MOISTURE RETENTION AND CONDUCTIVITY PROPERTIES OF WASTE REFUSE: A LABORATORY STUDY

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A thesis submitted to Napier University In Fulfilment of the requirements for the Degree of Doctor of Philosophy

School of Engineering and the Built Environment Napier University Edinburgh, UK 2007

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NAPIER UNIVERSITY SCHOOL OF THE BUILT ENVIRONMENT

Doctor of Philosophy

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ABSTRACT

The modelling of infiltration and moisture movement within a porous medium requires information on the moisture retention and hydraulic conductivity properties. In this study, the unsaturated hydraulic behaviour of a compacted waste sample based on the composition of Lyndhurst Landfill site in Melbourne, Australia was investigated in laboratory. Two fundamental aim of the study were to establish the moisture retention characteristics of Municipal Solid Waste (MSW) sample and measure its unsaturated hydraulic conductivity.

In landfilled waste, the particle and pore size distribution, heterogeneity of waste composition and leachate chemistry complicate the determination of moisture retention and hydraulic conductivity. In this study the modification and use of a standard pressure plate apparatus was described which can be used establish moisture retention properties of samples of 230 mm in diameter. The experiments showed that the moisture retention characteristics of compacted waste sample were comparable to soils. It has been shown that water retention in waste is a function of its position relative to the phreatic surface, in other words, its hydraulic boundary conditions which will vary with elevation. Some difficulties and limitations of using this method were discussed.

As with conventional inert soils, laboratory determination of unsaturated hydraulic conductivity is difficult and recourse is often made to analytical methods as those presented by van Genuchten (1980). One aim of this study was to compare the unsaturated hydraulic conductivity of MSW obtained using Passioura's (1976) one-step outflow test method with predictions using van Genuchten's model. Good

agreement is observed between the predictive model and experimental method for unsaturated hydraulic conductivities at low moisture contents but there is poor agreement at high degrees of saturation. This latter discrepancy is attributed to the difficulty of measuring retention properties of large pores at low suctions and the applicability of the van Genuchten model to such a material. Results also suggest that dual porosity exists within waste.

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DECLERATION

This thesis is submitted to Napier University for the degree of Doctor of Philosophy. The work described in this thesis was carried under the supervision of Dr. John McDougall and Prof. Ian Pyrah. The work has been undertaken in the School of Engineering and the Built Environment, Napier University, Edinburgh.

In accordance with the Regulations of Napier University governing the requirements for the degree of Doctor of Philosophy, the candidate submits that the work presented here in this thesis is original unless otherwise referenced within the text.

The following papers were derived from the work in this thesis. Those paper published by the time this thesis is prepared are included in the Appendix. Full permission from the relevant publisher or copy right holder has been obtained.

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List of Symbols

- Ψ_{total} total potential (equation 2.28)
- Ψ_{g} gravitational potential (equation 2.28)
- $\Psi_{\rm m}$ matric potential (equation 2.28)
- Ψ_{o} osmotic potential (equation 2.28)
- Ψ_p pressure potential (equation 2.28)
- Φ total head (equation 2.12)
- α contact angle in liquid/vapour interface measured in liquid (equation 2.3)
- α van Genuchten model parameter (equation 2.22 & 2.23)
- γ unit weight of the permeating fluid (equation 3.3 3.6)
- γ_d weight of unit volume of a waste component including dry micropore system (equation 5.4)
- γ_{si} individual waste component solid phase unit weights (equation 5.4)
- γ_{sat} weight of unit volume of a waste component including saturated micropore system (equation 5.4)
- γ_w unit weight of water
- ϵ vertical strain (equation 5.3)
- η tortuosity parameter in unsaturated conductivity function (equations 3.25 & 3.26)
- θ volumetric water content (equations 2.15, 2.18, 2.19, 2.20, 2.23, & 2.24)
- θ_r residual water content (equations 2.15, 2.18, 2.23)
- θ_s saturated water content (equations 2.15, 2.18, 2.19, 2.20, 2.23, & 2.24)
- θ^* normalised moisture content (equation 4.6 4.8)
- λ Brooks and Corey model parameter (equation 2.17)
- λ Campbell and Corey model parameter (equation 2.19 & 2.20)

- μ absolute viscosity (equations 3.1, 3.5, 3.6 & 3.8)
- v kinematic viscosity (equation 3.8)
- σ stress (equations 2.1, 2.2 &2.10)
- σ_v vertical stress (equation 5.1)
- σ_y stress in y-direction (equation 2.4 &2.5)
- ψ matric suction head (equation 2.12, 2.18, 2.19 & 2.22)
- ψ_{aev} matric suction at air entry value (equation 2.18)
- ψ_r suction value at residual water content
- B Clapp and Hornberger model parameter (equation 3.24)
- C specific moisture capacity
- E_o One dimensional compression modulus (equation 5.1)
- H hydraulic head
- K_r relative hydraulic conductivity (equation 3.22)
- K_s saturated hydraulic conductivity (equation 3.22)
- P_{atm} Atmospheric pressure (equation 2.33 & 2.34)
- R radius of the capillary tube (equation 2.4)
- R_c radius of curvature of air water interface (equation 2.6)
- S_e effective saturation (equation 2.15)
- u_a air pressure (equation 2.1)
- u_w water pressure (equation 2.1)
- a Fredlund and Xing model parameter (equation 2.24)
- a Brutseart model parameter (equation 2.21)
- b Brutseart model parameter (equation 2.21)
- b Cambell model parameter (equation 2.19)
- g Gravitational constant

- h_c capillary height (equations 2.4- 2.10)
- i hydraulic gradient
- length over which the piozemetric pressure difference acts (equations 3.1 &3.3)
- tortuosity parameter in unsaturated conductivity function (equations 3.25 & 3.26)
- m van Genuchten model parameter (equation 2.22 & 2.23)
- m Fredlund and Xing model parameter (equation 2.24)
- n van Genuchten model parameter (equation 2.22 & 2.23)
- n Fredlund and Xing model parameter (equation 2.24)
- n porosity
- p_c capillary pressure (equation 2.2)
- q Discharge velocity or Darcy flux
- v velocity
- w gravimetric water content (equation 5.1)
- z elevation head (equation 2.12 and 5.1)
- z_0 elevation head at phreatic surface (Figure 2.6)

Chapter 1

1 INTRODUCTION

Landfill is the major method of waste disposal in waste management because it is the cheapest way of eliminating Municipal Solid Waste (MSW) compared with other methods such as incineration and composting. However, landfill is not an ideal solution as it poses a threat, by liquid (leachate) and gaseous emissions, to the environment and consumes significant amount of land. Historically, it was generally believed that leachate from the waste was allowed to dilute and disperse and contamination of the groundwater was not a prime concern. Thus disposal of waste in the form of open dumps was an acceptable practice.

Due to increased understanding of the impact of landfills on groundwater contamination, dilute and disperse is now unacceptable and although landfill are still the predominant method of waste disposal in UK and elsewhere, it is by well engineered sanitary landfills. With increasing research and engineering input landfill design has become increasingly sophisticated over the past few decades. The aim of modern landfill management is to equilibrate the energy gradient between landfill and the surrounding environment in a controlled manner to a final storage quality where the emissions (leachate and biogas) have the minimum environmental impact. Quantity and quality of the leachate and biogas generation depend upon the characteristics of the waste, the design and operation of the landfill and the climatic conditions (temperature, precipitation, and evapotranspiration). Moisture and moisture flow were identified as the main factors determining the metabolism of landfills (Pohland, 1975; Leckie and Pacey, 1979). Moisture is an essential component for the biochemical decomposition of organic substances and is also needed for leaching of soluble compounds. Enhanced moisture contents through the waste leads to an acceleration of biochemical processes as moisture facilitates the redistribution of chemical micro-organisms and nutrients. Moisture is also needed for hydrolysis, which is the first step in the anaerobic biodegradation process.

Moisture in Landfill

There are two different approaches for the control of moisture in landfill sites. The first and most common one is primarily based on permanent storage and containment or the" dry cell" concept. With the dry cell concept, the idea is to place the waste in an engineered containment site with a liner, cover and hydraulic system to minimise the amount of moisture entering the waste and also prevent the migration of leachate away from the landfill into the surrounding hydrogeology. With the limited moisture present within the landfill, the biochemical processes which stabilise the waste cannot take place, therefore, the waste remains largely unchanged and the containment structures will require longer design lives.

In contrast to the first approach a landfill may be run as a bioreactor. The bioreactor concept allows enhanced biodegradation of the waste, thus promoting rapid stabilization and reducing the time required for the landfill for beneficial land use. Biodegradation may be enhanced by moisture control through leachate recirculation, nutrients and buffer addition, aerobic decomposition and MSW composition control. Among these leachate recirculation has received the most significant attention (Yuen et al., 1999) as it is the most practical approach for full-scale operations. On the other hand, when leachate recirculation devices are designed or operated incorrectly the landfill can develop many hydraulic problems including the increasing leachate heads on the clay liner and subsequent breakout of leachate from the landfill containment system, and potential slope instability problems due to reduction in shear strength of MSW.

Regardless of the type of landfill system, modelling of landfill hydraulics is a useful input into the design of leachate collection and removal systems, as well as for predicting the amount and first appearance of the leachate production. However, it is particularly relevant for the analysis of leachate recirculation systems, which must ensure an adequate distribution of moisture and biochemical entities.

Landfill Containment and Hydraulics

1.1.1 Containment

A typical Municipal Solid Waste Landfill (MSWLF) consists of several main components; a base liner, a leachate collection system (LCS), lined side-slopes, the contained waste mass including daily cover materials, and a final capping layer. MSWLF must be constructed with a composite base liner and a leachate collection system that is constructed to maintain leachate level over the liner below a certain depth specified by a competent authority. European Community (EC) Landfill Directive (1999) specifies that leachate accumulation at the base of a landfill should be less than 50 cm over the base liner. EC Landfill Directive (1999) requires a minimum 0.5 metres thick artificially reinforced sealing system overlying a geological barrier with saturated hydraulic conductivity less than 1 x 10^{-7} cm/sec and thickness greater than 1 meter as a composite base liner.

United States Environmental Protection Agency (USEPA) requires that MSWLF must be constructed with a composite base liner and a leachate collection system that is constructed to maintain less than 30 cm depth of leachate over the liner (USEPA, 1988). According to USEPA, a composite liner must consist of an upper component of minimum 6 mm high-density polyethylene membrane and a lower component of a minimum 60 cm compacted soil with saturated hydraulic conductivity no greater than 1×10^{-7} cm/sec. A minimum 30-cm-thick high permeability drainage layer of a granular soil or a geosynthetic drainage material is usually placed above the composite lining system. Perforated leachate collection pipes are placed within this high permeability drainage layer to increase the flow efficiency and direct the leachate towards a leachate collection sump. Side slopes are lined while the LCS is being constructed. Side slope geomembrane is attached to the base geomembrane and

is covered with a layer of soil to protect the liner form physical damage during infilling stage.

Once the base liner and LCS have been constructed, waste can be placed. Each lift of waste has to be covered with a material to limit access to insects, rodents, wind blown litter and fire. This material is usually a 15 cm compacted soil, but can be any of a number of synthetic materials (EC Landfill Directive, 1999).

Landfill Cover

Once a landfill unit has been filled to a capacity, a final cover lining (capping) is to be constructed over the surface profile on the landfilled waste. Cover is essentially used as a barrier

- to prevent the ingress of precipitation thus decreasing leachate generation,
- to prevent and/or managethe uncontrolled migration of gases and odour into the surrounding environment,
- for restoration and aesthetic purposes.

At the same time, the cover must function with minimum maintenance, promote drainage, and minimise erosion of the cover, and accommodate settling. Figure 1.1 shows a schematic of a composite (multilayer) cover system for a closed waste landfill. Alternative final cover systems may be designed to achieve aforementioned goals. Further recommendations for landfill cover design can be found at EC Landfill Directive (1999) and USEPA (1992). Benson (1999) presented detailed investigation on final covers for waste containment systems and provides a review of North American practise in final cover design over the last 20 years.

Once the landfill unit is closed, the standard procedure has been to drain the leachate from the landfill and remove it from the site. The disposition of incident rainfall is now largely to runoff and in the absence of any fractures or high permeability pathways, infiltration is limited by the permeability of the final cover. The moisture distribution throughout the waste is in steady state condition, and leachate discharge is negligible



Figure 1.1 A schematic of a composite final landfill cover

1.1.2 Landfill Hydraulics

A schematic diagram of the hydraulic regime of a typical landfilled waste disposal site is presented in Figure 1.2. Leachate formation in landfills is influenced by many factors; climatic and hydrogeologic, site operations and management refuse characteristics, and internal landfill processes. These factors can be divided into those that contribute directly to the landfill moisture (such as rainfall, snowmelt, groundwater intrusion, initial moisture content and recirculation) and factors that affect the moisture distribution within the landfill (such as composition, particle size, density and permeability).

During the infilling phase it is assumed that all incident rainfall infiltrates the landfilled waste. Surface infiltration is insufficient to fully saturate the waste fill, therefore, moisture movement occur under partially saturated conditions, although zones of full saturation may develop as moisture percolating down through the waste accumulates on the base liner or daily cover.



Figure 1.2. Hydraulic regime in a landfill site during (a) post closure and (b) active infilling.

If recirculation is applied for promoting stabilization, there are several techniques which can be used to apply leachate to the landfill. Moisture distribution patterns introduced by these recirculation techniques are desired to be uniform throughout the waste mass. These techniques are divided into surface and subsurface applications. Surface applications consist of:

- Spray infiltrators
- Surface ponds

Subsurface application techniques are:

- Vertical injection wells
- Sub-surface horizontal recirculation trenches.

Each of the techniques has specific benefits and disadvantages associated with it. Odour problems, poor aesthetics, and potential runoff of applied leachate into storm water management system are the major disadvantages of the surface applications technique. Sub-surface infiltration trench and vertical injection wells are the most common techniques reported. Often different methods are combined with an aim to achieve the best system to suite site-specific factors such as climate, waste depth, compaction, final cover and liner design (Reinhart, 1996; Yuen, 1999). Details of a conceptual sub-surface horizontal infiltration trench are shown in Figure 1.3.

Currently there is very little information regarding the effectiveness and performance of various recirculation techniques, particularly in terms of their influence zone, feeding capacity, spatial and temporal moisture distribution pattern, and induced hydraulic head on liner. No specific design guidelines are available for designing leachate recirculation devices (Reinhart, 1996 and Yuen, 1999).



