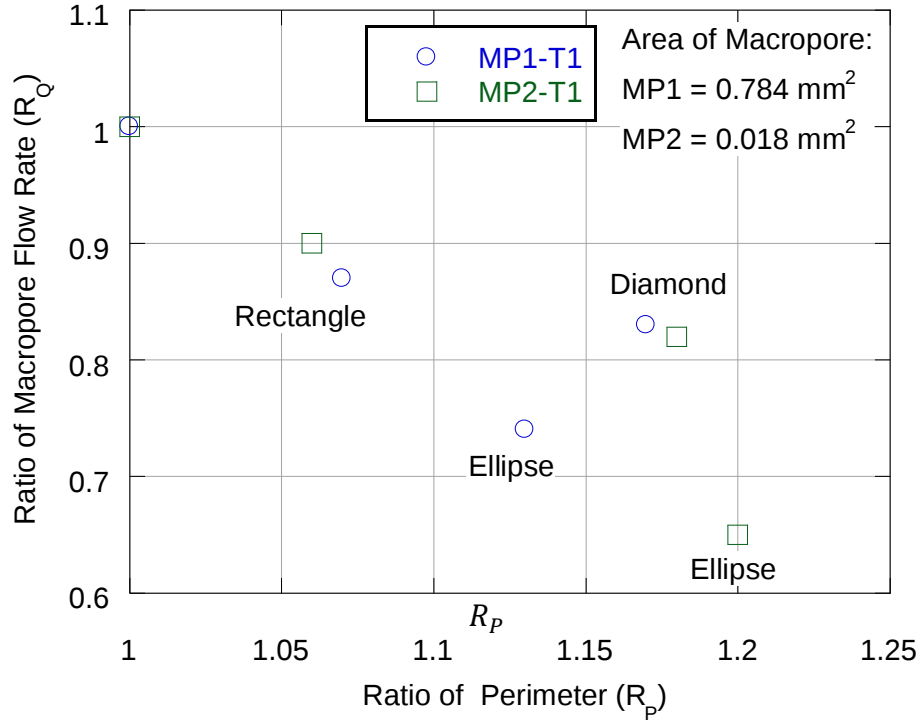


Figure 6.15: Effect of perimeter of macropore on macropore flow rate

The influence of aspect ratio on macropore flow rates (R_Q) of macropores with same sectional area but different aspect ratios (i.e., $D1/D2$) is shown in Figure 6.16. The flow rate decreases consistently with increasing aspect ratio. This is meaningful because as two solid (or low permeable) sides get closer and closer, the overall velocity will decrease because of wall friction. Both MP1 and MP2 follow the same line of reduction, indicating that this behavior is not a function of the cross sectional area of the pore. The maximum reduction of 35% in flow rate can be noticed for the maximum aspect ratio of 2.78 (MP2 ellipse).

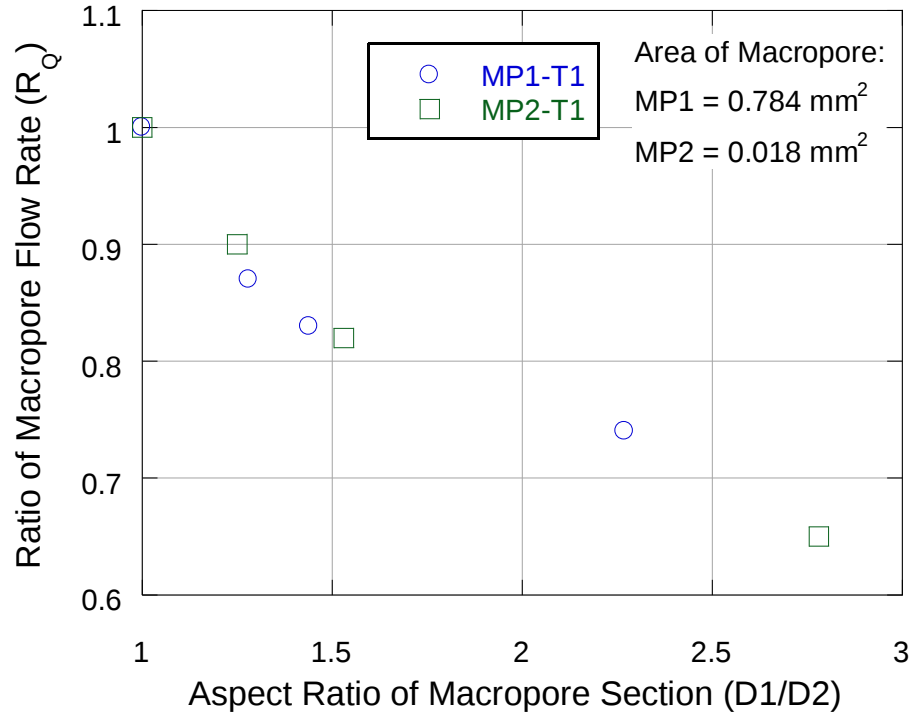


Figure 6.16: Effect of aspect ratio of macropore on macropore flow rate

Figure 6.17 shows the 3D visualization of absolute value of the velocity distribution for different cross sectional shapes. All of the subfigures are the simulations for tortuosity shape T4 illustrated in Figure 6.12. As shown in Figure 6.16, even though all the simulations were performed in the same condition (i.e., gravity), the cross sectional areas are the same, the velocity distribution exhibit significant difference for different cross sections. For example, the ellipse shape has much lower velocity than the circle (and the others). The ellipse shape has the highest aspect ratio and the flow rate through macropore is function of aspect ratio as explained previously. It is noted that the scale of the colorbars for each subfigure is the same, where the minimum (blue) shows 0 and the maximum (red) shows 7.28 mm/sec. The x-, y- and z- axis are in lattice units and can be converted to physical units by multiplying each coordinate with the

resolution, which is 0.005 mm/lattice. The domain shown is 120x120x180 lattice units, which corresponds to 0.60mm by 0.60mm by 0.90 mm domain size in physical units. The location of maximum velocity is not at the center of the cross section in tortuous flow path, because the fluid prefers to flow through the least resistance path (Clennell 1997).