Figure 1.3 Details of sub-surface horizontal trench.

Modelling of Landfill Hydraulics

The hydraulics of landfill sites are commonly evaluated using water balance models. In this method, the difference between the boundary input and output determines the amount of leachate generation. The rate of leachate discharge within a certain period provides information to design necessary storage tanks and treatment plants at the landfill site. However, water balance models can often over- or underpredict the volume of leachate generated in municipal solid waste landfills by up to three orders of magnitude (Zeiss, 1997).

The most significant disadvantage of water balance methods is related to its limited potential. The actual process of moisture transport through the porous media is not taken into consideration. With this method, the impacts of a single rainfall event on leachate generation cannot be evaluated. Therefore, neither leachate discharge rates nor spatial and temporal moisture distribution data are available. However, this is valuable information for analysis and design of leachate recirculation devices as moisture levels are required to be uniform throughout the waste during the recirculation.

The progress of biodegradation is widely accepted to contribute significantly to the magnitude of settlement in landfills. Also it is reported that both the leachate characteristics and moisture content have a fundamental influence on the progress of biodegradation (Pohland, 1975 and Yuen, 1999). Therefore, knowledge of the temporal and spatial moisture distribution is a key input into the formulation of a biodegradation model.

1.2.1 Variably Saturated Flow Theory

Spatial differences in hydraulic head cause flow of moisture in porous media. Darcy (1856) proved in his experiments that a direct relationship exists between the flow velocity within a saturated porous medium and the hydraulic gradient, i.e conductivity is constant. In unsaturated conditions, the pore water pressure become negative, and the assumption that hydraulic conductivity is a constant no longer applies. In fact it is a function of the volumetric moisture content. Richards (1931) has showed that a modified Darcy's law applies to partially saturated flow conditions. When Darcy's law is coupled with the law of continuity, this gives the Richards' equation (1931) which describes flow in partially saturated media. A full derivation of the flow equation is given in Chapter 3. Two fundamental soil water relationships are required for the solution of Richards' equation. The first relationship is between negative pore water pressure (or suction) and moisture content. The moisture retention curve is a graphical presentation of this relationship. The second relationship is between the unsaturated hydraulic conductivity and moisture content and is known as the relative permeability function.

The dependence of matric suction and the unsaturated hydraulic conductivity on moisture content means that unsaturated flow equation is highly nonlinear. Analytical solutions exist only for certain boundary conditions and simple geometries, therefore, numerical methods such as finite difference and finite element are usually applied for more complex problems.

The finite element method can easily simulate complex, irregular boundaries. It can easily handle non-homogeneous and anisotropic materials and very little extra effort is required to model problems with more than one material. This is particularly important in simulating landfill hydraulics as different hydraulic conductivities can be given to the waste, the drainage layer and the clay liner.

1.2.2 Hydraulic Properties of Landfilled Waste

Predicting the moisture distribution and leachate generation in landfilled waste using unsaturated flow analysis is dependent on the validity of unsaturated hydraulic properties of the landfilled waste. Unsaturated flow has been extensively researched in the fields of soil physics, hydrology, and geotechnical engineering. Although the unsaturated hydraulic properties of conventional soils have been investigated extensively, there is very limited evaluation of the landfilled waste (Korfiatis et al., 1984; McDougall et al., 1996).

There are several reported moisture retention curves for MSW. However, these are neither established in the laboratory using a representative volume waste sample, nor measured in the field. They are established by calibrating the simulation data to match the experimental data of leaching columns (Korfiatis et al., 1984). No evidence of a laboratory method for measuring the moisture retention curve of a representative MSW specimen has been found.

In order to consider the flow in both the saturated and unsaturated zones of a landfill, the hydraulic conductivity of the landfilled waste must be known both in the saturated and unsaturated zones. The saturated hydraulic conductivity of MSW has been reported by several researchers (Oweis et al., 1990; Beaven and Powrie, 1995). MSW landfills that are operated with engineering principles are far from leachate saturation. Hence, moisture transport within the landfill occurs mainly under unsaturated conditions. It is therefore crucial to characterise the unsaturated hydraulic conductivity of MSW. Direct measurement of the unsaturated hydraulic conductivity

of porous media is often expensive and difficult to conduct (Lam et al, 1987). In waste this problem is exacerbated due to its high compressibility and decomposable nature.

An alternative and well researched approach to establis the unsaturated hydraulic conductivity of a porous medium based upon its moisture retention curve, which is relatively simple to obtain (Childs and Collis-George, 1950; Brooks and Corey, 1966; and van Genuchten, 1980). It has been concluded that this generally gives accurate predictions of the experimentally measured hydraulic conductivity values of inert soils.

Some of the studies referred to above use unsaturated hydraulic conductivity of landfills waste obtained from water retention curve. By comparison to the inert soils, MSW is more heterogeneous, more compressible, has wider pore and particle size distributions, and is a biodegradable material which leads to a difficult and changing pore structure. It has not yet been shown that pore structure models leads to a meaningful prediction of the unsaturated hydraulic conductivity in MSW.

Summary

This chapter introduces the landfills and landfilling and summarises the existing approaches towards the hydraulic assessment of landfilled waste and the role moisture plays in its short and long term behaviour. The following conclusions can be made related to the modelling of landfill hydraulics:

- Variably saturated flow theory accounts for the flow mechanisms and has been applied to movement within the waste fill.
- No evidence of a laboratory method for measuring the moisture retention curve or unsaturated hydraulic conductivity of a representative MSW specimen has been found.

- Modelling of landfill hydraulics has potential as a useful tool as the moisture movement plays a key role in design of leachate collection and removal systems, evaluation and design of leachate recirculation devices, and simulation of long term biodegradation related settlements.
- Moisture retention curve of a porous medium provides an empirical method for calculating the unsaturated hydraulic conductivity using procedures such as those of van Genuchten (1980). It has not been proven that these procedures lead to a meaningful prediction of unsaturated hydraulic conductivity in MSW.

Chapter

2

2. PHYSICS OF SOIL WATER INTERACTION

Landfilled waste is a porous medium with solid material and pore space distributed throughout the volume. The pore space is filled by water and/or gas, whereby the gas can be composed of generated landfill gas or intruded air. In general a landfill can be a three-phase system, consisting of a solid phase, a liquid phase and a gaseous phase as shown in Figure 2.1. McDougall et al., (2004) discussed that the porous media, which is most comparable to solid waste landfills concerning its structure, porosity and gas content, is unsaturated soil. This finding has already been accounted for in present water flow models for landfills, as all introduced so far are derived from the same framework, which has been originally developed for soils. In this thesis, landfilled waste is likened to an unsaturated soil, i.e. a porous mediam comprising three phases: solid, liquid and gaseous. This chapter reviews the mechanisms of soil water interaction and soil water flow. The fundamental concepts and definitions of soil water interaction will be examined and their validity of application in MSW as the porous media will be discussed.



Figure 2.1 Three-phase system (e.g. Landfill waste and soil).

2.1 Properties of water in relation to porous media

Two fluids are immiscible if they retain a distinct phase identity when they are mixed. In other words the immiscible mixture of air and water is a combination of free air and water without any interaction, which is characterised by the separation produced by the air-water interface. As a consequence of the different degrees of attraction between molecules of a different nature, a tension exists at the air-water interface, which is called surface tension. Typically, the forces of attraction between molecules of water are greater than that between molecules of water and air hence there exists a surface tension at the air water interface. The surface tension σ has the dimensions of force per unit length (as shown in Figure 2.2).



Figure 2.2 Surface tension forces at fluid-fluid or fluid –solid interfaces.

If the interface between two fluids, e.g., water and air, in equilibrium is flat, the pressures (in the water and in the air) are equal. In contrast, if the interface is curved as shown in Figure 2.3, there exists a pressure difference between the two phases. At equilibrium for a spherical bubble of air and water, it can be shown from a consideration of balance of forces on a small element of interface (Figure 2.3) that

$$u_a - u_w = \frac{2\sigma}{R}$$
 equation 2.1

where u_a is the air pressure, u_w is the water pressure, and R is the radius of the bubble. The difference in pressure between the fluid at the higher pressure and the fluid at the lower pressure is called the *capillary pressure* and is usually denoted by the symbol P_c . If the interface is not spherical in shape (as in Figure 2.3), equation 2.1 generalises to a form, known as Laplaces's equation:

$$P_{c} = \sigma \left(\frac{1}{R_{1}} + \frac{1}{R_{2}}\right)$$

equation 2.2

where $(1/R_1) + (1/R_2)$ is the total curvature of the interface at point m, and R_1 and R_2 are the radii of the curvature of interface lines in any two mutually orthogonal normal planes at M.



Figure 2.3 Capillary force equilibrium at an interface between two immiscible fluids.

2.1.1 Wettability

Just as there exists a surface tension between immiscible fluids there exists a surface tension between a fluid and a solid. The surface tension between water and air, σ_{wa} , differs from that between water and solid material, σ_{ws} . A water drop on a glass plate tends to spreads as shown in Figure 2.2. The contact angle α between the water-air interface with the solid at equilibrium fulfils the requirement of zero resultant force at the contact of the three phases, and consequently,

$$\cos \alpha = (\sigma_{as} - \sigma_{wa})/\sigma_{wa}$$
 equation 2.3

Equation 3 is known as Young's Formula. As α is less than $\pi/2$, water is said to be the *wetting* fluid while air is the nonwetting fluid. In contrast, the contact angle of the air mercury interface is greater than $\pi/2$, in which case air is the wetting fluid (see Figure 2.4).



Figure 2.4 Contact angle of air-mercury interface.

2.1.2 Capillary Rise in a Tube

A capillary tube is a glass tube of fine diameter. Capillary rise is usually described by considering a capillary tube inserted into a basin of water at atmospheric conditions as shown in Figure 2.5. When the base of cylindrical capillary tube with radius **R** is vertically located in a water container, water will rise up in the tube as a result of the surface tension in the air-water interface and the tendency of water to wet the surface of the glass tube. At the static equilibrium the air water interface has the shape of a spherical meniscus concave towards the air with a radius of curvature (*cos \alpha/R*), where α is the contact angle.

At vertical force equilibrium of the capillary water in the tube shown in Figure 2.5, the following expressions can be written:

$$2\pi R \sigma_{y} = \pi R^{2} h_{c} \gamma_{w} \qquad \text{equation } 2.4$$

where R is the radius of the capillary tube (m)

 σ_y is the vertical component of pressure acting on inside the tube due to surface tension (KN/m),

h_c is the capillary height (m) and,

 γ_w is the unit weight of the water (KN/m³).

Equation 2.4 can be rearranged to give the maximum height of the water in the capillary tube, h_c :



Figure 2.5 (a) Physical model related to capillary rise, (b) forces acting on a capillary tube

$$h_{c} = \frac{2\sigma_{y}}{R\gamma_{w}}$$
 equation 2.5.

Figure 2.5 illustrates that the radius of capillary tube, R, is related to the radius of curvature, R_c , by:

$$R_c = \frac{R}{\cos \alpha}$$
 equation 2.6.

Substitution of equation 2.6 into equation 2.5 gives:

$$h_{c} = \frac{2\sigma_{y}}{R_{c}\gamma_{w}\cos\alpha}$$
 equation 2.7.

If the compressive stress acting on the wall of the capillary tube is the vertical component of surface tension of air-water interface, then;

$$\sigma_y = \sigma \cos \alpha$$
 equation 2.8.

Equation 2.8 can be combined with the equation 2.7 to give:

$$h_{c} = \frac{2\sigma}{R_{c} \gamma_{w}}$$
 equation 2.9.

Pore water pressure, u_w , just below the curved meniscus (point C in Figure 2.5) can be calculated as:

$$u_w = \gamma_w h_c = \frac{2\sigma}{R_c}$$
 equation 2.10.

If the atmospheric pressure is used as a reference pressure, then the air pressure at point C is atmospheric (i.e., $u_a = 0$) and the water pressure (gauge) at the interface is negative, i.e., less than atmospheric. In other words the water is under suction. The equilibrium at the air-water interface can be expressed as similar to equation 2.1 and written as:

$$u_a - u_w = \frac{2\sigma}{R_c}$$
 equation 2.11.

2.2 Equilibrium Moisture Profile and Moisture Storage in Unsaturated Porous Media

It is customary for soil scientists to view an unsaturated soil as consisting of capillary pores in which menisci separate the two phases. This viewpoint is usually valid in

.

granular soils at sufficiently large moisture contents where forces in the water body other than those due to individual fluid pressure, surface tension, and gravity can be neglected. At equilibrium it is assumed that for given water content, the air-water interfaces have the same constant total curvature throughout the porous medium. Soil scientists traditionally define this state by the capillary head, ψ =-P_c/ γ_w which is the negative of the capillary pressure head defined previously and also known as matric suction head. The total (hydraulic) head is thus

 $\Phi = \psi + z$ equation 2.12

where z is the elevation of the given water content.

Clearly at low water contents and with soils of fine texture such as clays, the major fraction of the water content in the medium is distributed in thin films covering the solid matrix. In such cases the interaction between the water-air interface and the water-solid interface must be considered, and the simple mechanical model for capillary pressure is no longer valid.

The soil water content may be expressed on the basis of weight (gravimetric water content, w, g/g), volume (volumetric water content, θ , m³/m³) or degree of saturation (volumetric water content divided by the porosity, θ/n). For the analysis of water flow in soil profiles, the use of volumetric water content is most convenient. Figure 2.6 shows a hydrostatic profile of water content θ . The volumetric water content, θ , is equal to the saturated water content, θ_s at the water table and the soil matric suction head, ψ , is equal to zero at the level of water table (phreatic surface) at z=z₀. The saturated water content is equal to the porosity, n, only under specific circumstances. Due to entrapped air, it has been suggested that $\theta_s \approx 0.85$ -0.90n (Hopmans and Dane, 1986). For many soils, the value of θ will remain at θ_s for values of matric suction head slightly less than zero. Therefore, immediately above the water table the rate of change of water content with elevation is negligible. The value of ψ at which the soil starts to desaturate is defined as the air entry value, ψ_{aev} . It is assumed to be inversely proportional to the maximum pore size forming a continuous network of flow paths within the soil. As ψ increases above ψ_{aev} , θ decreases according to a S-shaped curve with an inflection point.


Figure 2.6 Matric suction head versus water content.