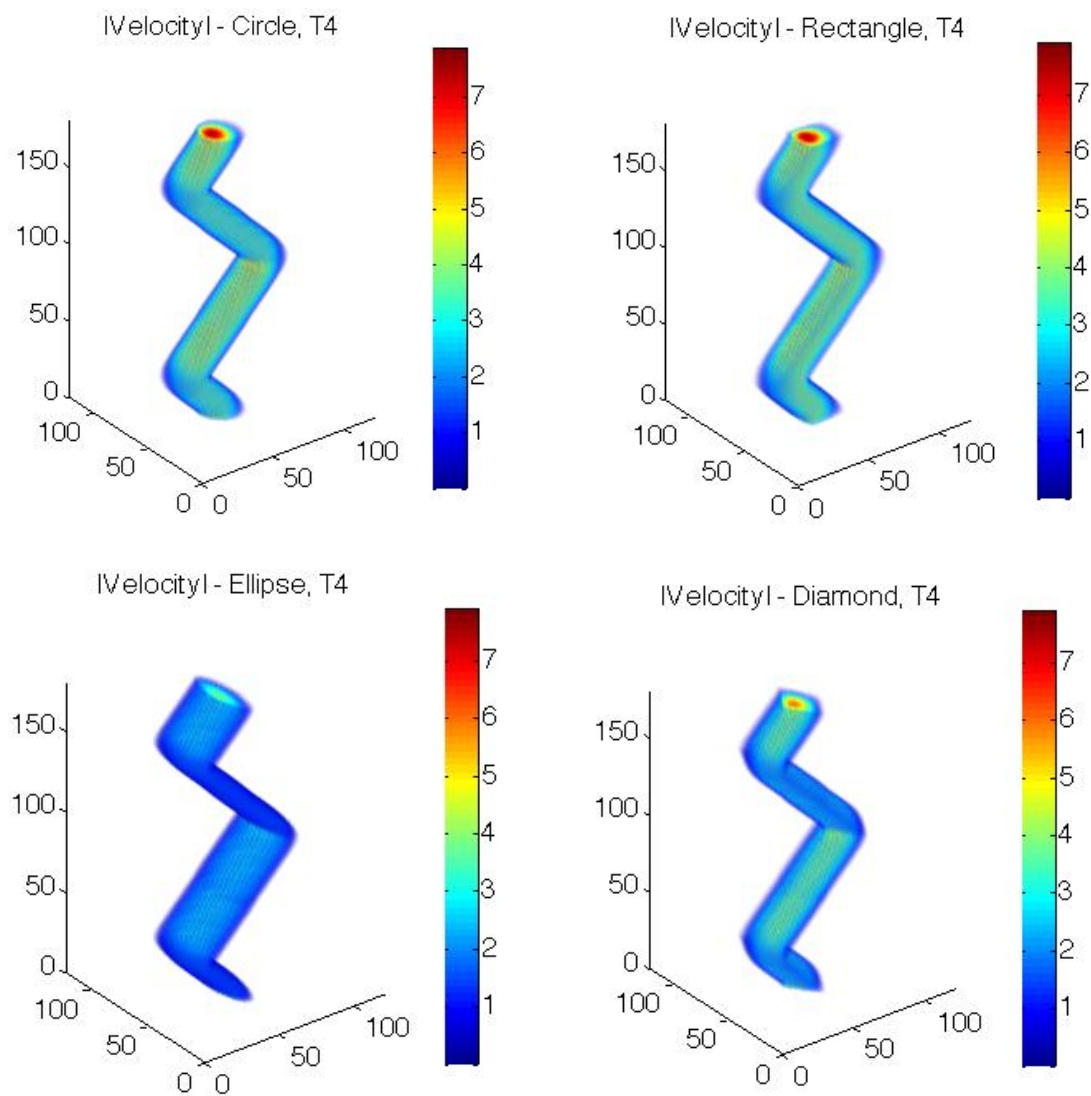


Figure 6.17: 3D visualization of absolute value of velocity distribution for different cross sections.

6.4.2 Effect of Tortuosity

Velocity vectors and streamlines are plotted in Figure 6.18 along the cross sectional plane X-Z for circular cross section macropore. The solid nodes, velocity vectors (at every other node), and streamlines (at interval of 4 nodes) are marked in gray color, red color arrows, and blue lines, respectively. The zoomed rectangle shows the nature of the velocity profile along the macropore of tortuosity of 1.41 (T4). The maximum velocity occurs away from the center line (i.e., centroid of the cross section) of the macropore. The streamlines show that micropore flow is minimal along convex side of the macropore bends and micropore flow prefers the concave side of the macropore where less friction paths are found. The most efficient path for fluid flow is not necessarily the shortest path (less tortuous) instead the path results in minimum energy dissipation (Clennell 1997).

Figure 6.19 presents comparison of macropore flow rate through inclined straight macropore and bended macropores. The flow rate through inclined straight macropores is generally higher than the flow rate through bended macropores. The macropore flow rates of inclined straight macropores and bended macropores were normalized with the vertical macropore flow rate (i.e., when $T=1$). For a particular shape of macropore, the normalized macropore flow rates are defined as:

$$R_{QTS} = \frac{\text{inclined straight macropore flow rate}}{\text{Flow rate of macropore when } T=1} \quad \text{Eq. 6.20}$$

$$R_{QTB} = \frac{\text{Bended macropore flow rate}}{\text{Flow rate of macropore when } T=1} \quad \text{Eq. 6.21}$$

where R_{QTS} is the normalized macropore flow rate for inclined straight macropores and R_{QTB} is the normalized macropore flow rate for bended macropores.

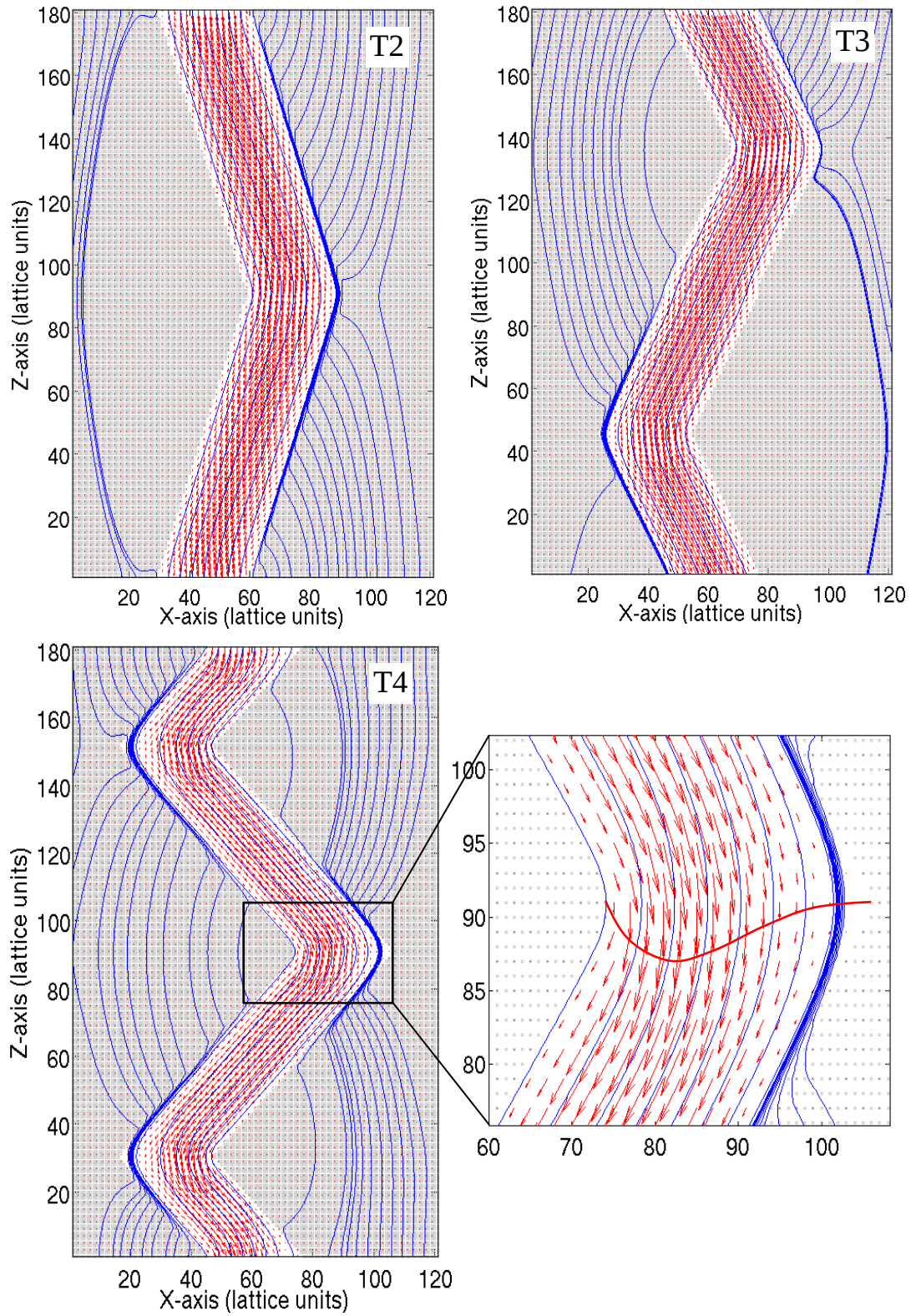


Figure 6.18: Velocity vectors and streamlines along the X-Z plane of circular cross section.

The R_{QTS} quantifies the influence of flow angle from the direction of gradient and the influence of increase in effective length of flow path. The difference between R_{QTS} and R_{QTB} shows the effect of multiple turning or bends in flow path.

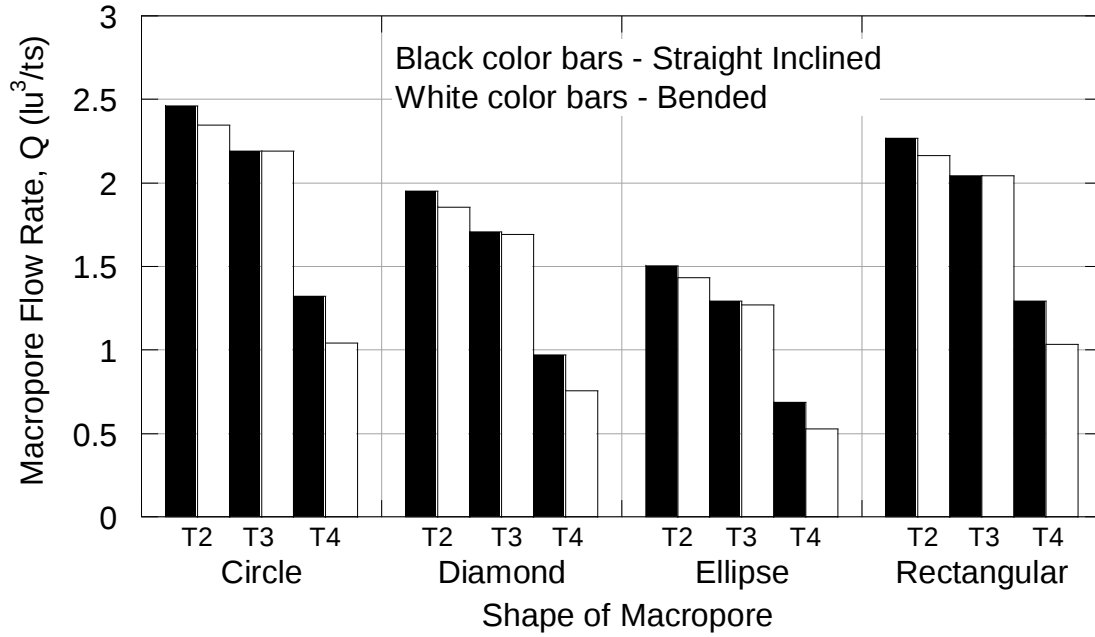


Figure 6.19: Comparison of flow rate through tortuous path and straight inclined path.

Figure 6.20 presents the normalized flow rates R_{QTS} and R_{QTB} with tortuosity. The macropore flow rate decreases consistently with increasing tortuosity (increasing inclination angle, effective length, and number of turnings/bends). The maximum effect of bends is about 25% on overall decrease of flow rate due to tortuosity for ellipse shape with three bents (T4). Ellipse shape shows the maximum impact due to overall tortuosity and the macropore flow rate reduces by about 70% for tortuosity of 1.41 ($\alpha = 45^\circ$). The lowest flow rate through ellipse shape is in consistence with the straight vertical macropores which can be explained using aspect ratio.

Similarly, other shapes followed the same pattern in magnitude of flow rates through tortuous macropores as straight vertical macropores. The effect of increase in effective length and inclination angle shows more influence in decreasing flow rate than number of bends for the tortuosity considered in this study. This shows that the tortuosity of a crack affects the flow rate significantly and needs to be included in the analyses.

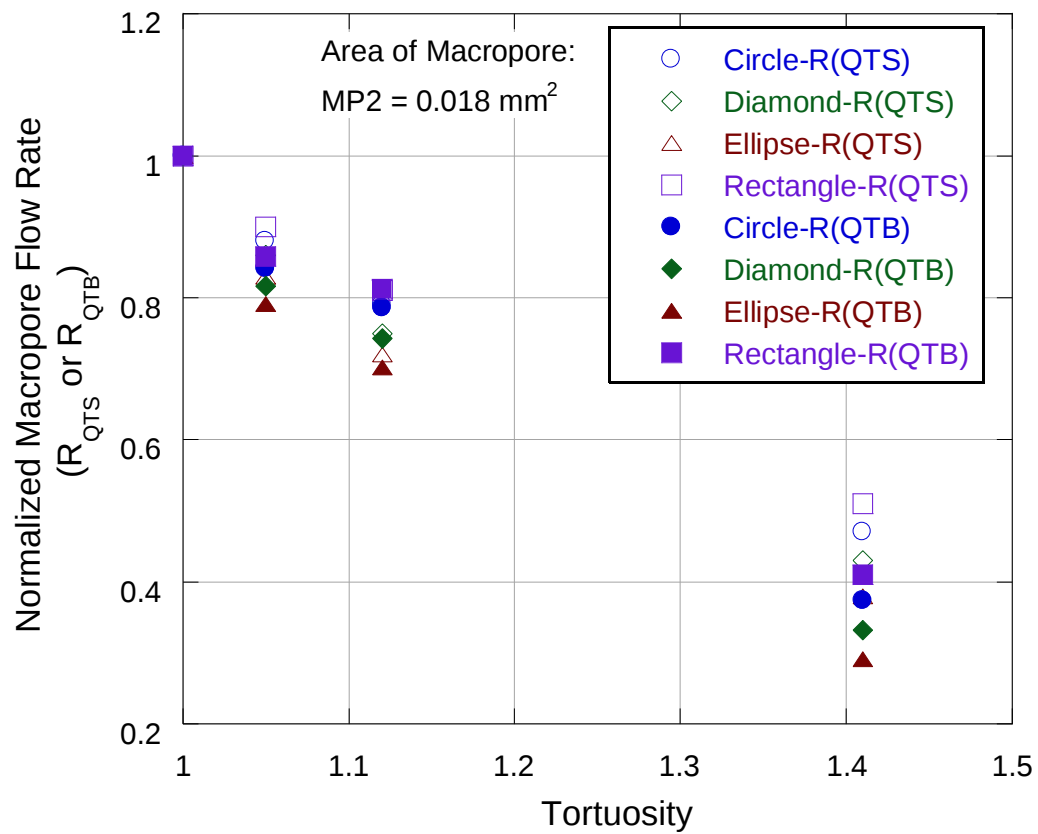


Figure 6.20: Influence of tortuosity on macropore flow rate.

6.5 Development of a Simplified Predictive Equation for Macropore Flow

From the results presented on macropore flow rate through different shapes and tortuosity (Figure 6.16 and Figure 6.20), we can come to a conclusion that the macropore flow rate is a function of aspect ratio and tortuosity. Change in velocity direction, increase in effective length, and bends/turnings are the influencing parameter in tortuosity. However, a particular pattern was not noticed on the effect of bends for the tortuous paths considered in this study. Hence, an equation can be formulated using the aspect ratio and tortuosity to predict the flow rate through different shapes and tortuosity based on the flow rate of straight vertical cylinder. Such an equation can be implemented in water balance models (e.g., RZWQM) in order to enhance the macropore flow module to include different shapes and tortuous macropores without much complication in programming. The flow rate of different shapes and tortuous macropore is inversely proportion to the tortuosity and aspect ratio (Figure 6.16 and Figure 6.20). Carman (1997) pointed out that the combined influence in flow due to change in velocity direction and increase in effective length can be represented by the tortuosity factor T^2 . Figure 6.16 shows that the effect of shape can be represented by $\sqrt{R_A}$ of the shape, where R_A is aspect ratio. Hence, following equation is formulated:

$$Q_p = \frac{Q_s}{T^2 R_A} \quad \text{Eq. 6.22}$$

where Q_p is the predicted flow rate; and Q_s is the straight vertical cylindrical macropore flow rate. Figure 6.21 presents the predicted vs. simulated flow rates in lattice units. Predicted macropore flow rates of straight inclined macropores match well with simulated macropore flow rate. For the bended macropores, at lower tortuosity or lesser number of bends the prediction is

comparable with the prediction for straight inclined macropores. However, at higher tortuosity (tortuosity more than about 1.3) the predicted flow rates are higher than the simulated flow rates as expected. More detailed study is required to identify the influence of bends on macropore flow rate and to come up with a factor for prediction equation.

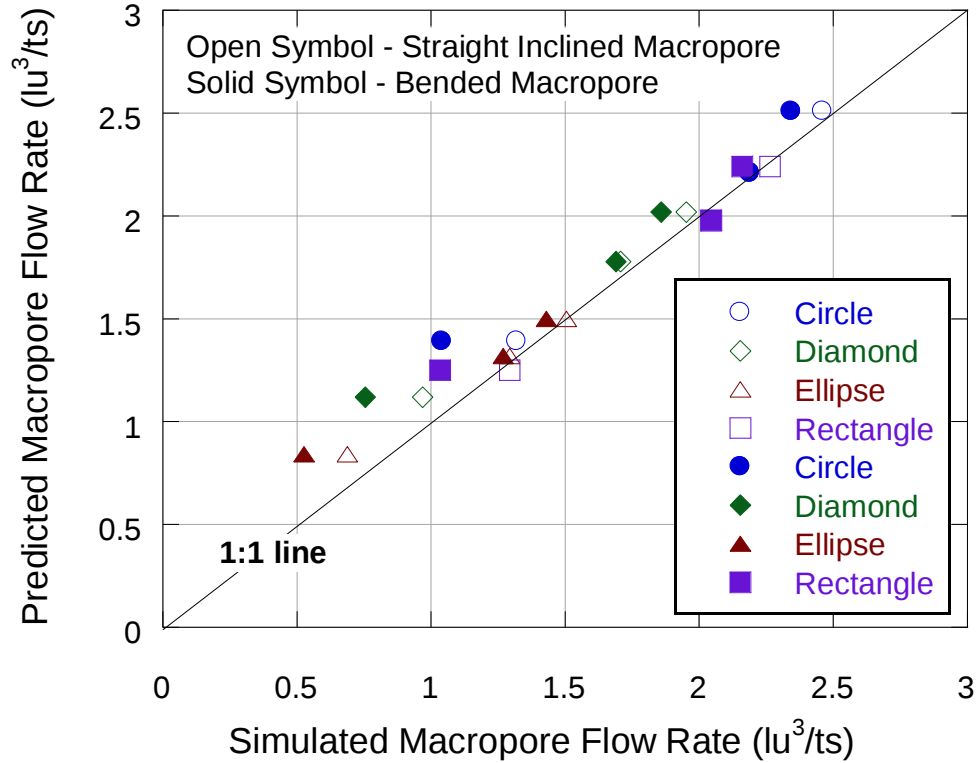


Figure 6.21: Comparison of simulated and predicted macropore flow rate.