In figure 2.6 the ψ at the inflection point is denoted by ψ_i . As ψ increases further, θ decreases asymptotically towards a soil minimum water content known as the residual water content, θ_r . This low residual value of water content may be observed at more than several meters or more above the phreatic surface depending on the texture of the soil. As water is in equilibrium throughout the soil, the total head Φ is also constant and equal to z_o . Then the value of ψ for a given equilibrium water content is determined from the total head equation, for Φ equals constant, yielding: $\psi = (z-z_o)$ equation 2.14 where z is the elevation of the given water content.

Most retention models describe the retention curves in the range of $\theta r \leq \theta \leq \theta_s$. As a result it is convenient to define an effective saturation as:

$$S_{e} = \frac{(\theta - \theta_{r})}{(\theta_{s} - \theta_{r})}$$
 equation 2.15

which varies between zero and one. It should be noted that the nature of θ_r is still controversial since the water content theoretically goes to zero as ψ becomes infinitely negative. In practise θ_r is treated as fitting parameter. Many functions have been proposed to relate the matric suction head to volumetric water content. Most of these functional relationships are empirical in nature, but might include parameters that have a physical basis.

The dependence of ψ on the soil water content is referred by various names, such as *water retention curve* (WRC), soil water characteristic curve (SWCC), water content-matric potential curve, and capillary pressure head- saturation relation. It is a fundamental part soil hydraulic property and is required to solve the Richards' (1931) equation for unsaturated water flow. Specifically the slope of the water retention curve is required which is defined as specific water capacity, $C(\psi)$:

$$C(\psi) = (d\theta/d\psi).$$
 equation 2.16

The soil water capacity is always positive since a decreasing matric potential is associated with a decreasing θ , corresponding to the drainage of smaller sized pores. The water retention curve also indicates physical properties of the soil such as texture and structure and determines the water availability at various boundary conditions. Figure 2.7 shows $\psi(\theta)$ curves for sands and silt loams. The difference between the two extreme types is considerable: The porosity generally increases, as the soil texture gets finer. While sand particles function as independent units, fine texture soils tend to develop structure with different degrees of stability. Small particles adhere together with the aid of colloidal material to create greater particles, called aggregates, with greater pore space between them. Hence the observed the observed water content at $\psi=0$ in fine-grained soils is greater than in sandy soils.



Figure 2.7 Water retention curve for sand, fine sand, and silt loam (after Brooks and Corey, 1966).

The $\psi(\theta)$ curve of granular soils displays an abrupt drop in water content within a small range of decrease in ψ . It occurs at a relative high value of ψ (ψ >-100 cm of water). From the mechanical capillary perspective, the implication is that sands have a narrow pore-size distribution. On the other hand, for soils of fine texture the capillary pores represent only a small portion of the total void volume. Even at relatively high water contents, most of the water lies in the thin films covering the solid particles. Strong forces hold this film water to the soil, and high energy is required to extract it. The rate of change of water content with ψ is very small, and

the effective range of values of ψ may be as high as or even higher than 150 m of water. The residual water content at high values of ψ , where $d\theta/d\psi$ tends to zero, is much greater in fine-grained soils (as high as 10-15%) than in sands (usually less than 6%).

The shape of the $\psi(\theta)$ curve is affected by both soil and fluid properties. Beside the factors previously mentioned-namely, soil texture, structure, and interface contact-angle, the following factors play a significant role.

- the type of minerals
- the composition
- amount of organic fraction because of its ability to absorb moisture and indirect effects on soil structure
- the chemical components of the fluids considered
- the history of the wetting-drying process.

The history of wetting and drying process is very important and will be discussed briefly. θ during drainage is larger than during wetting for the same value of ψ value; that is the water retention curve is not unique and exhibits hysteresis. Hysteresis can be attributed to the ink-bottle effect, entrapped air, and the difference in contact angle between an advancing and a receding liquid front over a solid surface (Hillel, 1998). For a typical hysteretic soil water retention curve, all soil water retention data are enclosed within a main hysteresis loop, consisting of the main drying curve and the main wetting curve. Wetting and drying cycles that do not initiate from points of θ_s and θ_r , result in drying and wetting paths within the region enclosed by the main curves and are referred to as drying scanning curves and wetting scanning curves as shown in Figure 2.8.

The water retention curves $\theta(\psi)$ are determined experimentally. In next section proven laboratory methods to determine the soil water retention curve will be described.



Figure 2.8 General nature of the hysteresis curves

2.3 Functional Forms of Water Retention Curve

No theory has yet been developed that is accurate or simple enough to derive analytically the $\theta(\psi)$ curve. There is, however, value in fitting the observed data by analytical expressions. Such analytical yet empirical expressions serve two purposes:

- 1. They permit solutions to unsaturated flow problems in closed form,
- 2. They eliminate the truncation errors introduced in the estimation of ψ and $d\psi/d\theta$ in numerical solutions.
- 3. They are used with the saturated coefficient of permeability to predict the hydraulic conductivity function for an unsaturated soil

A variety of expressions have been proposed in the literature. Four of the more important equations of water retention curve are now described in detail.

2.3.1 Brooks and Corey (1964)

Brooks and Corey (1964, 1966) concluded from comparisons with a large number of experimental data that the soil water retention curve could be described reasonably

well with the following general equation; which expresses the effective saturation, S_e , as a power function of ψ :

$$S_{e} = \left(\frac{\Psi}{\Psi_{aev}}\right)^{-\lambda}$$
 for $\Psi > \Psi_{aev}$

equation 2.17

$$S_e = 1$$
 for $\psi < \psi_{aev}$

The soil water content, θ , as a function of matric suction head is given by Equation 2.15 and Equation 2.17, i.e.,

$$\theta = \theta_{\rm r} + (\theta_{\rm s} - \theta_{\rm r}) \left[\frac{\Psi}{\Psi_{\rm acv}} \right]^{-\lambda}$$
 equation 2.18

The Brooks and Corey model requires the determination of three physical parameters ψ_{aev} , θ_s , and θ_r and one independent model parameter, λ , from which the soil water content over matric suctions greater than ψ_{aev} is calculated. The dimensionless parameter λ characterises the width of the pore-size distribution, and is referred to as the *pore-size distribution index* (Brooks and Corey, 1964). λ values are usually in the range between 0.3 and 10.0. Approximate values of both ψ_{aev} and λ can be obtained by plotting log (S_e) versus log (ψ). The absolute value of the slope of the resulting line is equal to the value of λ and ψ_{aev} can be determined from the intercept. The parameters can also be achieved by model fitting. Brooks and Corey expression usually shows good agreement with experimental data for soils with well-defined airentry values, however, as van Genuchten and Nielsen (1985) pointed out, the model may give relatively poor fits for soils with S-shaped retention data, such as fine-grained soils.

2.3.2 Campbell (1974)

The retention model used by Campbell (1974) is identical to the power function of Brooks and Corey (1964). However, the dependent variable is defined as the degree of saturation, S, that is, θ/θ_s , instead of effective saturation, S_e:

$$\frac{\theta}{\theta_{s}} = \left(\frac{\psi_{aev}}{\psi}\right)^{\lambda} \qquad \text{for } \psi > \psi_{aev}$$
equation 2.19
$$\frac{\theta}{\theta_{s}} = 1 \qquad \text{for } \psi < \psi_{aev}.$$

Equation 2.19 can be rearranged to obtain a more general form:

$$\psi = \psi_{aev} \left(\frac{\theta}{\theta_s}\right)^{-\lambda}$$
 equation 2.20.

2.3.3 van Genuchten (1980)

Brutsaert (1966) proposed the following model, which describes an S-shaped water retention curve;

$$S_{e} = \frac{a}{[a + (\psi_{m})]^{b}}$$
 equation 2.21

where a and b are fitting parameters which can be determined by model fitting. A more general version of equation 2.21 was suggested by van Genuchten (1980) and is currently the most commonly used soil water retention model:

$$S_c = [1 + (\alpha \psi)^n]^{-m}$$
 equation 2.22

where α is a parameter to scale the matric suction (L⁻¹); and **n** and **m** are dimensionless parameters. The soil water content, θ , as a function of matric suction head is given by Equation 2.15 and Equation 2.20, i.e.,

$$\theta = \theta_{r} + (\theta_{s} - \theta_{r}) \left[\frac{1}{1 + (\alpha \psi)^{n}} \right]^{m}$$

equation 2.23

The *n* parameter is related to the pore size distribution of the soil and its value is generally restricted to values larger than one, so that the slope of the soil water retention curve, $d\theta/d\psi$, is zero as the water content approaches the saturated water content, θ_s (van Genuchten, 1980). The m parameter is related to the asymmetry of the model. If *m* is fixed at a value of one, this model reduces to Brutseart model where $a=a^{-n}$ and b=n.

Instead of using a constant value for m, van Genuchten (1980) proposed the relationship of m=1-1/n. Using this restraint, van Genuchten model does not account for an air-entry value, but it includes an inflection point, allowing this model to perform better than the Brooks and Corey model for soils with S-shaped retention curves. The parameter α is related to the inverse of the air-entry value; however, the strict definition of this parameter is unclear. Fitting algorithms such as RETC can be used for estimating parameters α and n.

2.3.4 Fredlund and Xing (1994)

Fredlund and Xing (1994) proposed a three parameter model in which provides a continuous soil water retention curve and can be used to fit the laboratory data over the entire soil matric suction range. The Fredlund and Xing model is written as follows:

$$\theta = C(\psi) \left[\frac{\theta_s}{\ln \left[e + \left(\frac{\psi}{a} \right)^n \right]} \right]^m$$

equation 2.24

This model uses three fitting parameters; namely a, n, and m. The parameter a is related to the air-entry value, the n parameter is related to the pore size distribution of the soil and m parameter is related to the asymmetry of the model and to the residual water content, θ_r . C(ψ) is a correction factor that forces the soil water characteristics curve through a suction of 1 000 000 kPa and zero water content and is defines as:

$$C(\psi) = \left(1 - \frac{\ln[1 + \psi/\psi_r]}{\ln[1 + (100000)/\psi_r]}\right)$$
 equation 2.25

where ψ_r is the suction value corresponding to residual water content, θ_r . In Fredlund and Xing (1994) model, the residual water content is obtained in a graphical construction method described by Vanapalli et al., (1999).

2.3.5 Multimodal Water Retention Functions

So far, it has been assumed that soils exhibit unimodal water retention curves, characterised by a single pore-size distribution function. On the other hand, soils may exhibit retention curves with more than one inflection point. This multimodality of pore-size distribution may be the result of specific particle-size distributions or may be attributed to a secondary pore systems (macroporosity) by various soil genetic processes such as soil aggregation or biological soil forming (Durner, 1994). For these types of soils, the fitting of a single, sigmodial retention curve model will be unsatisfactory.

Soil Water Retention curve Fits

In general, two approaches have been proposed to fit soil water retention functions to bimodal soil water retention data. The two proposed approaches therefore have been based only on a modified form of the unimodal van Genuchten function.

The first approach is described by Smettem and Kirkby (1990), Smettem et al. (1991), and Wilson et al. (1992). In this approach, the soil water retention curve is separated into two regions joined at a common suction value, referred to as the matching point. The data in each region are fit separately using a unimodal soil water

retention curve functions. The result is two sets of parameters with one set of parameters valid at suctions less than the common suction value and the other set of parameters valid at suctions greater than the common suction value. This procedure can be explained further with the aid of the conceptual bimodal soil water retention curve shown in Figure 2.9 In this approach, a suction value, ψ_j , and the corresponding volumetric water content, θ_j , were selected at the junction where the macroscopic porosity appears to have completely desaturated and the microscopic porosity begins to desaturate. Smettem and Kirkby note that the selection of the exact position of this junction or matching point (ψ_j , θ_j) is to some extent arbitrary. Based on this approach the bimodal water retention curve can be described using the van Genuchten function with the constraint that m=(1-1/n) as follows:

$$\theta = \theta_{\rm r} + \left(\theta_{\rm j} - \theta_{\rm r}\right) \left[\frac{1}{1 + \left(\alpha'\psi\right)^{n'}}\right]^{\left(1 - 1/n'\right)} \qquad \text{for} \qquad \text{for} \quad \psi_{\rm j} < \psi$$



Figure 2.9 Illustration of a conceptual bimodal water retention curve (from Burger and Shackelford (2001)

The second approach is proposed by Othmer et al., (1991), Durner (1992, 1994), Ross and Smettem (1993), and Pachepsyky et al (1992), describes the retention function of these types of soils by a multimodal function:

$$S_{e} = \sum_{i=1}^{N} w_{i} S_{e,i}(\psi_{m})$$
 equation 2.27

where N is the number of pore systems from which the total pore-size distribution is determined and w_i is the weighting factor for each pore system i, subjected to the constraint that $0 < w_i < 1$ and $\sum w_i = 1$. Hence, for a bimodal soil system, N=2. Any soil water retention model can be substituted into equation 2.27, provided it fits the soil water retention data. Excellent results obtained by fitting bimodal retention functions using van Genuchten model (equation 2.23, with m=1-1/n) to data for an aggregated soil presented by Smettem and Kirkby (1990). The multimodal approach will obviously increase the number of fitting parameters, but will maintain the functional properties of each specific retention model. However, Durner (1994) cautions that unless the retention data are distinctly multimodal with little overlap of pore-size distributions, physically based parameters might loose their meaning and be considered curve-shape parameters only.

2.4 Energy State of the Soil Water

Water in porous media contains energy in varying forms. The movement of water in porous media (soil and soil like materials) is quite slow, therefore, its kinetic energy is generally considered to be negligible. On the other hand the potential energy, which is due to position or internal condition, is of primary importance in determining the movement of water in the porous media.

The potential energy per unit mass of water in the soil varies over a wide range. Differences in potential energy of water between one point and another give rise to the tendency of water to flow within the soil. Water in porous mediums obeys a universal rule in which a matter in nature is to move from the point of high potential to a point it is lower, and eventually reach an equilibrium state with its surrounding. In soil, water moves constantly in the direction of decreasing potential energy. Therefore, knowledge of the relative potential energy state of soil water at each point within the soil is necessary to evaluate the forces acting on the soil water in all directions.

The gradient of potential energy with distance is the force causing the flow. In view of that the force acting on soil water is equal to the negative potential gradient ($d\Phi/dx$), which is a change of energy potential Φ with distance x. The total potential at a point in the soil was defined by the terminology committee of the International Soil Science Society (Aslyng, 1963) as:

"The amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally to the soil water at a considered point, an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure to the soil water at a specified point."

The total potential of soil water in soil science literature is given as:

$$\Psi_{\text{total}} = \Psi_{g+} \Psi_{m+} \Psi_{o+} \Psi_{p} \qquad \text{equation } 2.28$$

where

Ψg	=	the gravitational potential,		
Ψ_{m}	=	the matric potential,		
Ψο	=	the osmotic potential,		
Ψ_p	=	the pressure potential,		

and some additional terms are theoretically possible.

Pressures in the pore fluid of a soil can be expressed in several ways, and the total pressures may involve several contributions. In hydraulic engineering, problems are often analysed using Bernoulli's equation for the total heads, and head losses associated with flow between two points; that is,

$$Z_{1} + \frac{p_{1}}{\gamma_{w}} + \frac{v_{1}^{2}}{2g} = Z_{2} + \frac{p_{2}}{\gamma_{w}} + \frac{v_{2}^{2}}{2g} + \Delta h_{1-2}$$
 equation 2.29

where Z_1 and Z_2 are the elevations of points 1 and 2, p_1 and p_2 are the hydrostatic pressures at points 1 and 2, v_1 and v_2 are the flow velocities at points 1 and 2, γ_w is the unit weight of water, g is the acceleration due to gravity, and Δh_{1-2} is the head loss in head between points 1 and 2. The total head H (dimension L) is

$$H = z + \frac{p_1}{\gamma_w} + \frac{v^2}{2g}$$
 equation 2.30

Flow results only from differences in total head, on the other hand, if the total heads of two points are same, there can be no flow, even if $Z_1 \neq Z_2$ and $p_1 \neq p_2$. If there is no flow there is no head loss and $\Delta h_{1-2}=0$.

The flow velocity through the soils is low, and as a result, $v^2/2g \rightarrow 0$ and may be neglected. The relationship

$$z_1 + \frac{p_1}{\gamma_w} = z_2 + \frac{p_2}{\gamma_w} + \Delta h_{1-2}$$
 equation 2.31

is the basis for evaluation of pore pressures form flow net solutions to seepage problems.

The use of several terms to describe the status of water in porous mediums such as potential, head and pressure may cause confusion in the flow and pressure analysis. The status of water in a soil can be expressed in terms of the free energy relative to free pure water (Aitchison et al., 1965). The free energy can be explained in three different ways, including:

- 1. Potential (dimensions, ML^2T^{-2}/M ; Joules per kg).
- 2. Head (dimensions, L; m).
- 3. Pressure (dimensions, $ML^{-1}T^{-2}$; kN/m^2).

The selection of the components of the total potential ψ (head, H; pressure, p) is somewhat arbitrary (Bolt and Miller, 1958); however, the following appears to have gained acceptance for geotechnical work (Aitchison et al., 1965).

2.4.1 Gravitational Potential

The gravitational potential energy on a mass basis, Φ_g (J/kg), is the amount of work required to move a unit mass of water from the reference elevation to the point of measurement. It accounts for the body forces of gravity on water molecules themselves. The attraction any mass toward the centre of the earth is a function of the mass, gravitational acceleration constant and some height above an arbitrary unit:

 $\Phi_{g} = gz$

equation 2.32

where

g = the gravitational acceleration constant, LT^2 ,

z = height above an arbitrary datum.

Gravitational potential ψ_g , (head Z, pressure p_z) corresponds to elevation head in normal hydraulic usage.

2.4.2 Pressure Potential

Most of the soil physicists prefer to separate the positive soil water pressure and negative soil water pressure (matric potential). It is accepted as that soil water may have either of the two potentials, but not both at the same time. According to this view, an unsaturated soil has no pressure potential, only a matric potential which is expressed in negative pressure units. It is advantageous to use one continuous pressure potential to describe the entire soil profile in the field; including the saturated region and unsaturated region, below and above the water table.

When soil water is at pressure grater than atmospheric, its pressure potential is considered positive. When it is at a pressure lower than atmospheric, the pressure potential is considered negative. Thus water under a free-water surface is at positive pressure potential, while water at such a surface is at zero pressure potential, and water that is raised in the capillary pores of the soil above that surface is characterised by a negative potential. This principle is already explained in Section 2.2.2 and 2.2.3 and illustrated in Figure 2.5.

Matric potential results from the composition of water adsorptive forces exerted by particle surfaces and capillary forces maintained within the soil pore. These forces typically are not separated during measurement or analysis. Hillel (1998) illustrates these two mechanisms as shown in Figure 2.10. Energy must be exerted onto the water molecule in order to break the van der Waals bond to the soil particle. Similarly energy must be exerted to distort the meniscus at the air-water interface within the soil pores. The energy required to overcome these adsorptive and capillary forces in the soil is equal but opposite to the matric potential. Thus, matric potential is always a negative quantity in unsaturated material. Apparatus and technique used to measure matric potential will be explained in next section.



Figure 2.10 Water in unsaturated soil is subjected to capillarity and adsorption, which combine to produce a "negative" matric potential.

2.4.3 Osmotic Potential

Osmotic potential energy accounts for the decrease in vapour pressure of the soil water in the presence of solutes and occurs when a semi-permeable membrane separates fluids containing different concentrations of dissolved solutes. The tendency for systems to move toward thermodynamic equilibrium causes the migration of water molecules from the zone of lower solute concentrations to the higher solute concentrations. This in turn causes an increase in the osmotic potential, reducing the total water potential. The osmotic potential in the in the soil water

systems is usually ignored because semi-permeable membrane do not naturally exist. The lack of membranes permits dissolved constituents to migrate with the bulk water or diffuse into "cleaner" soil water through Brownian motion. Both processes reduce the differences in solute concentrations, thereby reducing the osmotic effect as well.

2.5 Instruments and Methods for Measuring Matric Potential

There are a wide variety of instruments that have historically been used for measuring soil suction. Matric potential can be measured either in a direct or indirect manner. The details of many of these methods have been extensively discussed by Fredlund and Rahardjo (1993) and Ridley and Wray (1996). Some of these techniques will now be considered.

2.5.1 Direct Methods

The general way of determining the water retention relation in a direct way involves establishing a series of equilibrium between water in the porous medium (usually soil) and a body of water at known potential. The water in the porous system is in hydraulic contact with the body of water, usually by means of a water saturated porous plate. At each equilibrium, the volumetric water content, θ , of the porous medium is determined and paired with a value of the matric suction head, ψ_m , determined from the pressure in the body of water and the gas phase pressure in the porous medium. Each data pair (θ , ψ_m) is a point in the retention relation. Data points can be obtained during drainage of water from the sample or wetting of the sample. Soil water retention data pairs are determined stepwise, waiting until static equilibrium has been reached at each time step.

Hanging Water Column

The hanging water column technique to determine a water retention curve is performed in a Haines apparatus. In this apparatus (Haines, 1930) the wet sample is in hydraulic contact with the bulk water through a porous plate as shown in Figure 2.11. The gas pressure in the soil sample is at atmospheric pressure, whereas the pressure in the bulk water is reduced the subatmospheric levels, either by reducing the z_1 or by decreasing the controlled gas pressure. The subsequent reduction in hydraulic head caused the water to flow from the soil sample. At static equilibrium, the water pressure head, h(m) decreases linearly with the elevation according to:

$$h(z) = -z + z_1 + (P_g - P_{atm}) / \rho_w g \qquad \text{equation } 2.33$$

where

z(m) is elevation (positive if above z=0 and negative if below z=0),

 $z_1(m)$ is the distance from the water level to the reference level for gravitational head,

 $\rho_{\rm w}$ is the density of the water, (kg/m³),

g is the gravitational field strength, (N/kg^{-1}) .

It may be easiest to start with $z_z=0$ and then to step-wise decrease h by decreasing z_1 followed by the step-wise reduction of P_g . Water flows out of the sample until static equilibrium is reached. Outflow volumes and pressures in the bulk water are measured at each step to allow calculations of θ and the corresponding h_m values. If the air pressure in the sample is maintained at atmospheric pressure, $h_m=h$. Consequently, h_m varies linearly with elevation in the same manner as h. The absolute pressure in the bulk water cannot be reduced below its vapour pressure, as it would spontaneously vaporise (boil). In practise, because of the dissolution of gases from the bulk water, the hanging water column method is limited to an h_{min} value of about -8.5 m (or -85 kPa).



Figure 2.11 Illustration of the hanging water column

Tensiometers

Tensiometers are used for both in the laboratory and in the field as instruments for measuring the matric potential. A tensiometer actually measures the negative-pore water pressure in a porous medium. In the laboratory the experiment should be performed on a soil sample that has the size of a representative volume. A tensiometer is made up of a water reservoir connected to a porous cup, which is placed in contact with the porous medium. The porous cup acts as interface between the water in the porous medium and the water in the cup and in the porous medium, while preventing gas entering. This goal is achieved by selecting an appropriate pore size for the cup, in which the air-entry pressure is greater than the anticipated range of tensions to be measured during the experiment. The term cup is used in literature in general sense to represent a high air-entry porous ceramic membrane and it can be of any geometry.

Energy equilibrium between the tensiometer and the surrounding porous medium is achieved through the water movement across the tensiometer's porous cup. Water flows in the direction of decreasing potential. When the matric potential in the porous medium is lower than the water potential inside the tensiometer, water will move into the surrounding porous medium through the pores of the cup. The experiment is performed in a step-wise fashion. At every time step the pressure in the reservoir is lowered, producing drainage of water from the reservoir into the sample. Drainage of water continues at a decreasing rate and eventually the potential difference between the water inside the tensiometer and the porous medium will be zero, at which the static equilibrium is achieved. For fine materials this may take a very long time. After the water in the cup has come to equilibrium with the porous medium, the pressure of the water in the reservoir is measured with a pressure gauge or a pressure transducer connected to the tensiometer. The saturation of the sample is determined from the information on the quantity of water removed from the reservoir.

From a practical standpoint, the lower limit for the tensiometer method is approximately between -80 and -90 kPa due to the possibility of cavitation of the water in the reservoir (Fredlund and Rahardjo, 1993). When the pore-water pressure in the tensiometer reservoir approaches -100 kPa, water vapour will spontaneously come out of solution, causing the water to "boil".

The soluble salts and ions are small enough to move freely through the porous cub. This provides the chemical potential to be uniform over the volume of the sample as well as the measuring device during testing. Under these conditions the osmotic potential are negligible and tensiometers only measure the matric potential (Nittao and Bear, 1996).

Pressure Plate Extractor

Both the hanging water column and the tensiometer methods are limited to a matric suction value of between -80 and -90 kPa. The use of a pressure plate apparatus avoids this limitation because it is built to resist high pressures. The principles are different to those discussed for the hanging water column and tensiometers. Since this method is able for dealing with much higher matric potential, the change in matric

potential within the test sample is negligible compared with the value of matric potential itself. In pressure plate apparatus, the pore water pressure in the porous medium is maintained at atmospheric pressure because the pore water is exposed to atmosphere at the outflow end of the specimen. The pore gas pressure is raised to apply the matric potential. This principle is known as axis translation. The matric suction head values can therefore be calculated from:

$$\psi_m = -(u_a - P_{atm})/\rho_w g$$
 equation 2.34

In this method, the test sample resting on a porous plate is placed in a sealed pressure chamber. The lower side of the plate is in contact with a reservoir of saturating liquid at atmospheric pressure. The gas pressure in the cell is changed in steps by way of a gas port. After each change in pressure the sample in the cell is allowed to equilibrate with the reservoir. Liquid water can enter or escape through the porous plate without gas escaping because the pores in the porous plate are chosen sufficiently small, such that the plate remains saturated.

When equilibrium is assumed to be reached, the gas pressure within the pressure chamber is assumed to be uniform. The water volume expelled from or imbibed into the cell can be measured, so that the volumetric water content, θ , can be determined

The chemical potential of water is uniform over the sample; porous plate and the reservoir and only matric potential can be measured. Each porous plate has a screen to promoter the lateral movement of water and a rubber sheet covering the bottom. The rubber sheet is mounted to the edge of the plate. An outlet from the space between the backing leads through the ceramic. The details of a porous ceramic plate are shown in Figure 2.12. This outlet is connected by a short piece of pressure tubing to an outlet in the pressure chamber. This outlet is in turn connected to a burette slightly filled with water in atmospheric pressure. Water present between the porous plate and the rubber backing the sheet is at atmospheric pressure.



Figure 2.12 (a) The details of a porous ceramic plate; rubber membrane and outlet (b) The outlet and the screen between the ceramic plate and the rubber membrane

2.5.2 Indirect Methods

Indirect methods described in the literature require equilibration of some medium (usually a sensor) in which the matric or total potential of a porous medium can be determined from a previous calibration. In other words the matric potential of the medium is equal to that of the porous medium under equilibrium conditions. The indirect techniques can be divided into

- those that measure matric potential
- those that measure total potential which is the sum of matric and osmotic potentials.

Matric potential is determined when the sensor matrix is in direct contact with the porous medium, so salts are free to diffuse in or out of the sensor matrix. Total potential is determined when the sensor matrix is separated from the porous medium by a vapour gap, so salts are not free to move in or out of the sensor and the equilibrium measurements reflects the sum of the matric and osmotic potentials acting on the water. Only filter paper method will be described in detail in next section. Other methods that include thermocouple psychrometry, heat dissipation sensors, and time domain sensors are described in Scanlon et al. (2002) and Fredlund and Rahardjo (1993).

The Filter Paper Method

If an initially dry paper is placed in intimate contact with a porous medium and allowed to absorb moisture from the sample, the two will reach equilibrium when the matric potential in the filter paper is equal to the matric potential in the porous medium. The commonly adopted types of filter paper are Whatman No. 42 and Schleicher and Schuell No. 589.

If each initially air-dry filter paper is left to equilibrate with the soil for at least 7 days before measuring its water content, the acknowledged relationship between the matric potential and the filter paper water content are bilinear, with the change in sensitivity occurring at a water content of about 45 % for Whatman No. 42 and about 54 % for Schleicher and Schuell No. 589 paper as shown in Figure 2.13.

It is essential to maintain intimate contact between the specimen of soil and the filter paper. In places where the filter paper are not making contact the transfer of water will occur partly through the vapour phase, and the time to reach the equilibrium will increase. Dineen (1997) presented the comparisons between the matric potential measurements made with Whatman No. 42 filter paper and the suction probe (Ridley and Burland, 1993) on the same sample. Both methods produced identical results over a wide range of matric potential measurements.