6.6 Verification of the Simplified Predictive Equation for Macropore Flow

The prediction equation developed in section 6.6 was used to predict the k_{sat} of macroporous specimens using the X-ray CT scan images. The image analysis and macropore characterization methodologies are presented in section 5.4 and section 5.5. The equivalent cylinders relevant to

minimum radii were used to predict the macropore flow rate through the specimens and hence the k_{sat} of specimens. The cross section of minimum radii slices are shown in Figure 6.22. The parameters used to calculate the aspect ratio of the macropore shapes were marked in Figure 6.22. The tortuosity was calculated for each macropore according to the definition given in section 6.4. The macropore shape parameters and tortuosity are listed in Table 6.2. Also, the predicted k_{sat} of macroporous specimens using equation Eq. 6.22 are presented in Table 6.2. Calculated k_{sat} using LBM are presented in Table 6.2 for comparison.

Figure 6.23 presents the comparison of calculated vs. predicted and measured k_{sat} of macroporous specimens. For specimens S1 and S2, the prediction was about 20% less than the calculated k_{sat} . However, for specimen S3 the prediction is slightly higher. Specimen S3 had the tortuous macropore (tortuosity of 1.38) compare to specimen S1 and S2. The effect of number bending on macropore flow is not included in the prediction equation. However, the predictions of k_{sat} using the equation for the macroporous specimens are comparable with the calculated k_{sat} . Hence, X-Ray CT images can be used to predict the k_{sat} of the specimen using the prediction equation.

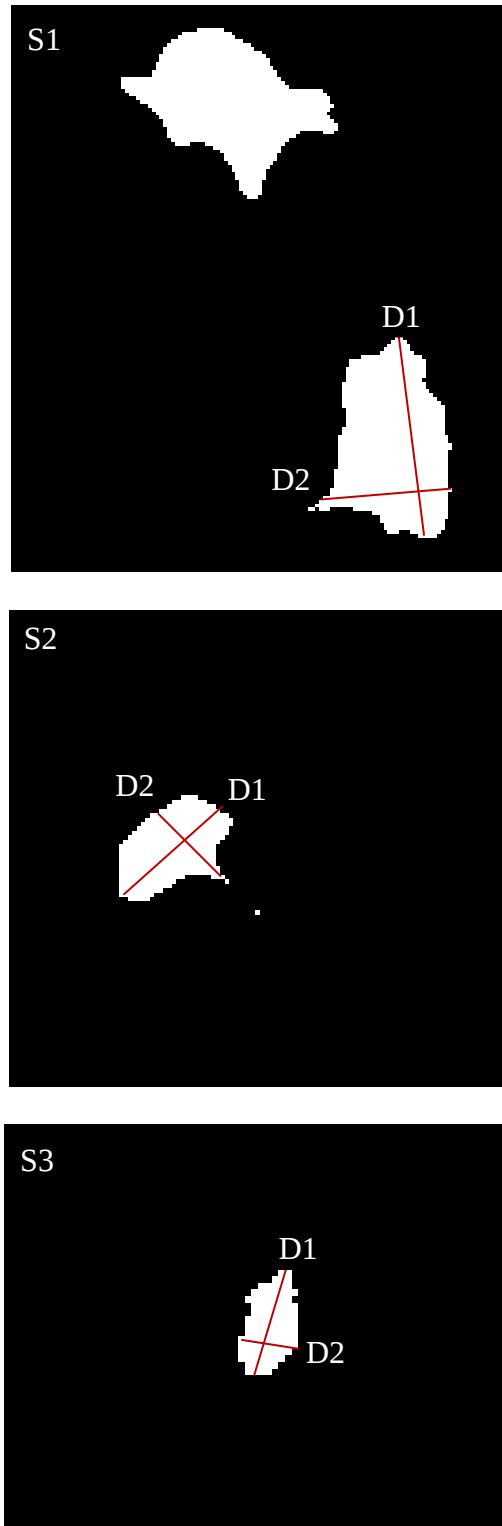


Figure 6.22: Cross section of macropore relevant to minimum equivalent radius (not to scale).

Table 6.2: Characteristics of macropore, and calculated and predicted k_{sat}

Sample ID	Macro-porosity (%)	Min. Radius (mm)	Estimated k_{sat} using Poiseuille law (mm/s.)	Tortuosity (-)	D1	D2	Aspect ratio	Simulated k_{sat} using LBM (mm/s.)	Predicted k_{sat} using Eq. 6.22 (mm/s.)
S1	6.84	3.340	118.4	1.10	8.78	5.06	1.49	98.9	80.3
S2	0.51	1.973	14.4	1.05	4.73	3.88	1.22	14.9	11.9
S3	0.28	1.966	14.2	1.38	2.70	1.20	2.25	3.9	5.0

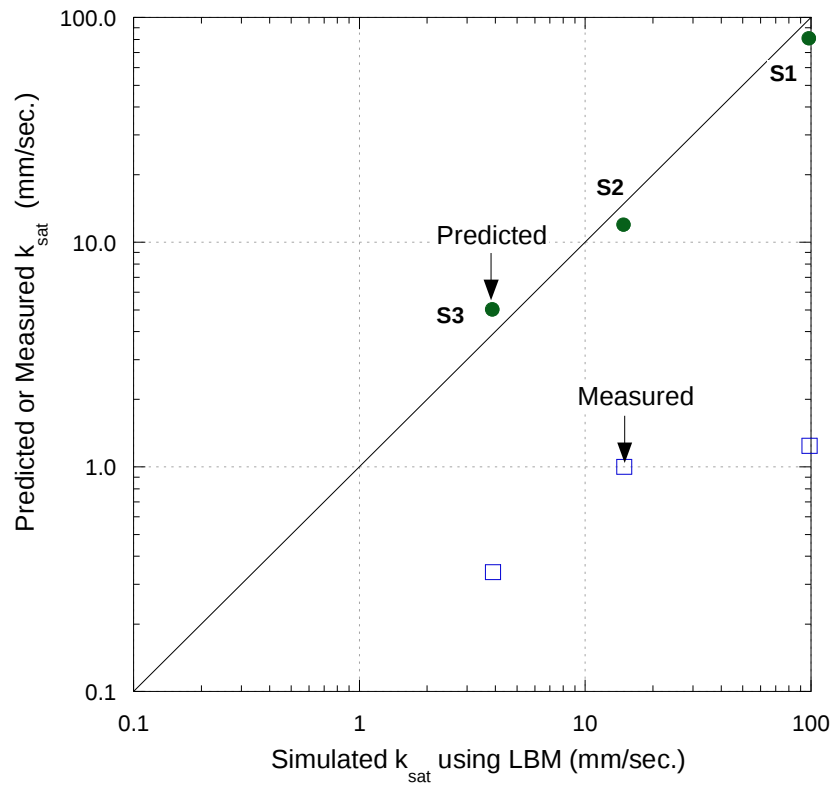


Figure 6.23: Calculated vs. predicted and measured k_{sat} of macroporous samples

6.7 Multiphase LBM

6.7.1 Shan-Chen (SC) Multiphase Model

The inclusion of an attractive force between neighbor particles, which leads to phase separation is the principal characteristic that differentiate the Shan-Chen (SC) model from single phase model (Sukop and Or 2004). The attractive force F_{int} is incorporated in LB algorithm as proposed by Shan and Chen (1993). For the D2Q9 model the F_{int} is as follows:

$$F_{int}(x,t) = -G\psi(x,t)\sum_i W_i \psi(x+e_i,t)e_i \quad \text{Eq. 6.23}$$

where G is interaction strength constant that is negative for particle attraction; and the function ψ is depend on density as follows:

$$\psi(\rho) = \psi_0 \exp\left(-\rho_0/\rho\right) \quad \text{Eq. 6.24}$$

where ψ_0 and ρ_0 are constants and the values of these constants can be varied arbitrarily (Sukop and Thorne 2006).