First Ridley and Edenmosun (1999) and later Ridley et al. (2003) reported that the equilibrium water content in filter paper measurements is significantly influenced by the presence of salts in the soils. The equilibrium water content of the filter paper reduces when there is salt present in the porous medium. Therefore matric potential measurements in porous mediums, which contain salts and ions, may be overestimated.



Figure 2.13 Calibration curves for two types of filter paper (from ASTM D 5298-94)

2.6 Summary

This chapter reviews the fundamental physics of soil water interaction. Their validity of application in MSW will be discussed in chapter 6. In particular the following points can be noted.

- The relation between soil water content and matric potential is a fundamental part of the characterisation of the hydraulic properties of a porous medium.
- Total soil water potential is based on the pressure and elevation potentials.
- Proven laboratory methods to determine soil water retention data are described.
- An overview of the theory and application of established parametric models to fit measured water retention data is presented.

Chapter 3

equation 3.1

3 FLOW OF MOISTURE THROUGH POROUS MEDIUM

Water in a porous medium flows continuously from a point of high hydraulic headto a point with low hydraulic head until an equilibrium state is established. One of the first successful attempts to describe flow through porous media is given by Darcy (1856). He showed that there exists a direct relationship between the flow velocity and hydraulic gradient. Darcy's law was established based on the results of flow tests through sand columns. It has general validity for the description of hydraulic flow through soils and has been verified by many subsequent studies (Hubbert, 1940). The constant of proportionality is usually termed the hydraulic conductivity by geotechnical engineers, is a basic property of the porous material. Practically all steady state and transient flow analyses are based on Darcy's law.

3.1 Saturated Flow

Poiseuille's law for flow through a circular capillary, which gives the volumetric discharge rate, is a common starting point for the derivation of flow in a porous medium. Poiseuille's equation is given by,

$$Q = -\frac{\pi R^4}{8\mu} \frac{dp}{dl}$$

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where Q is the volumetric discharge rate, (m^3/sec) , R is the radius of the pipe, p is the piezometric pressure (kN/m^2) , 1 is the length over which the piezometric pressure difference acts and μ is the absolute viscosity, (Pa. sec).

A theoretical expression for the hydraulic conductivity can be deduced by applying Poiseuille's law for flow through capillaries as a result of a pressure gradient, which does not driven gravitationally. If the porous medium is considered a bundle of straight tubes, each uniform in radius, the overall flow rate will be equal to the sum of the separate flow rates through the individual tubes. Knowledge of the size distribution of the tube radii provide to calculate the total flow through the tubes, caused by the known pressure difference using Poiseuille's equation.

Darcy's law can be written as,

where q is the discharge velocity, (m/sec), K is the hydraulic conductivity (m/sec) and i is the hydraulic gradient (m/m, dimensionless). The hydraulic gradient is related to the pressure gradient, and is given by

$$i = \frac{1}{\gamma} \frac{dp}{dl}$$
 equation 3.3

where γ is the unit weight of permeating fluid (kN/m³). For dimensional consistency with equation (3.1), Darcy's law can be rewritten as,

$$Q = -\frac{KA}{\gamma} \frac{dp}{dl}$$
 equation 3.4

where A is the cross sectional area normal to flow. Comparison of equation 3.1 with equation 3.4 shows that,

$$K = \frac{\pi R^4 \gamma}{8\mu A}$$
 equation 3.5

which for a circular pipe reduces to

$$K = \frac{R^2 \gamma}{8\mu}$$
 equation 3.6

From which it can be seen that the hydraulic conductivity is a coefficient of resistance to flow related to a pore geometry area term, the unit weight of the permeating fluid and the viscosity. In fact it is the term representing the pore geometry or tortuosity of the flow pathways that is correctly referred to as the coefficient of permeability, and denoted by the symbol, k. In the case of the circular pipe

$$k = \frac{R^2}{8}$$
 equation 3.7

And has dimensions of m^2 . More generally, equation 3.6 can be given as,

$$K = \frac{k\rho g}{\mu}$$
 equation 3.8

where ρ is the density of permeating fluid.

3.2 Unsaturated Flow

3.2.1 Derivation of the Governing Differential Equation

Although Darcy's law was derived for saturated flow, it was extended by Richards (1931) to unsaturated flow, with the provision that the conductivity is now a function of the volumetric moisture content, θ [i.e., K=K(θ)]:

 $q = -K(\theta)\nabla H$ equation 3.9

where ∇ H is the hydraulic head gradient which includes both pore water pressure and gravitational components.

To obtain a general flow equation which accounts for transient and steady state flow processes Darcy's equation is coupled with the law of continuity, which contains the conservation of mass law in mathematical form (Richards, 1931):

$$\frac{\partial \theta}{\partial t} = -\nabla \cdot \mathbf{q}$$
 equation 3.10

Thus,

$$\frac{\partial \theta}{\partial t} = -\nabla \left[\mathbf{K}(\theta) \nabla \mathbf{H} \right]$$
 equation 3.11

The hydraulic head is the sum of the pressure head and the elevation head, z: so

$$\frac{\partial \theta}{\partial t} = -\nabla \left[K(\theta) \nabla (\psi - z) \right]$$
 equation 3.12

Since ∇z is zero for horizontal flow and unity for vertical, flow equation can be rewritten as follows:

$$\frac{\partial \theta}{\partial t} = -\nabla \cdot \left[K(\theta) \nabla (\psi) + \frac{\partial K}{\partial z} \right]$$
 equation 3.13

or

.

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial x} \left(K \frac{\partial \psi}{\partial x} \right) - \frac{\partial}{\partial z} \left(K \frac{\partial \psi}{\partial z} \right) + \frac{\partial K}{\partial z}$$
equation 3.14.

The volumetric water content and the matric suction gradient in Equation (3.14) can be linked to the water retention characteristics of the porous medium. Expanding the time derivative by chain rule gives the following:

$$\frac{\partial \theta}{\partial \psi} \frac{\partial \psi}{\partial t} = -\frac{\partial}{\partial x} \left(K \frac{\partial \psi}{\partial x} \right) - \frac{\partial}{\partial z} \left(K \frac{\partial \psi}{\partial z} \right) + \frac{\partial K}{\partial z}$$
equation 3.15.

The derivative of $\partial \theta / \partial \psi$ is the specific moisture capacity, C, hence, equation (3.15) can be written:

$$C \frac{\partial \Psi}{\partial t} = -\frac{\partial}{\partial x} \left(K \frac{\partial \Psi}{\partial x} \right) - \frac{\partial}{\partial z} \left(K \frac{\partial \Psi}{\partial z} \right) + \frac{\partial K}{\partial z}$$
equation 3.16.

Flow process may also occur in one-dimensional horizontal systems in which ∇z are negligible compared to the strong matric suction gradient $\nabla \psi$. In such cases,

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial x} \left(\mathbf{K} \frac{\partial \Psi}{\partial x} \right)$$
 equation 3.17.

3.2.2 Hydraulic Diffusivity

Efforts have been made to simplify the mathematical treatment of unsaturated flow process by casting the flow equation into a form analogous to the equations of diffusion and heat conduction. One-dimensional vertical form of the Darcy's equation, which accounts for gravity, can be rewritten as follows:

$$q = K(\theta) \frac{\partial}{\partial z} (\psi + z)$$
 equation 3.18.

By expanding the matric suction gradient by chain rule, Equation (3.18) can be written as

$$q = -K(\theta) \frac{\partial \psi}{\partial \theta} \frac{\partial \theta}{\partial z} + K(\theta)$$
 equation 3.19.

where $\partial \psi / \partial \theta$ is the reciprocal of the specific moisture capacity, C(θ). Child and Collis-George (1950) introduced a function called the hydraulic diffusivity, D(θ):

$$D(\theta) = K(\theta) \frac{d\psi}{d\theta} = \frac{K(\theta)}{C(\theta)}$$
 equation 3.20.

When this form of Darcy's equation is coupled with the law of continuity gives the following alternative, θ – based formulation of the Richards' equation, known as Philips equation:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial z} \left(D(\theta) \frac{\partial \theta}{\partial z} \right) + \frac{\partial K}{\partial \theta} \frac{\partial \theta}{\partial z}$$
equation 3.21.

3.2.3 Discussion on the various forms of the Richards Equation

Because of the highly non-linear $K - \psi$ and $\theta - \psi$ relationships, analytical solutions are not generally possible. Instead numerical solution methods have been used. Most commonly, numerical methods use the ψ based form of the equation. Its advantages are that it can be applied to both saturated and unsaturated conditions, as well as layered soils, where ψ is continuous but θ is usually not. The disadvantages of this formulation are that it may require very small time and space intervals to achieve satisfactory mass balance and numerical stability.

The advantage of the θ based formulation is that the D(θ) does not vary with θ nearly as much as K(θ) varies with ψ . The disadvantage is that it cannot be used for simulating flow in soils at or near saturation, since in that range D(θ) becomes infinite since C(θ) tends to zero. The θ based formulation also fails in the case of layered soil profiles, where abrupt transition occurs from one layer to another, since in such cases θ is not continuous.

3.2.4 Solution of Unsaturated Flow Equation

While analytical solutions are useful for a number of applications, they are only applicable to highly simplified systems, and as such are not well suited for the more complex situations normally encountered in the field. Consequently, numerical solutions are often used. Finite difference methods are well developed to predict unsaturated flow only. For typical examples, see Hanks and Bowers (1962), Rubin and Steinhardt (1963), and Brandt et al. (1971). One and two-dimensional finite difference schemes were subsequently developed that consider the dynamics of both the unsaturated and saturated zone in one scheme (Freeze, 1971a). The work by Freeze (1969, 1971a, b) in this period was especially significant since for the first time a single equation was used to describe transient unsaturated-saturated flow. The flow equation accounts not only for changes in water storage in the unsaturated zone, but also considers transient changes in the saturated zone.

Finite element solution techniques became available in the late sixties. They were initially applied only to saturated flow problems, but slowly became also popular for unsaturated flow problems (Neumann, 1973; Thomas and Rees, 1991). Perhaps the most important advantage of finite element techniques over standard finite difference methods is the ability to more accurately describe irregular system boundaries in twodimensional simulations, as well as to include more easily nonhomogeneous medium properties. Several authors have also suggested that finite element methods lead to more stable and accurate solutions, thus permitting larger time steps and/or coarser grid systems and hence leading computationally more efficient numerical schemes (Neumann, 1973). Conflicting evidence exists about the relative accuracy of finite element versus finite difference techniques with respect to solution of the highly nonlinear flow equations (Pinder and Gray, 1977, van Genuchten 1981). It appears that at least for one-dimensional simulations, finite difference methods are no better nor worse than finite element schemes. With the introduction of increasingly sophisticated numerical models, the real challenge remains that of an accurate characterisation of relevant system parameters, especially the unsaturated hydraulic functions.

3.3 Hydraulic Conductivityin Unsaturated Soils

Permeability is a property of a soil (or any porous medium) that permits the transmission of fluids. This property, denoted by k, is also called intrinsic permeability to stress that k is only a property of the soil and is independent of fluid

properties such as viscosity or density. The permeability is related to the hydraulic conductivity (K) by the relation given in equation 3.8 before;

$$K = \frac{k\rho g}{\mu} = \frac{kg}{\nu}$$
 equation 3.8

where ρ is fluid specific mass, g is the acceleration of gravity, μ is the dynamic viscosity, and v is the kinematic viscosity. Because K depends on both soil and fluid properties, it measures the mobility of a given fluid in a given porous medium distinctly defined by the Darcy's law.

In unsaturated soils, K can be considered a function of the moisture content, θ , for a given soil. Like water retention data, experimental determination of unsaturated hydraulic conductivity data for a wide range of moisture contents is laborious, time consuming, and costly especially when field measurements are concerned. So theoretical determinations have been widely used. It is commonly assumed K(θ) relates to the saturated hydraulic conductivity K_s by a unique function, the so called relative hydraulic conductivity, namely,

$$K_r = \frac{K(\theta)}{K_s}$$
 equation 3.22

The K(θ) relationship constitutes a hydraulic property, which together with the corresponding $\theta(\psi)$ function, defines the flow. They may permit solution of unsaturated flow problems in analytical closed form and minimize the truncation error in numerical solutions. It is worthwhile to note that the K(ψ) relationship displays a considerable hysteresis, therefore, it is generally preferable to use K(θ) as this relationship is less sensitive to hysteresis and in principle better adapted to solution of unsaturated flow equation.

Unsaturated hydraulic conductivity models, based on pore-size distribution, pore geometry, and connectivity, require integration of water retention functions to obtain expressions for the unsaturated hydraulic conductivity. The resulting expressions relate the relative hydraulic conductivity K_r to the effective saturation by summation

of the contributions of the individual pores according to the Poiseuille's flow equation to yield a macroscopic hydraulic conductivity expression. Solutions require the definition of an effective pore radius distribution, validity of the capillary law (equation 2.10 and 2.11), and incorporation of tortuosity and connectivity as they affect the flow. Reviews of independent developments linking macroscopic flow to microscopic pore geometry using statistical models were presented by Mualem (1986), which includes the conductivity models of Childs and Collis-George (1950), Burdine (1953), and Mualem (1976).

If the moisture retention data of a soil is represented by the Campbell (1974) model (equation 2.20), based on the unsaturated conductivity models of Childs and Collis-George, the equation describing the relative hydraulic conductivity becomes:

$$K = K_{s} \left[\frac{\theta}{\theta_{s}} \right]^{2b+3}$$
 equation 3.23

The Clapp and Hornberger (1978) power law model has identical form to Campbell (1974) moisture retention model, however, the relative permeability model differs from that given by Cambell and is given by;

$$K = K_{s} \left[\frac{\theta}{\theta_{s}} \right]^{-B}$$
 equation 3.24

Mualem and Dagan (1978) summarised Burdine's (1953) and Mualem's (1976) model to develop a generalised unsaturated conductivity function, which can also be written as

$$K_{r} = S_{e}^{l} \begin{bmatrix} S_{e} & |\psi_{m}|^{-\eta} dS_{e} \\ 0 & |\psi_{m}|^{-\eta} dS_{e} \end{bmatrix}^{\gamma}$$
equation 3.25

•••

where l and η are parameters related to the tortuosity of the soil pores, and the value of the parameter γ is determined by the method of evaluating the effective pore radius. In the original model models of Burdine (1953) and Mualem (1976) the parameter set of (η, γ) is equal to (2,10) and (1,2), respectively. Table 3.1 summarises the relative hydraulic conductivity functions, $K_r(S_e)$, obtained by substituting the listed water retention models (section 2.4) into Equation 3.25. The corresponding $K_r(\psi_m)$ functions can be derived by substituting the $S_e(\psi_m)$ relationship in each of the listed $K_r(S_e)$ expressions.