The interaction forces (F) (fluid/fluid or fluid/solid) can be incorporated as velocity shifts as follows (Sukop and Or 2004):

$$U = u + \frac{\tau F}{\rho} \quad \text{Eq. 6.25}$$

where U is the macroscopic velocity. The velocity U is used to compute f_i^{eq} . The equations from Eq. 6.1 to Eq. 6.6 and Eq. 6.24 to Eq. 6.25 form the single component multiphase (e.g., water and vapor) model. This algorithm can be extended to multi component multiphase (e.g., oil and

water) model by adding individual distribution functions for each component (f_i^σ where σ indicates the component of the fluid). For multicomponent model, the $f_i^{\sigma(eq)}$ is calculated from composite macroscopic velocity,

$$u = \frac{\sum_{\sigma} \frac{1}{\tau_{\sigma}} \sum_i f_i^{\sigma} e_i}{\sum_{\sigma} \frac{1}{\tau_{\sigma}} \rho_{\sigma}} \quad \text{Eq. 6.26}$$

Figure 6.24 presents the phase separation simulated using 2D single component multiphase (liquid-vapor) SC model (blue and gray colors indicates water and vapor, respectively). A domain of $200 \times 200 \text{ pixel}^2$ was used for the simulation with average initial density 200 in lattice units and perturbed with random density of 1 in lattice units. Figure 6.24 shows that initially the phase separation occurs rapidly and eventually it slows down due to the fact that large numbers of small droplets start competing for the liquid particle in the vapor phase (Sukop and Thorne 2004). During the phase separation, interfaces formed to minimize their total length in 2D, a consequence of free energy minimization and occurs in part by geometric rearrangement in to the minimum surface area volume (a circle in 2D) (Sukop and Thorne 2004). Also, the smaller droplets are more unstable compare to large droplets due to the surface tension effects on the interface (Begum and Basit 2008).

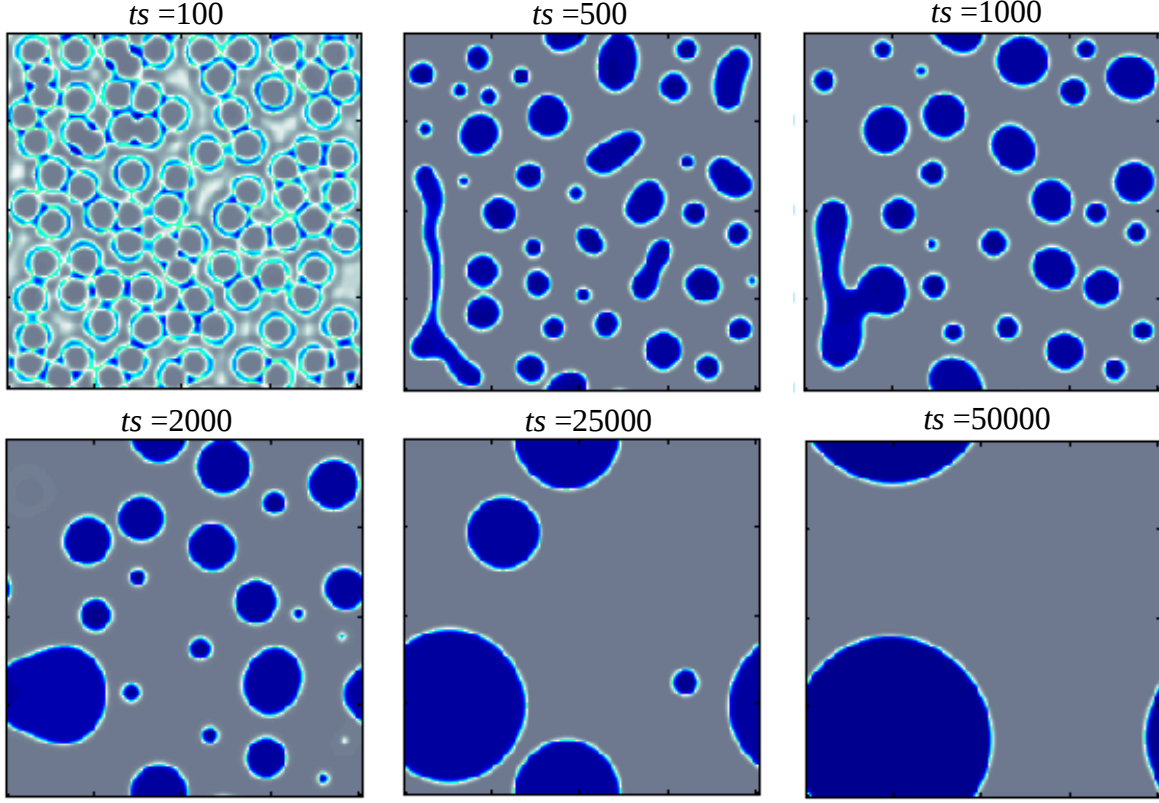


Figure 6.24: Phase transition simulated using single component SC multiphase model

Equations Eq. 23 and Eq. 24 lead to a non-ideal equation of state (EOS) for SC model and the EOS (SC model EOS) is given by,

$$p = c_s^2 \rho + \frac{c_s^2}{2} G[\psi(\rho)]^2 \quad \text{Eq. 6.27}$$

If there is no interaction force, that is function ψ reaches zero, the EOS (Eq. 6.27) reduces to ideal gas EOS (Eq. 6.7). EOS defines the relationship between pressure, temperature and volume (or density). In SC model EOS, the temperature is not explicitly defined but the temperature is dictated by G .

The SC model EOS is qualitatively similar to the van der Waals (vdW) EOS. However, the lack of a repulsive force in SC model EOS has led to a behavior where liquid phase is actually more compressible than the vapor phase which is generally not physically correct (Sukop and Throne 2006). Also, the spurious velocity (unphysical velocities occurs in two phase LBM at the interface region) is a challenge in SC model since the large spurious velocity will make the simulation unstable (Yuan and Schaefer 2006). The spurious velocity limits the density ratio since increasing density ratio results in an increase in the spurious velocity (Yuan and Schaefer 2006). Yuan and Schaefer (2006) recommended that spurious velocity can be reduced and higher density ratio can be achieved by changing the EOS. The EOS can be changed by changing the form of function ψ . The function ψ can be derived from Eq. 6.27 as follows:

$$\psi(\rho) = \sqrt{\frac{2(p - c_s^2 \rho)}{c_s^2 G}} \quad \text{Eq. 6.28}$$

Yuan and Schaefer (2006) studied different form of ψ namely the vdW EOS, Carnahan-Starling (C-S) EOS, Redlich-Kwong (R-K), Redlich-Kwong Soave (RKS), and Peng-Robinson (P-R). Huang and Lu (2009) used R-K EOS to study the relative permeability in steady-state gas/liquid flow in porous media. Similar approach is followed in this study to simulate percolation of water through unsaturated macropores. The R-K EOS is defined as,

$$p = \frac{\rho RT}{1 - b\rho} - \frac{a\rho^2}{\sqrt{T}(1 + b\rho)} \quad \text{Eq. 6.29}$$

where p is the pressure; R is the gas constant; T is the temperature; a is the attraction parameter; and b is the repulsion parameter. The function ψ for R-K EOS can be derived by replacing p in Eq. 6.28 according to Eq. 6.29.

The adsorption force between fluid particles and solid surfaces (F_{ads}) is introduced as follows (Huang and Lu 2009):

$$F_{ads}(x,t) = -G\psi[\rho(x,t)]\sum_i W_i\psi(\rho_w)s(x+e_i)e_i \quad \text{Eq. 6.30}$$

where ρ_w is density of solid phase; and s is equal to 1 or 0 for a solid or pore respectively. The ρ_w is not true density of solid phase but it is a parameter used to tune different wall properties (Huang and Lu 2009). When the ρ_w changes between density of liquid (ρ_l) and density of air (ρ_a), the contact angle changes between 0° to 180° .

Different contact angles were simulated using a domain of 200×200 pixel². A rectangle fluid was placed on the solid at the center of the domain. The parameters required for R-K EOS were assigned according to Huang and Lu (2009). The parameters a and b were set to 2/49 and 2/21, respectively. And, R is 1 and T is a function of T_c , $T=0.85T_c$ where T_c is 0.1961. The liquid and gas densities were set to 6.06 and 0.5, respectively. Figure 6.25 presents the three different contact angles of 12° , 75° , and 180° simulated using 5.5, 3.0, and 0.8, respectively, for ρ_w . Blue, gray, and yellow colors indicate liquid, gas, and solid phase, respectively. The dx and dt were set to 1.0 mm/pixel and 0.1667 sec./ts. The relaxation parameter was assigned as 1.0. The simulations reached steady-state in about 3000 ts.

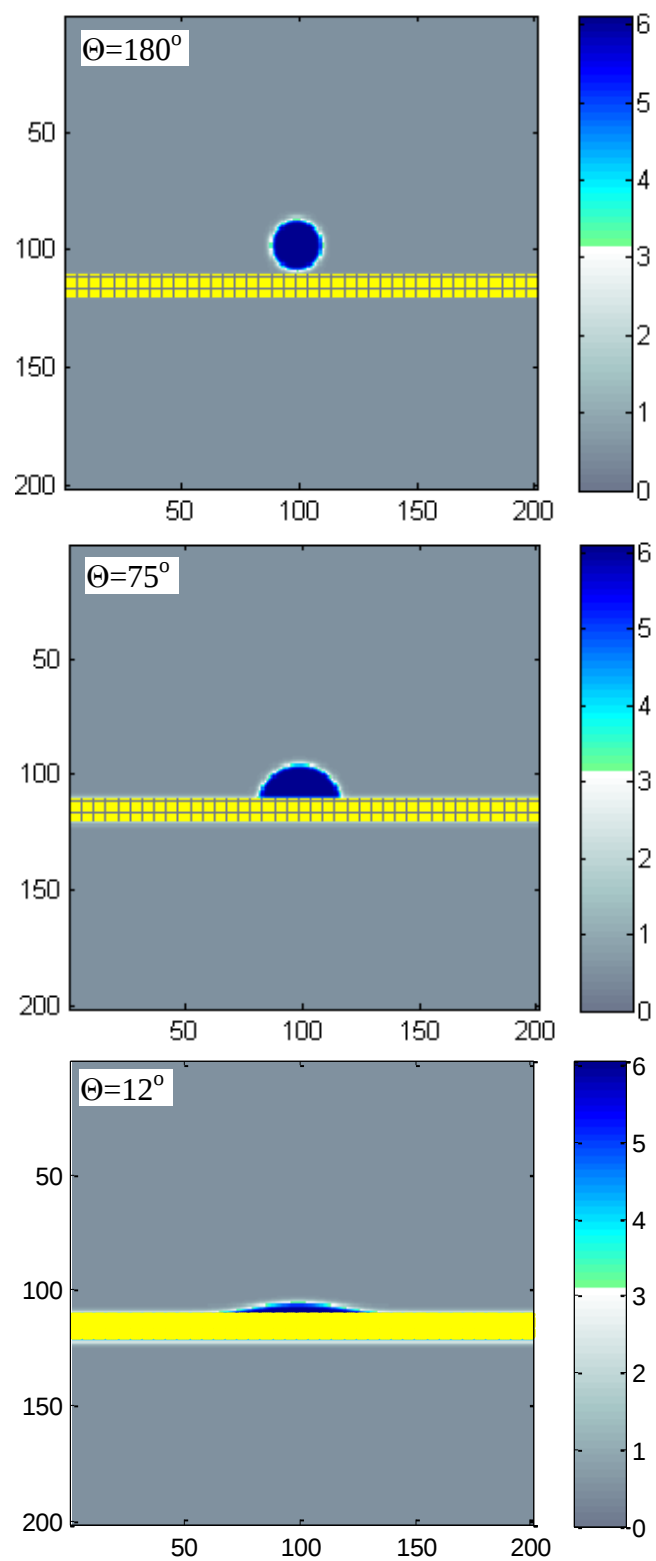


Figure 6.25: Simulated different contact angles (color bar shows the density of fluid)

Figure 6.26 presents the simulation of infiltration of liquid through unsaturated macroporous soil matrix using 2D single component multiphase SC model. The soil matrix was considered impermeable. Hence, water can flow only through unsaturated macropores. Blue, gray, and yellow colors indicate liquid, gas, and solid phase, respectively. The simulation parameters were assigned similar to the previous simulations (contact angle simulations). The density ratio was about 12. The contact angle between liquid and solid was set to 180° . Velocity boundary condition was assigned at top and bottom boundary. Periodic boundary condition was assigned for east and west boundary. The liquid infiltration during four time steps was shown in Figure 6.26. The liquid flows through bigger pores initially and then flow occurs through some smaller pores. The model was able to simulate the flow of liquid qualitatively correctly. However, model was unstable after 20000 ts. Also, model was unstable for gravity flow simulations.

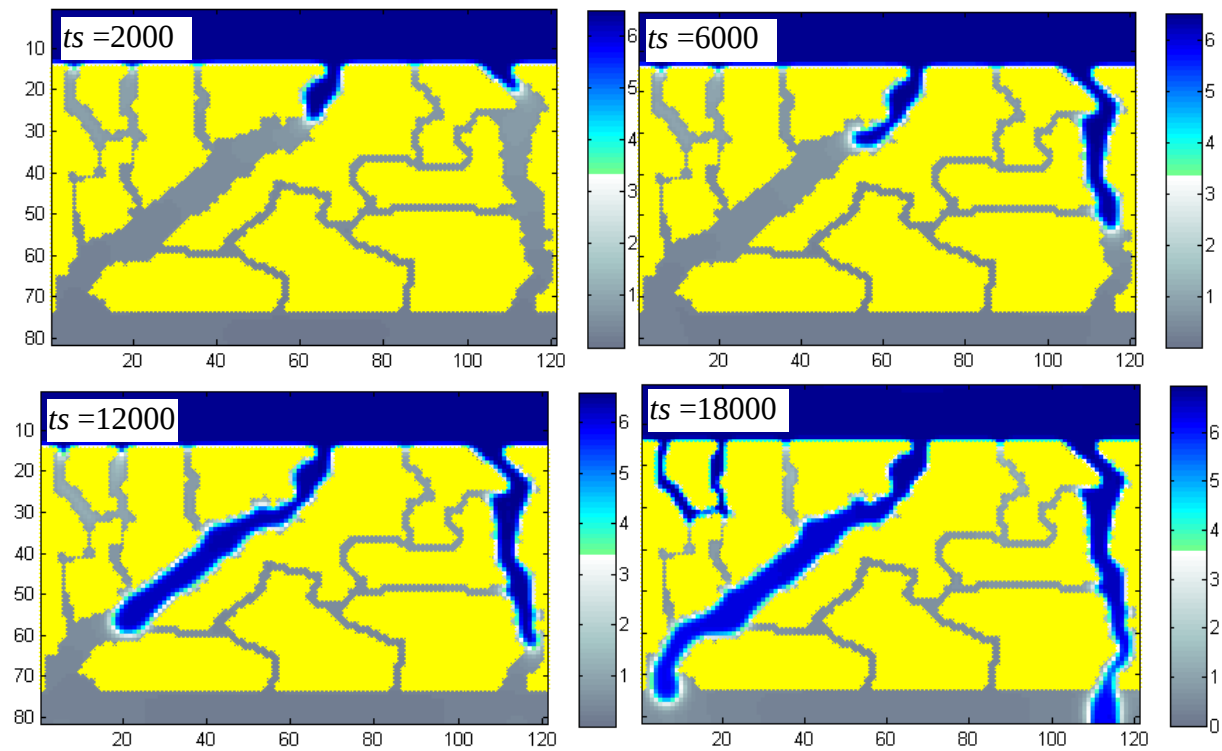


Figure 6.26: Simulation of infiltration of liquid through macropores using SC model