The tortuosity parameter, l, has been suggested to have a fixed value of 2 by Burdine (1953) or a fixed value of 0.5 by Mualem (1976). Recent studies suggest that prediction errors based on either the Burdine (1953) or Mualem (1976) model are partially the result of large variations in the tortuosity parameter l between soils. For example, Wosten and van Genuchten (1988) showed that l can vary between –16 and 2.2, depending on the soil type. They concluded that using a fixed l value resulted in unacceptable fits for medium and fine-grained soils. The l values determined by Schuh and Cline (1990) ranged from about –9 to 15.

Combining the van Genuchten (1980) water retention model (equation 2.22), using the relationship of m= 1-1/n, with Mualems (1976) model (equation 3.25, with η =1 and γ =2) produces the following closed form equation for K_r:

$$K_r = S_e^l \left[1 - (1 - S_e^{1/m})^m \right]^2$$
 equation 3.26

which is one of the most commonly used hydraulic functions.

3.4 Summary

This section provides the derivation of the governing equation for variably saturated flow. Characterisation of unsaturated flow in porous media includes the estimation of the moisture retention curve and the unsaturated hydraulic conductivity function for a wide range of water content values. The theory of hydraulic conductivity models associated with the various soil moisture retention models has been introduced.

Retention model	Brooks and Coror	Van Genuchten		Comphall	Fardlund and Ving
	Brooks and Corey	m=1-1/n	m,n variable	Campben	
Se	$\left(\frac{\Psi_{m}}{\Psi_{aev}}\right)^{-\lambda} \Psi_{m} > \Psi_{aev}$ $1 \qquad \Psi_{m} < \Psi_{aev}$	[1+($(\alpha \psi_m)^n$	unused	$C(\psi) \left[\frac{1}{\ln \left[e + \left(\frac{\psi}{a} \right)^n \right]} \right]^m$
θ	$\theta_{\rm r} + (\theta_{\rm s} - \theta_{\rm r}) \left[\frac{\Psi}{\Psi_{\rm aev}} \right]^{-\lambda}$	$\theta_{r} + (\theta_{s} - \theta_{s})$	$\partial_r \left[\frac{1}{1 + (\alpha \psi)^n} \right]^m$	$\theta_{s} \left(\frac{\Psi}{\Psi_{aev}} \right)^{-1/b}$	$C(\psi) \left[\frac{\theta_{s}}{\ln \left[e + \left(\frac{\psi}{a} \right)^{n} \right]} \right]^{m}$
с	$\frac{\lambda(\theta_{s} - \theta_{r})}{\Psi} \left(\frac{\Psi_{aev}}{\Psi}\right)^{1+\lambda} \psi_{m} > \psi_{aev}$ $0 \qquad \psi_{m} < \psi_{aev}$	(θ _s - θ _r)mnα(- α	$(\psi)^{n-1} \left[1 + (-\alpha \psi)^n \right]^{-m-1}$	$\frac{\theta}{\Psi_{eav}} \frac{1}{b} \left(\frac{\theta}{\theta_s}\right)^{-(b+1)}$	$\frac{\frac{\psi}{\psi^2 \left[\left(1 + \frac{\psi}{\psi_r}\right) \ln \left(1 + \frac{10^6}{\psi_r}\right) \right]} - \frac{10^6 \ln \left(1 + \frac{\psi}{\psi_r}\right)}{\ln \left(1 + \frac{10^6}{\psi_r}\right) \psi^2 \left(1 + \frac{10^6}{\psi_r}\right)}}{n \left[e + \left(\frac{\psi}{a}\right)^n \right]^m}$
Kr (Burdine model)	$S_e^{i+i+2/\lambda}$	Unused	$S_e^{I}I_{S_e^{1/m}}(n+(2/n),I-(2/n))$ n>2	Unused (see chapter 4)	Unused
Kr (Mualem model)	$S_e^{l+l+2/\lambda}$	$S_e^{I}\left[1 - \left(1 - S_e^{1/m}\right)^m\right]$	$S_{e}^{l} \left[I_{S_{e}^{l/m}}(m + (l/n), l - (l/n)) \right]^{2}$	Unused	Unused

Table 3.1 Commonly used water retention curves and corresponding specific water capacity functions, C, and relative hydraulic conductivity

Chapter 4

4. AN OVERVIEW OF LANDFILL HYDRAULICS MODELLING AND HYDRAULIC PROPERTIES OF MSW

4.1 Introduction

The processes such as infiltration of moisture in landfilled waste can be simulated using numerical models. The ability to predict and evaluate a variety of different scenarios without the effort and expense of physical experimentation is the greatest advantage of numerical models. Prior to undertaking any simulation and modelling effort, it is a good practise to study similar modelling projects. This provides understanding the idealisation of the physical processes such as flow pattern of leachate, assumptions and limitations within the numerical model. This chapter reviews the numerical flow models for simulation of landfill hydraulics. The saturated/unsaturated hydraulic properties of the MSW have direct effect on the results of any numerical modelling of landfill hydraulics. Therefore, an overview of the hydraulic properties of MSW will also be presented.

4.2 Numerical Flow Models

A number of numerical models have been developed to simulate moisture movement within the landfill. These models fall into several categories:

- Water balance methods
- Layer models

- Saturated flow models
- Saturated/unsaturated flow models
 - o One-dimensional models
 - o Two-dimensional models
- Two-domain models

4.2.1 Water Balance Methods

The water balance method (WBM) is by far the most commonly used method to estimate the volume of leachate generated from a landfill (El-Fadel, et al., 1997). It can be expressed as:

 $PERC = P - ET - RO + GI - \Delta S$

Equation 4.1

where

- PERC = percolation at the bottom of the landfill, mm P = precipitation, mm, ET = evapotranspiration, mm,
- RO = runoff, mm
- GI = groundwater intrusion, mm
- $\Delta S =$ change in storage, mm.

The WBM says that water infiltrating through the landfill cover and past the depth of the landfill influenced by evapotranspiration will eventually emit from the landfill as leachate. This is valid after the MSW reaches its absorptive capacity for holding the moisture. Figure 4.1 describes a generalised conceptual representation of the variables used in a WBM. Although the method is theoretically correct and relatively simple, a great degree of uncertainty is associated with estimating its variables. These variables are either stochastic in nature (weather variables, precipitation, wind, temperature) or
dependent on parameters that are difficult to define with great accuracy (such as runoff coefficients, refuse degree of compaction, or moisture content).



Figure 4.1. Generalised variables of WBM in hydraulic regime of a landfill

Early water balance analyses for landfilled waste were carried out on laboratory columns, where boundary conditions are exactly definable (Quasim & Burchinal, 1970; Fungaroli & Steiner, 1971). Water was added by surface irrigation. Evaporation was prevented by sealing the top of columns. The amount of moisture stored inside the waste was either determined by weighing the whole column or by sampling and weighing the moisture content of the waste was either determined by weighing the moisture content of the waste at the end of the experiment.

Spill and Collins (1986) reported water balance calculations for landfilled MSW which include evapostranspiration. They carried out water balance analysis on a

waste lysimeter over a period of five years. Leachate discharge was estimated by calculating the difference between precipitation and actual evapotranspiration. The water balances were carried out on a weekly basis. A data base for water balance parameters was obtained for five years period.

Baccini et al (1986) conducted water balance analysis of MSW landfills. Baccini at al reported that moisture production and moisture consumption due to biological degradation processes to be negligibly small. The amount of moisture stored in the landfill was determined by measuring the moisture content of the landfill at undisturbed drilling cores. Their measurements indicate that the moisture storage inside the landfill stays constant over larger periods and equal to the initial moisture content of the waste prior to landfilling.

4.2.2 Layer Models

In layer models, the landfilled waste is assumed to be homogeneous and is divided into several horizontal layers. The movement of moisture is gradually computed from layer to layer whereby leachate flow to underlying layers occurs only when the moisture content exceeds the field capacity. Field capacity is described as the amount of moisture which can be held by a porous media against gravity force. If the moisture content of the first layer exceeds its field capacity, the excess moisture percolates to the layer beneath. As a result the moisture is distributed throughout the landfill from surface of the landfill to the base. Therefore, leachate will not be generated until the moisture content in the bottom layer reaches its field capacity. Moisture withdrawal from the landfill by evaporation is only considered from the surface (top) layer and upward moisture movement in the underlying layers due to capillary forces is neglected.

Early applications of the layer models were presented by Remson et al. (1968) who used this approach to conduct moisture routing in an unsaturated landfill for different soil cover conditions. It was then used to develop the most common model for estimating leachate generation from landfills called Hydrologic Evaluation of Landfill Performance (HELP) model (Schroeder et al. 1984a, 1984b; Peyton & Schroeder, 1988). The HELP model simulates the hydrologic processes for a landfill by performing daily, sequential water budget analysis using a quasi-two-dimensional, deterministic approach. The HELP model accounts for lateral drainage, snow melt, and freezing conditions taking into account the properties and composition of the landfill cover. The landfill, including cap, waste, daily cover material, and leachate collection system components, are modelled as a series of layers each with its own hydraulic properties. The HELP model uses the "field capacity" concept to model the moisture storage in MSW. The most significant development to the layer models that is incorporated in the HELP model is the capability to calculate a flow rate through the refuse which allows the estimation of the time of first leachate appearance.

The flow mechanisms made use of in HELP models are noted as follows:

- Surface runoff and actual evapotranspiation from the landfill cover are calculated in the model. Only gravitational forces are responsible for moving pore water through a final cover system and capillary forces are neglected.
- The vertical moisture flow in waste layers is calculated using a modified form of the Darcy equation (1956) assuming that the hydraulic conductivity is directly proportional to the water content in the single layers. When the moisture content drops below the field capacity the hydraulic conductivity becomes zero.
- Percolation rate through a liner is computed using Darcy's law with saturated hydraulic conductivity.
- Lateral flow above the liner is modelled based on a linearization of the steady state Boussinesq equation.

It provides the flexibility of introducing the boundary and initial conditions and includes a database of meteorological information for many cities in United States. It is currently used widely in engineering practice to predict leachate generation at landfill sites. HELP allows the users to model leachate recirculation by specifying the percentage of leachate that is extracted and the location it is reinjected.

A limitation in the application of layer models is the lack of field data for calibration, which limits the confidence in predictive simulations. Benchmark studies to test the reliability of the HELP model reported some successful or satisfactory simulations however, significant limitations were also identified. Peyton and Schroeder (1988) verified the HELP model by simulating the performance of 17 landfills located in California, Kentucky, and Wisconsin. In this study the HELP model simulated cover layer flux well under in humid climate conditions however; the results demonstrated over-estimation in the model predictions for arid conditions. HELP also overestimated the moisture flux at the bottom of the landfill under all conditions. In addition to these there are some limitations regarding the model input parameters. The models require several input parameters which are not directly measurable and are typically selected based on user judgement and past experience with the model. Furthermore these models has the assumption that the landfill conditions and MSW properties remain uniformity constant which is highly unlikely as landfill itself is growing in size and depth during active infilling and MSW undergoes changes physically due to biodegradation processes during active infilling and after closure.

It can be concluded that although layer based models are widely used in practise to estimate the amount of leachate that will ultimately reach the bottom of the landfill, they have some limitations as mentioned above. These models are not able to simulate the spatial distribution of moisture within a landfill during operation or after closure.

4.2.3 Saturated/ Unsaturated Flow Models

Straub and Lynch (1982) made the first attempt to combine the unsaturated flow and transport theory to simulate leachate flow and quality. Although their model accounts for inorganic contaminant strength, they also provide the background of the hydraulic flow behaviour of landfill. The one-dimensional, finite-difference flow model was based on the supposition that the contaminated moisture present in the placed waste is first supplemented by infiltrating moisture which raises the moisture content to field

capacity while leaching and solublizing components from the solid waste mass. Once field capacity is exceeded, leaching begins. Thus, the first flow of leachate is highly contaminated. As liquid continues to infiltrate; the waste mass remains at field capacity and the leachate contaminants are diluted. The dilution process continues until equilibrium is reached between the leaching and dilution process. The effect of moisture diffusion on movement of moisture is minimum as compared to gravity drainage resulting in a strong moisture gradient and the propagation of a wetting front travelling downwards. It was assumed that the unsaturated properties associated with fine-grained materials could be used due to dominance of paper and fibrous materials in the waste mass. Following good overall agreement of the model with experimental leachate production investigations, they concluded that a landfill can be modelled as unsaturated porous media and that ultimately; these concepts could be applied to field-scale problems.

Korfiatis et al. (1984) formulated and calibrated a mathematical model for the simulation one-dimensional, vertical movement of moisture through waste. The mathematical model was based on the one-dimensional, the diffusion version of Richard's equation for unsaturated flow, solved via finite differences (using the power law equations of Clapp and Hornberger (1976) for the interrelationship of saturation, suction head and permeability). A laboratory-scale leaching column was constructed using a 0.56 m diameter by 1.82 m deep drum to simulate vertical moisture movement. Two experiments were run; both used approximately six months old waste obtained from a local landfill. Leachate was applied in a uniform manner to the upper surface using perforated tubing. In the first experiment, the moisture content was at or below field capacity. Leachate was first produced 222 hours after the onset of drainage. In the second experiment the waste was at or above field capacity. Leachate was first produced 30 hours after the onset of moisture application. Both experiments showed moisture redistribution to be slow process after the cessation of moisture application. The results from the second experiment showed that 16.4 litre of the 85. 20 litres applied moisture were retained 800 hours after the cessation of application. The introduced model enabled to simulate the general pattern of the leachate discharge from small scale waste columns.

Demetracopoulos et al. (1986) performed a sensitivity analysis on the model formulated by Korfiatis et al. (1984). The analysis consisted of assessing model outputs for both saturated and unsaturated surface conditions. Unsaturated surface conditions were most sensitive to changes in saturated hydraulic conductivity and the fitting parameter, B. Grid and time-step size had a little effect on simulation results. A grid size of 30 cm and time steps of one day were recommended for simulating full-scale landfills. Saturated surface condition simulations were most effected by the time span over which rainfall events were averaged. Once again, grid and time step size had little effect on simulation results.