6.7.2 Color Indices (CI) Model

Misici and Palpacelli (2005) presented a two-fluid LBM based on color indices. In their algorithm, a color distribution function evolves together with the standard density distribution function. Except the evolution of the color distribution function, the rest of the algorithm is same as the single phase standard LBM algorithm (previously presented). Hence, only the evolution of color distribution function is described in this section. The presence of two fluids (red and blue fluid) is described by an indicator function ϕ :

$$\phi = \begin{cases} 1 & \text{if } \alpha \geq 1 \\ 0 & \text{if } \alpha \leq 0 \\ \frac{\sin[(\alpha_i - 0.5)\pi] + 1}{2} & \text{otherwise} \end{cases} \quad \text{Eq. 6.31}$$

where α is color distribution. The interface of the two fluids is those nodes for which $0 \leq \phi(x, t) \leq 1$ and one of the two fluids is at nodes for which $\phi(x, t) = 1$ and the other fluid is at nodes for which $\phi(x, t) = 0$. The color distribution (α) is calculated as follows:

$$\alpha = \sum_i \alpha_i(x, t) \quad \text{Eq. 6.32}$$

The color distribution function is defined as:

$$\alpha_i(x, t) = \alpha_i(x - e_i, t - 1) - \omega_\alpha [\alpha_i(x - e_i, t - 1) - \alpha_i^{eq}(x - e_i, t - 1)] \quad \text{Eq. 6.33}$$

where ω_α is relaxation parameter of color distribution function and it is function of relaxation parameters of individual fluids (ω_r for red fluid and ω_b for blue fluid):

$$\omega_\alpha = \omega_r \phi - \omega_b (1 - \phi) \quad \text{Eq.6.34}$$

The equilibrium color distribution function is given by:

$$\alpha_i^{eq} = \frac{\alpha(x,t) f_i(x,t)}{\rho} \quad \text{Eq. 6.35}$$

Finally the surface tension term is added to the f_i^{eq} (of the standard LBM) in the following form for a 2D model (the general term can be found in Misici and Palpacelli, 2005):

$$S_i = W_i \frac{9}{2} \sigma \left[\left(\frac{(G_{\phi x} + G_{\phi y})^2}{\|G_\phi\|} - 2\|G_\phi\| \right) \left((e_{ix} + e_{iy})^2 - \frac{2}{3} \right) \right] \quad \text{Eq. 6.36}$$

where σ is the surface tension strength parameter; and G_ϕ is the gradient of the ϕ .

Figure 6.27 presents the simulation of infiltration of water through macropores using 2D color indices model. Actual values of density and kinematic viscosity of water and air (blue and gray color in Figure 6.27, respectively) were used as input parameters for the simulation. Also, the real gravitational acceleration was applied. Due to the instability of the model, very small time step was used ($dt = 1 \times 10^{-6}$ sec/time step) which caused longer computer time. Regardless of the very small time step used, the model showed instability near about 2.5×10^5 ts (Figure 6.27) and the water area showed decreasing pattern. Refinement of the code is required for further study.

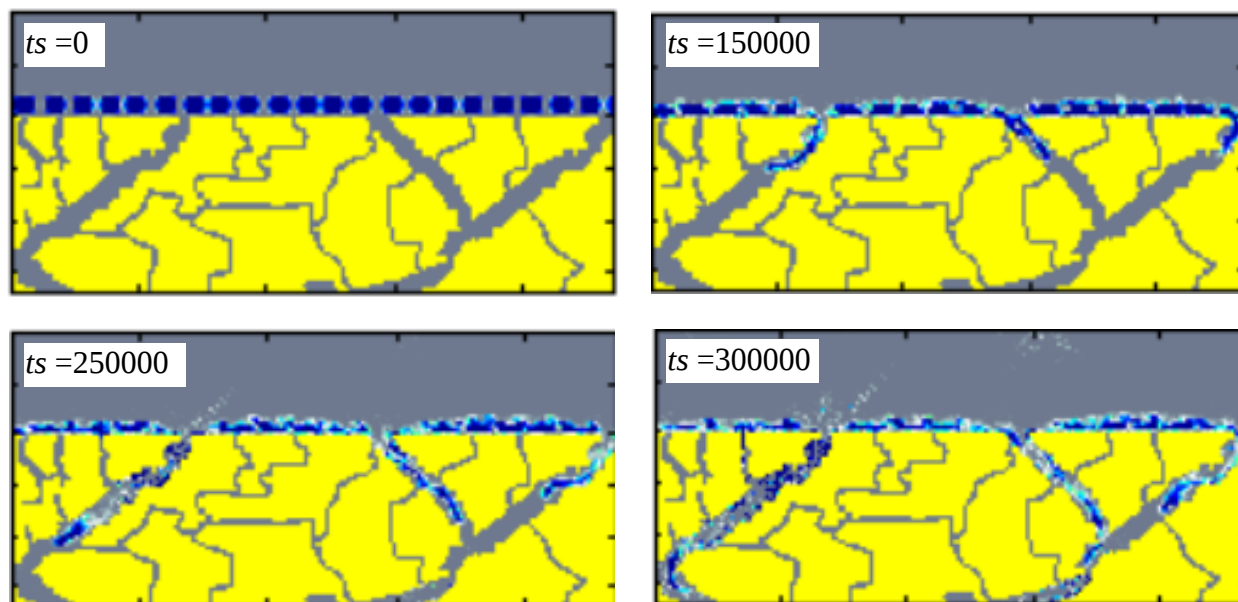


Figure 6.27: Simulation of infiltration of water through unsaturated macropores using CI model.

CHAPTER 7: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FURTHER STUDIES

7.1 Summary

The long-term change in hydraulic properties of earthen landfill final covers is one of the major challenges in cover design as it impacts the long-term percolation into the waste and impacts the long-term risk for ground water and surface water contamination. Formation of macropores and resulting flow through macropores increases the percolation through earthen landfill covers during service. Water flow in micropores can be downward or upward depending on the hydraulic gradient due to the soil capillarity and gravity. However, water flow in macropores is predominantly downward. Presently available models used for water balance modeling of earthen covers are based on Richards' equation that simulates only the micropore flow (capillary flow). Hence, a model that can simulate micropore flow as well as macropore flow is required to simulate long-term hydrology of earthen covers. The key objectives of this dissertation were to: (1) quantify micropore flow vs. macropore flow through an engineered earthen landfill final cover; (2) identify and validate numerical model capable of simulating micropore flow as well as macropore flow through earthen landfill covers; and (3) develop a model based on lattice Boltzmann method that can simulate saturated flow through micropores as well as macropores.

7.1.1 Field Data

A field-scale test section of an earthen cover was constructed at a landfill located near Detroit, Michigan and monitored for about four years. The cover consisted of 1.5 m thick compacted clay overlain by 0.3 m thick topsoil. The test section was instrumented to measure water contents, water potentials and percolation. Measured soil water storage (SWS) and percolation were analyzed for influence of macropore flow. The SWS calculated using point measurement of water content could not show the influence of macropore flow. Hence, SWS alone cannot be used to identify the presence of macropore flow in earthen covers.

Measured annual percolation for the first year was about 7 mm whereas the annual percolations for the second and the third years were 75 mm and 136 mm, respectively. Annual precipitations recorded for the 1st, the 2nd, and the 3rd years were 792 mm (35 percentile), 1,104 mm (98 percentile), and 828 mm (48 percentile), respectively. While the increase in annual precipitation and higher winter and spring precipitation may have contributed to higher percolation in Years 2 and 3, formation of macropores also contributed to the increase.

The test section was subjected to controlled irrigation during the 1st year and the 4th year of service to evaluate macropore flow. The field test section reached similar degrees of saturation at the end of each of the two irrigation tests. While the first irrigation test did not show distinct breakthrough, the second test resulted in breakthrough within few hours confirming macropore flow. Hence, controlled irrigation coupled with instrumentation can be used to assess evolution of macropore flow. Percolation measured during the four years of service was used to estimate effective hydraulic conductivity (k_{eff}) of the test section. The average degree of saturation of the storage layer was about 80-87% during the observed breakthroughs. The k_{eff} increased by about

an order of magnitude during the four years of service. The increase in k_{eff} is an indication of the increase in field k_{sat} . Formation of macropores caused the increase in k_{eff} .

Methane (CH_4) injection tests were carried out in the field to evaluate CH_4 oxidization capacity of earthen covers. The results aided in identification of macropores and their locations and to distinguish the active and non-active macropores. The width of the macropores ranged from few mm to about 4 cm and the length of the continuous segments of the macropores that could be measured from the surface were from 1 cm to 60 cm. Only one visible surface crack was identified in the lysimeter area. The average measured CH_4 flux through macropores was about two orders of magnitude higher than the average CH_4 flux through intact ground surface. The CH_4 oxidization capacity of cover where a macropore present was almost zero while the CH_4 oxidization capacity of intact cover ranged from 0% to 30%. Two orders of magnitude higher CH_4 flux and almost zero CH_4 oxidization capacity indicate that those macropores had reached the lysimeter.

7.1.2 Water Balance Modeling

Field evaluation of RZWQM was carried out using the data collected from the field test section. Numerical predictions using commonly used numerical model UNSAT-H were also compared with RZWQM predictions. For the first year, both models simulated cumulative percolation and SWS relatively accurately. However, both models are not capable of simulating frozen ground and hence SWS predictions of both models were not as accurate during winter and spring months. The numerically predicted annual percolation using UNSAT-H and RZWQM

were about 50% of measured annual percolation during the second year. The measured percolation during the second year was affected by macropore flow. UNSAT-H does not simulate macropore flow and the macropore flow component was not activated in RZWQM in the initial runs. UNSAT-H and RZWQM (without macropore flow) were able to simulate about 90% and 70% of cumulative percolation for the third year, respectively. However, the simulated percolation had a delay of about four months compared to measured percolation. In the field, the onset of percolation was four months early due to the relatively rapid flow through the macropores.