Noble and Arnold (1991) evaluated several engineering models for moisture transport within a landfill. They developed the FULFILL program, a one-dimensional linearized finite difference solution of the diffusion version of the governing differential equation known as Philip's equation which includes the effects of gravitational forces, in conjunction with newspaper-filled columns to evaluate several models for moisture transport within the landfill.

$$\frac{\partial \theta}{\partial t} + \frac{\partial K(\theta)}{\partial z} - \frac{\partial}{\partial z} \left(D(\theta) \frac{\partial \theta}{\partial z} \right) = 0$$
 Equation 4.2
where

θ	=	volumetric moisture content, dimensionless;
K(θ)		hydraulic conductivity as a function of the moisture content;
D(θ)	=	moisture diffusivity;
Z		vertical coordinate;
t	=	time.

FULFILL calculates transient moisture content and flux profiles over time from specified top and bottom boundary conditions. Vertical infiltration and capillary rise experiments were conducted to asses the predictive capabilities of FULFILL. The results from FULFILL were found to compare well with the experimental results, however the application was limited to small scale experiments.

The Flow Investigation for Landfill Leachate model (FILL), Ahmed et al. (1992) and Khanbilvardi et al. (1995), reported the first use of a two-dimensional numerical model which used a combination of saturated and unsaturated flow theory to model leachate the time variation of leachate flow in landfills due to infiltration. Their model used the following two-dimensional form of the Philips equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left(D(\theta) \frac{\partial \theta}{\partial x} \right) + \frac{\partial}{\partial z} \left(D(\theta) \frac{\partial \theta}{\partial z} \right) - \frac{\partial K(\theta)}{\partial z}$$
 Equation 4.3

They also included various time-dependent boundary conditions in their finite difference model to account for runoff, evapotranspiration, and infiltration. The model results include moisture content at grid points within the waste mass and the depth of the leachate head on the liner. The leachate accumulation was determined from the time history of moisture content.

Ahmed et al. (1992) used their model to simulate the leachate flow rates in Fresh Kills Landfill, in New York, utilizing the site geometry and climatic data. In their analysis, they adopted the values of b, B, and ψ_{aev} equal to 4, 11, and 46 cm of water, respectively. However, they did not provide any information for obtaining these unsaturated hydraulic parameters. Although they reported the model results can be used to obtain variation of leachate flow rate successfully, a rigorous validation of the model was not presented in this paper. Their confidence about the validity of the FILL model is not gained by comparing the model results with the field results but by comparing the model results with the HELP model results.

McDougall et al. (1996) applied the saturated/ unsaturated flow theory to simulate leachate movement in saturated and unsaturated zones in landfills. No case history has been simulated in this study, but they discussed the hydraulic characterisation of the waste and interpretation of boundary flow conditions to an idealised landfill site. The numerical model introduced can simulate the active landfilling phase both spatially and temporally. During active infilling all precipitation was treated as infiltration. After closure the precipitation is directed to both infiltration and surface runoff. The governing differential equation used in their model is two-dimensional form of Richard's equation given in equation 3.15:

$$\frac{\partial}{\partial x}K(\theta)\frac{\partial \psi}{\partial x} + \frac{\partial}{\partial z}K(\theta)\frac{\partial \psi}{\partial z} + \frac{\partial K(\theta)}{\partial z} = C\frac{\partial \psi}{\partial t}$$
 Equation 3.15

where

C = specific water capacity $(\partial \theta / \partial \psi)$; ψ = suction head; K(θ) = unsaturated permeability.

In a more recent study, McCreanor (1998) used United States Geological Survey's <u>Saturated Unsaturated Transport (SUTRA)</u> model to simulate leachate application to waste masses. McCreanor simulated the site recirculation system via horizontal trench, and operational procedures at the Deleware Solid Waste Authority Test Cells and the Yolo County Leachate Recirculation Demonstartion Project. In this analysis, cumulative measured and simulated leachate generation were compared. McCreanor reported that there was a significant difference between the measured and predicted volumes of leachate generation. It was concluded that the discrepancy of results is due to the effects of the channelled flow.

SUTRA uses a two-dimensional hybrid finite element and integrated finite difference method to approximate the governing equations of flow and transport. SUTRA is capable of performing steady state and unsteady state simulations. The fluid mass balance governing equation used in SUTRA is:

$$\left(S_{w}\rho S_{op} + \varepsilon \frac{\partial S_{w}}{\partial p}\right)\frac{\partial p}{\partial t} + \left(\varepsilon S_{w}\frac{\partial \rho}{\partial U}\right)\frac{\partial U}{\partial t} - \nabla \left[\left(\frac{kk_{r}\rho}{\mu}\right)(\nabla p - \rho g)\right] = Q_{p} \qquad \text{Equation 4.4}$$

where

 $S_w = water saturation;$

 ρ = liquid density;

S_{op} = specific pressure storativity;

3	=	porosity;
р	=	pressure;
t	=	time;
U	=	solute concentration or temperature, $M_{solute}/M_{fluid}~~ or~^0C$
k	=	saturated permeability;
k _r	=	relative permeability;
μ	=	viscosity;
g	=	gravity acceleration vector;
Q_{p}	=	fluid mass source.

Terms one, three, and four seem to have importance in simulating landfill leachate generation. Term two has no effect due to the fact that there are no changes in temperature or solute concentration in landfills (McCreanor, 1998).

Yuen (1999) used SEEP/W to simulate moisture content changes in a full-scale landfill cell due to leachate recirculation located in Lyndhurst Sanitary Landfill Site, Melboune, Australia. SEEP/W is a two-dimensional finite element model originally proposed by Lam et al. (1987) to simulate moisture transport in soils in both saturated and unsaturated zones.

SEEP/W seeks solution in terms of total head and the governing differential equation used in the formulation of SEEP/W is:

$$\frac{\partial}{\partial x} \left[K_x \frac{\partial H}{\partial x} \right] + \frac{\partial}{\partial z} \left[K_z \frac{\partial H}{\partial z} \right] + Q = \frac{\partial \theta}{\partial t}$$
 Equation 4.5

where

Н	=	total head
K _x	=	hydraulic conductivity in the horizontal direction,
Kz	=	hydraulic conductivity in the vertical direction
Q	_	applied boundary flux,
t	=	time,
θ	=	volumetric moisture content.
R _z Q t θ	=	applied boundary flux, time, volumetric moisture content.

In this study, the movement and distribution profiles were monitored using the neutron probe technique in the full-scale landfill cell. Deep recharge wells and surface infiltration trenches were being used as recirculating techniques. Yuen (1999) concluded that classical theory based on saturated/ unsaturated flow through a homogeneous porous media is not applicable in predicting moisture distribution patterns introduced by leachate recirculation.

4.2.4 Tracer Tests and Dual Domain Models

All models mentioned in section 4.2.3 are based on the saturated/unsaturated flow theory assuming that the landfill body to be a homogeneous media, resulting in uniform water distribution. The assumption of a uniform flow regime is probably the valid for laboratory experiments, but not full scale landfills as tracer experiments show. This conclusion is supported by the fact a good match between observed and predicted (assuming a homogeneous flow field) leachate discharge was only achievable for small scale experiments. However, as different field investigations showed, water distribution in landfills is far from being uniform. This is explained by preferential flow paths that shortcut through landfill. The importance of these preferential flow paths has been ignored in most landfill models.

Some modelling efforts were made to divide the landfill into domains with different hydraulic characteristics. The terms of two- or multiple domain models are used in this context. Therefore, the consideration of preferential flow within the landfill was facilitated.

Young and Davies (1992) were the first who suggested the concept of a two-domain water flow. The flow field (the landfill) was supposed to be divided into a macro- and a micro-pore domain with different hydraulic properties. Moisture flow is calculated separately for each domain applying Richards equation (1931). The main focus of the proposed model was given to the biodegradation processes of organic matter. In particular the generation of landfill gas and its governing factors were described. The

model however, did not progress from its initial stage of development. No comparison of the concept with field data is available.

Zeiss and Major (1993) investigated the moisture flow pattern in small waste columns of 1.8m high and 0.51m diameter which were equipped with flow sensors. They discussed that the flow patterns are characterised by larger chanels through which some of the moisture flow downwards rapidly. In between these channels, slow movement of the wetting front occurs and eventually contributes to the overall flow. Zeiss and Ugucciono (1995, 1997) conducted similar tests in same size and larger tests cells and confirmed their findings. They reported that the resulting velocities are far higher than predicted by saturated/unsaturated flow models. The results of their investigation indicate that moisture patterns are strongly affected by channelling and preferential flow paths.

Based on these findings, Ugucciono, and Zeiss (1997) compared two different approaches to simulate water transport through MSW. They applied one-dimensional layer model HELP and the two-dimensional flow model PREFLO (Workman and Skaggs, 1990) for fractured porous media to predict the leachate generation from pilot scale test cells with an average waste volume of 4 m³. PREFLO assumes that the rapid water flow in the channel domain follows Poiseuille's Law (1841) and the lateral moisture transfers from the channels into the matrix occurs according to Richards Law (1931). Despite the fact that PREFLO seems to display the flow processes physically more realistic than HELP, both models were unable to predict the exact shape of the observed leachate hydrographs. Dependent on the chosen parameter values either the simulated breakthrough time (initial leachate generation) was too long or the cumulative water discharge is too high. Due to these unsatisfactory simulation results, Ugucciono and Zeiss (1997) called for a new twodomain model approach that reflects channel and matrix flow.

Rosqvist, Bendz, et al. (1997) monitored moisture content variations and performed tracer test in a pilot scale landfill of 570 m^3 . To monitor changes in moisture content, sensors were placed in a netwok at three depths in the landfill. The moisture content measurements indicated a spatial dependence of moisture content. An increase in

moisture content values with depth was monitored. The tracer results has similar findings with Zeiss and Major (1993) and Zeiss and Ugucciono (1995, 1997). They discussed that tracer test results indicated a two-domain moisture flow in MSW. One flow domain was characterised by flow in larger voids in which the flow velocity was higher and the other flow domain was characterised by smaller pore systems in the matrix.

Bendz et al. (1997) investigated the leachate discharge from landfills and recognised the importance of heterogeneities (particularly fissures and channels) for the water movement. In order to take these heterogeneities into account he introduced a twodomain flow concept composed of channel and matrix domain. Contrary to the approach of Young and Davis (1992) the water flow in the channel domain (macropores) is computed by applying the kinematics wave equation according to Beven and Germann (1981). For the matrix domain (represents micropores) Richards' equation is used to describe the water movement. The interaction between both flow domains is regarded by simple source and sink terms. In addition to water transport, Bendz and Singh (1999) incorporated solute transport processes into the model. Between the two domains diffusive transport of solutes can take place. Tracer experiments in the laboratory were conducted in conjunction with the modelling effort to obtain data sets for the calibration of the model. The concept enabled to simulate the leachate generation and the tracer breakthrough in small scale experiments. An up-scaling of the introduced model to real landfill size has not been performed.

4.3 Hydraulic Properties of MSW

In this section an overview of hydraulic properties of MSW reported in literature will be presented. Generally the following parameters are needed to characterise the hydraulics properties of MSW

- Saturated hydraulic conductivity;
- Relative permeability function;
- Porosity, and;
- Moisture retention characteristics

4.3.1 Saturated Hydraulic Conductivity

The saturated hydraulic conductivity of waste has been reported by a number of researchers.

- Oweis et al. (1990) determined saturated hydraulic conductivities for municipal solid waste based on a series of constant rate pumping tests on an 11 m leachate mound in a MSW landfill in northern New Jersey. The study identified a range of saturated hydraulic conductivities for MSW of 10⁻³ 10⁻⁵ cm/sec. The study also led to the conclusion that the governing moisture movement in soils (Darcys law) can be applied on a macroscale to MSW.
- Korfiatis et al. (1984) found waste samples tested in the laboratory to have saturated hydraulic conductivities approximately 10⁻² cm/sec.
- Bleiker et al. (1993) calculated a hydraulic conductivity range of 10⁻⁴ 10⁻⁷ cm/sec for solid waste samples from the Brock West landfills, Toronto, Ontorio. The Bleiker study also demonstrated that as density increases, the hydraulic conductivity decreases, suggesting that with increasing compaction, moisture flow is impeded.
- Beaven and Powrie (1995) used a large scale compression cell to simulate loads on waste equivalent to a 60 metre depth of landfill. They reported that hydraulic conductivity of the waste decreases with increasing overburden pressure. Hydraulic conductivity measurements of a waste obtained from a landfill were reported ranging between 3.5 x 10⁻³ and 1 x 10⁻⁵ cm/sec at different applied stresses.

Figure 4.2 gives the summary of the saturated hydraulic conductivity of MSW from the above mentioned studies.



Figure 4.2 Saturated hydraulic conductivity of MSW

4.3.2 Porosity

The porosity is a measure of the void space in a porous medium. It is defined as the ratio between pore volume and total volume. Under saturated conditions the void space is totally occupied by water. It is the upper limit of the water storage capacity. In the literature, porosity values of MSW were reported between 0.30 to 0.65 as shown in Table 4.1. Majority of values are around 0.50. Porosity of the landfilled waste decreases with increasing compaction energy and overburden pressure (Beaven and Powrie, 1995).

Reference	Bulk density (kg/m ³)	Porosity n (m ³ /m ³)
Oweis et al. (1990)	640-1100	0.40-0.50
Landva and Clark (1990)	1000-1400	0.30-0.60
Zeiss and Major (1993)	360-550	0.47-0.58
Beaven and Powrie (1995)	800-1070	0.46-0.56
Yuen et al. (2001)	840	0.55

Table 4.1 Porosity of landfilled MSW reported in the literature

4.3.3 Water Retention Characteristics of MSW

The mechanisms of soil moisture retention have been described in Chapter2. Moisture retention characteristics of MSW are important for the evaluation of moisture storage inside the landfill. The retention characteristics of MSW can be expressed either using a single parameter called field capacity or a defined relationship between the volumetric moisture content and matrix suction potential resulting in so called moisture retention curve.

Field capacity is defined as the maximum moisture that is retained against gravity force in a porous medium without producing downward percolation. As explained in section 4.2.1, water balance methods use field capacity concept to model moisture storage in MSW landfills. Blight et al. (1992), El-Fadel et al. (1997) and Yuen (1999) indicated that field capacity is a function of the waste composition, density and porosity. Also it is expected to change with time as the degradation of the waste alters its composition. Typical field capacity values for MSW landfills reported in literature are given in Table 4.2.