The macropore parameters required for the macropore flow component of RZWQM were calibrated using the flow rate measured during the second irrigation test and the number of macropores identified using methane injection tests. Calibrated macropore parameters based on the results of the second irrigation test and methane tests were used to simulate percolation during the second and the third year of service. The micropore and macropore flow simulations using RZWQM produced better percolation prediction compared to micropore only simulations for the second year, but about 13% less than the measured cumulative percolation. However, the micropore and macropore flow simulations using RZWQM for the third year simulated cumulative percolation that matched very closely with measured cumulative percolation. The size of the macropore can change in the field due to swelling or shrinkage of clay, plant roots penetration and death, and animal activity. Hence, periodic field calibration of macropore flow parameters may yield more accurate predictions of macropore flow.

7.1.3 Formation of macropore in Laboratory Specimen

Experimentally simulating macropore flow through cracks in clay in the laboratory is challenging due to the self-healing nature of cracks in clay and the effect of setup walls on the formation of cracks. A new technique was developed to create macropores in compacted clay in the laboratory. Food grade sugar in crystal form wrapped into an insect mesh was placed within clay specimen during compaction. During permeation, sugar dissolves while leaving a void which is a macropore. Control tests were carried out to test the effect of sugar on hydraulic conductivity of compacted clay specimen. Double ring rigid wall permeameter was used to measure the hydraulic conductivity of compacted specimens. The macropore resulted in an increase in the hydraulic conductivity by at least four orders of magnitude. High resolution X-ray CT scans of compacted clay specimens were used to develop 3-D structure of macropore(s). Macroporosity of macropores were estimated using the X-ray CT images.

7.1.4 Lattice Boltzmann Model (LBM)

A 3-D LBM simulating saturated flow through micropores and macropores was developed. Verification of the LBM was carried out using analytical solutions. Simulated k_{sat} of macroporous specimens were about an order of magnitude higher than the laboratory measurement of k_{sat} . The X-ray CT scans were performed on partially dry specimens. Unlike macropores in macroporous rock or compacted aggregate, the size of macropores within compacted clay can change due to swelling of clay during wetting. Hence, saturated samples need to be subjected to X-ray CT scans in order to develop structure of macropores.

Influence of macropore morphology defined by shape and shape related parameters, and tortuosity were systematically investigated via numerical simulations (3-D LBM). Constant cross sectional area and volume of macropores with various shapes were considered. The influence of turnings/bends in flow paths, increase in effective length of the flow path, and inclination of flow paths were analyzed. It was observed that the macropore flow rate decreases by about 10% to 70% as compared to a circular cross section when the tortuosity is increased by 40% or when the shape of the cross section is altered. Increase in aspect ratio of sectional shape shows decrease in macropore flow rate. Tortuosity plays a significant role in macropore flow where the macropore flow rate reduces by about 70% for tortuosity of 1.41 as compared to a tortuosity of 1. About 25% of overall reduction in flow rate was due to bends in flow path for tortuosity of 1.41.

A prediction equation was formulated to estimate the flow rate of arbitrary shape and tortuous macropore using the flow rate of straight vertical cylinders. The predicted flow rate of different shapes and tortuous macropores based on straight cylindrical macropore gives good match with simulated flow rate using LBM. However, more detailed study is required to predict the flow rate of bended macropores with tortuosity higher than about 1.3. The prediction equation was used to predict the k_{sat} of macroporous specimens. Equivalent circular area of macropores on each slices of X-ray CT images of macroporous compacted clay specimens were calculated. The equivalent cylinders relevant to minimum radii were used to predict the macropore flow rate through the macroporous specimens and hence the k_{sat} of the specimens. The macropore shape parameters required for prediction equation were estimated from the cross section of macropore on minimum radius slice for each specimen. Also, the tortuosity was calculated for each macropore from the 3-D structure of the macropores. Comparison of the predicted k_{sat} using the proposed formulation and simulated k_{sat} using the LBM were showed

excellent match. Hence, X-Ray CT images can be used to predict the k_{sat} of the macroporous specimen with the help of the proposed prediction equation.

7.2 Conclusions

The key conclusions of this study are:

1. Formation of macropores alters the long-term hydraulic properties of earthen landfill final covers. Field irrigation tests and estimation of k_{eff} indicated that the saturated hydraulic conductivity of the field-scale earthen final cover test section increased by about an order of magnitude due to the formation of macropores over the four years of service life. Controlled irrigation tests coupled with instrumentation can be used to quantify macropore flow through earthen landfill final cover.
2. RZWQM developed by Agricultural Research Services (ARS), USDA was evaluated to simulate hydrology of earthen landfill final cover using the data collected from the field-scale test section prior to the formation of macropores and RZWQM results were compared with commonly used micropore flow model UNSAT-H. The simulation results showed that RZWQM can be used to model long-term hydrology of earthen landfill final covers.
3. Macropore flow through earthen landfill final cover can be modeled using RZWQM as long as site specific macropore parameters are input. Macroporosity or number of macropores and average diameter of macropores are the important calibration parameters require to model the macropore flow.

4. Size of macropore can change in the field due to swelling and shrinkage, animal activity, and plant root penetration. Hence, measurement or calibration of macropore parameters needs to be done periodically.
5. Laboratory experiments on macropore flow through cracks in clay is challenging due to the self-healing nature of the cracks. Hence, a new technique was developed to introduce continuous macropores within lab-scale compacted clay samples and the technique yielded consistent results.
6. 3-D LBM developed in this study can be used to simulate saturated flow through micropores as well as macropores. Verification of the model confirmed the accuracy of the model. Laboratory validation of the model was difficult due to the swelling nature of the compacted clay specimen.
7. The LBM aided in quantification of the effect of macropore parameter and tortuosity in macropore flow. Tortuosity and aspect ratio are the two key parameters that influence flow through macropores of the same cross sectional area. The macropore flow rate reduced by about 35% and 70% when the aspect ratio and tortuosity were increased to about 2.8 and 1.4 from 1, respectively.
8. The prediction equation developed using LBM simulations on the effect of macropore parameter and tortuosity can be used to predict the macropore flow rate as long as scan images of macropores are available. The prediction equation requires only two parameters, aspect ratio and tortuosity, other than the sectional area of macropore.
9. The prediction equation can be implemented in water balance models (e.g., RZWQM) in order to enhance the macropore flow module to include different shapes and tortuous macropores without much complication in programming.

7.3 Recommendations for Further Studies

The macropore flow component of RZWQM was calibrated using the irrigation test performed on the test section during the 4th year of service. The simulated percolation using the calibrated macropore parameters provided excellent match with measured percolation for the third year field data but not for the second year field data. The size of the macropore can change in the field due to swelling of clay, plant roots penetration and death, and animal activity. Hence, in the further studies, it is recommended to perform controlled irrigation tests during different time spans in service to create a data base for macropore parameters. Also, the calibrated macropore parameters can be verified to simulate the macropore flow through earthen landfill final covers at different climate zones in future studies.

The 3-D LBM was verified using analytical solutions. High resolution X-ray CT scans were performed on compacted clay specimens to develop 3-D structure of macropore and to validate the LBM using the measured k_{sat} . Unlike macropores in macroporous rock or compacted aggregate, the size of macropores within compacted clay can change due to swelling of clay particles. Hence, saturated samples needs to be subjected to X-ray CT scans in order to develop structure of macropores and to validate the LBM. In future studies, it is recommended to use improved permeameter to measure the k_{sat} of macroporous compacted clay samples and to perform X-ray CT scan on saturated samples in order to validate the LBM to simulate macropore flow through compacted clay samples.

The prediction equation developed to estimate the flow rate of arbitrary shape and tortuous macropore using the flow rate of straight vertical cylinders was able to predict the flow rate through macroporous compacted clay samples. The effects of sectional shape and tortuosity are

included in the equation. The effect of tortuosity can be due to change in velocity direction, increase in distance, and bends/turnings. However, the effect of bends/turnings is not considered in the equation. The LBM simulations showed that the effect of bends/turnings in macropore is small compare to the effect of change in velocity direction and increase in distance. However, it is recommended to study the effect of bends in detail in future studies. Also, the prediction equation can be validated using samples collected from field in further studies.

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