Reference	Reported field capacity v/v
Remson et al. (1968)	0.29
Straub and Lynch (1982)	0.30 - 0.40
Korfiatis et al. (1984)	0.20 - 0.30
Oweis et al (1990)	0.20 - 0.30
Zeiss and Major (1993)	0.12-0.14
Schroeder et al. (1994)	0.29
Yuen et al. (2001)	0.34

Table 4.2 Field capacity of MSW reported in the literature

The wide range in reported field capacity values is attributed to the differences in composition, density and porosity. Yuen (1999) discussed that the method of measurement can also lead to a substantial difference. In most laboratory studies, commonly the waste samples are first fully saturated by flooding and then subjected to prolonged drainage. The field capacity is then taken to be the amount of moisture retained in the sample. Yuen (1999) described a method to calculate the field capacity of full-scale landfills. In full-scale situations, the field capacity is generally determined from a water balance of the whole cell. Initially level of the saturated waste (height from the clay liner) is determined within the cell. Then the leachate is drained to another level. As the initial moisture content of the waste as transported to the landfill and the amount of moisture from this drained zone is known, the in-situ field capacity can then be calculated. Assuming the cell reaches its field capacity, and when water is added an equal quantity of leachate will drain out of the cell to restore equilibrium.

Vorster (2001) was the first to demonstrate that moisture retention in waste is a function of its position relative to the phreatic surface. It is inadequate to define moisture retention in waste only as a characteristic of the material. Therefore, a better way of charactering the moisture retention properties of MSW is to refer to the moisture retention curve. A summary of the moisture retention curves of MSW

reported in literature which has been used in unsaturated flow models with some success for the analysis of landfill hydraulics is presented here.

Straub and Lynch (1982) were the first researchers to report on the application of unsaturated flow theory to the solid waste landfill. Power Law equations suggested by Clapp and Hornberger (1978) were used to approximate $K(\theta)$ and $\psi(\theta)$ of the MSW. Straub and Lynch assumed that due to dominance of paper and fibrous materials in waste that moisture retention characteristic of fine-grained materials could be used as a preliminary description for the moisture retention characteristics of solid waste. In simulation of the observed leachate production reported for an experimental landfill column by Quasim and Burchinal (1970), Straub and Lynch (1982) used values of 100 cm, 7, and 8 for ψ_s , b, and B, respectively. In their analysis, the saturated conductivity, K_s, was set to equal to the daily average moisture content application rate while the saturated moisture content, θ_s , was set equal to the field capacity. Setting θ_s equal to the field capacity was justified by the assumption that leachate will not be produced until the moisture content exceeds the field capacity. Values of 0.544 cm/day for K_s and 0.375 cm/cm for θ_s showed good agreement with experimental results of cumulative leachate production. However, they reported moisture content values greater than θ_s in their simulated moisture profiles.

Straub and Lynch (1982) used their model to simulate also the data from an experimental landfill lysimeter reported by Fungaroli (1971). Refuse depth in the lysimeter was 2.10 m, with a field capacity of 0.31 mc/cm and K_s of 0.214 cm/day which was equal to the average daily moisture application rate. Estimating values 0f 100 cm, 7 and 9 for ψ_{aev} , b, and B they predict good overall agreement between the simulated and observed flow patterns. However, the predicted moisture content profiles contain moisture content values greater than the saturated moisture content of MSW.

Korfiatis et al (1984) used a 56 cm diameter laboratory column packed with heterogeneous mixture of approximately six-month old waste obtained from a MSW landfill to simulate the vertical movement of the leachate within the landfill. The

column was equipped with in-situ pressure transducers to determine the relationship between suction pressure and saturation.

A 15-cm diameter column packed with waste was used to determine the saturation/suction pressure curve. The column was packed with waste of known moisture content. After packing was completed, pressure measurements were taken. This procedure was repeated "three" times at different moisture contents in order to determine the characteristics of the saturation/suction pressure curve. The power law relationship proposed by Clapp and Hornberger (1978) were used to fit the data. The saturation suction head was determined to be 6.2 cm of water. Measurements of the saturated moisture content ranged from 0.5 to 0.6; a value of 0.5 was recommended. The suction head fitting parameter b, was determined to be 1.5. However, the measurement technique did not account for channelling and most likely underestimated the suction head fitting parameter, b. Channelling could be accounted for by increasing the suction head fitting parameter in models that use moisture diffusion theory to model unsaturated flow. The best correlation between the equations and experiments were obtained for b equal to 4. The field capacity was found to vary from 20% to 30%. A value of 11 was recommended for the permeability fitting parameter, B. Saturated hydraulic conductivities ranging from 1.3 x 10⁻² cm/s to 8 x 10⁻³ cm/s were determined for waste samples subjected to the constant head permeability test. Calibration of the model based on the experimental results indicated that setting the suction head fitting parameter equal to four and the permeability fitting parameter equal to 11 yielded the best result. A sensitivity analysis indicated that large change in the suction head fitting parameter b, had little effect on the results, while small changes in the permeability fitting parameter, B, effected moisture content and flux results more significantly. It was found that doubling b, from 4 to 8, had little effect but increasing B from 10 to 11 increased the cumulative volume measurement by 30%. These two relative permeability functions are compared in figure 4.3. These results suggest that hydraulic conductivity dominates the diffusion process. It was concludes that capillary diffusivity contributes little at moisture contents above field capacity due to the large pore structure of the waste material which inhibits the development of relatively larger suction heads.

A primary difference between the Korfiatis et al. (1984) study and Straub and Lynch (1982) study was the definition of θ_s and K_s . Korfiatis defined θ_s as the actual saturated moisture content where as Straub and Lynch defined θ_s as the field capacity of the refuse. Similarly, Korfiatis defined K_s as the measured saturated hydraulic conductivity while Straub and Lynch defined it as the moisture application rate.



Figure 4.3 Comparison of relative permeability functions with different permeability fitting parameters (B) (from Korfiatis et al (1984).

An important conclusion drawn in the Korfiatis study was that the driving force of capillary diffusivity, the suction head was negligible compared to gravitational forces once the saturation increased above field capacity. However, when the moisture content was below field capacity, capillary diffusivity was the dominant driving force. The results obtained were for a one dimensional vertical flow situation. The study results also showed that the field capacity tended to increase the after drainage had started. The authors hypothesized that this result indicated that secondary absorption and capillary action redistribute the moisture into the waste from the primary flow channels. Results also indicated that the redistribution process was slow in comparison to the breakthrough time.

Noble and Arnold (1991) compared the power law equations proposed by both Korfiatis et al. (1984) and Straub and Lynch (1982); to an exponential relationship:

$$K = K_{s} e^{\gamma(\theta^{*} - I)}$$
Equation 4.6
$$\psi = \psi_{max} e^{-\alpha \theta^{*}}$$
Equation 4.7
$$\theta^{*} = (\theta - \theta_{ad})/(\theta_{s} - \theta_{ad})$$
Equation 4.8

where

÷.,

ψ_{max}	=	maximum suction head;
α	=	curve fitting parameter;
γ	=	curve fitting parameter;
θ^{*}	=	normalised moisture content;
θ_{s}	=	saturated moisture content;
θ_{ad}	=	air dry moisture content.

Shredded newspaper waste was used as a solid waste surrogate in their laboratory experiments that were one-dimensional vertical flow situations. Noble and Arnold (1991) reported the following values for use with equation; ψ_{max} equals 22.5 cm of water, α equals five or seven, and γ equals eleven. An important distinction between the exponential and power equations is that the exponential equations predict a maximum value of ψ_s at dry conditions (θ equals to zero) where as power equations predict an infinite value.

Al-Yousfi (1992) performed a statistical analysis based on probabilistic entropy, the concept that a system has a natural tendency to approach and maintains its most probable state, and maximization and minimization techniques ("game theory") in combination with randomness and observation techniques ("information theory") to develop relations of hydraulic conductivity as a function of saturation. It was assumed that the hydraulic conductivity was zero for saturation less than the residual saturation. Al-Yousfi (1992) proposed the following equation:

$$K(\theta) = -K_{s}(\theta - \theta_{s}) \ln \left\{ 1 + \left[\exp\left(\frac{-1}{\theta - \theta_{r}}\right) - 1 \right] \frac{\theta}{\theta_{s}} \right\} \qquad \text{for } \theta > \theta_{r}$$

 $K(\theta) = 0$

Equation 4.9 for $\theta < \theta_r$

where

K(θ)	=	hydraulic conductivity as a function of the moisture content;
θ	=	volumetric moisture content;
Ks	_	saturated hydraulic conductivity;
θr	=	residual moisture content;
θs	=	saturated moisture content.

In McDougall et al. (1996) model the water retention curve for MSW has been established from laboratory experiments performed on a mix of partially humified peat and cocoa shells using hanging water columns. The saturated moisture content of the sample was measured as 82% which is considerably larger than typical values reported for MSW, such as 55% by Korfiatis et al. (1984) and 42% by Ahmet et al. (1992). Therefore, the experimental results have been translated to a more accepted moisture range. Water retention curve of MSW was represented by the relationship proposed by McKee and Bump (1984):

$$\theta = \exp\left[-\left(\frac{\psi - a}{b}\right)\right]$$

Equation 4.10

where

Ψ = suction head;
a = curve fitting parameter;
b = curve fitting parameter.

The relative conductivity function has been approximated by the relationship proposed by Davidson et al. (1969) and is given by:

$$K_{\rm r} = 10^{10n(\rm S-1)}$$
 Equation 4.11

where

n	=	porosity;
S	=	degree of saturation.



More recently, McDougall uses van Genuchten in the HBM model.

Figure 4.4 Comparison of moisture retention curve for MSW.

Figure 4.4 gives an overview of the reported moisture retention curves for MSW. The results vary over a great range in matric suction for given moisture content. Some of the moisture retention curves are suggested as a result of calibration effort to give the best simulation results. Therefore, this difference between curves can be attributed to differences in waste composition, compaction and the biodegradation state of the waste used in laboratory models. The relative conductivity function of MSW reported are summarised in Figure 4.5. Al-Yousfi's equation (Eq 4.10) does not compares well with the equations from Noble and Arnold (1991), McDougall et al. (1996) and Korfiatis et al. (1984).

McCreanor (1998) and Yuen (1999) used the power law equations as discussed previously. McCreanor used the set of parameters suggested by Korfiatis et al. (1984). Yuen used two sets of parameters in his simulations, each based on Korfiatis et al. (1984) and Ahmed et al. (1992), as listed in Table 4.3.



Figure 4.5. Comparison of relative permeability functions for MSW.

Material type	Type A	Туре В
Sauraa	Korfiatis et al	Ahmed et al.
Source	type Type A Korfiatis et al (1984) 4 11 6 1.2 x 10-4 m/sec	(1992)
b	4	4
В	11	11
ψ_{aev}	6	42
V c	1.2 x 10-4	2.0 x 10-4
KS	m/sec	m/sec

Table 4.3. Unsaturated flow parameters for MSW

The unsaturated flow characteristics used by Yuen were based on published parameters. The differences between the Type A and Type B materials were in the ψ_{aev} and Ks values. Ks differed only slightly but ψ_{aev} was much higher in type B. Yuen reported that these two parameter sets produced quite different moisture.

4.4 Conclusions

Leachate generation is an inevitable consequence of the practise of waste disposal in landfills. Many environmental factors and operational practises influence landfill processes resulting in temporal and spatial variations in the quantity and quality of landfill leachate. Numerical models have been developed to simulate leachate generation and moisture transport processes in landfills. The predictive capabilities of the landfill hydraulic models, however, are limited by the inadequate understanding of the hydraulic properties of landfilled waste. While the numerical models have been advanced for hydraulic modelling of landfills, the ability to determine the fundamental hydraulic properties of MSW has developed more slowly. This chapter presents a review of the numerical models designed to simulate leachate generation and moisture transport in MSW landfills. An overview of the fundamental hydraulic properties of MSW published in the literature has been presented. In particular the following points can be noted.

- Some researchers (Bendz et al., 1997, Yuen, 1999) reported a limitation of variably saturated flow theory to landfill hydraulics is that the potential occurrence of channeling flow due to dual porosity of MSW is not taken into consideration which can be significant.
- The most important aspect of the MSW for accurate predictions of moisture movements within a landfill is the modelling of its unsaturated properties. These properties are water retention curve of the waste and the relative permeability function. In this study, both of these properties have been investigated through published research. Any further research documenting the experimental measurements of these two properties could not be located in the published material investigated throughout this study. However, some researchers estimated these properties in their modelling effort.

- Sensitivity analysis performed by Korfiatis et al. (1984) indicated that slight changes in the relative permeability function have great effect on the moisture content pattern and flow quantities.
- Yuen (1999) reported that ψ_{aev} has also influence on moisture content patterns even if the other hydraulic parameters remain same during the analysis.

Chapter 5

5. EXTENDED PHASE RELATIONS AND CLASSIFICATION OF MSW

5.1 Interpretation of MSW as a Soil

Landfilled MSW is due to its origin and it composition is a highly heterogeneous media. The grain size varies from 0.5 mm up to 1000 mm (Turczynski, 1988). Hydraulic properties of each component can be different. It ranges from highly water adsorbent (e.g. paper, textiles, and timber) to moisture inert materials (e.g. plastics and glass), from high permeable (e.g. textiles, paper, and daily cover) to impermeable materials (plastic bags and cans). Nevertheless, it is possible to determine its hydraulic parameters.

McDougall et al. (2004) discussed that the porous media, which is most comparable to solid waste landfills concerning its structure, porosity and gas content is unsaturated structured soils. Therefore, they linked the moisture retention curve and mechanical compression behaviour of landfilled waste as an unsaturated structured soil. The following section highlights the arguments of McDougall et al. (2004).

Fine-grained alluvial or marine soils that have not been subjected high stresses typically have a structure in which clay particles are aggregated to form clay pockets or clay clods. Clay clods are approximately 1-5 μ m in size and behave like silt particles. There are interconnected large pore spaces (macropores) between the clay clods. Microscale pores of approximately 0.1 μ m or smaller between the particles of clay within the clods as shown in Figure 5.1. An important characteristic of the micropores is that they tend to remain fully saturated under a wide range of hydraulic

conditions. The retained moisture is in a quasi-immobile state and is little affected by loading processes. At low or residual saturation states, the moisture is retained in the micropore system. In contrast, the macropores retain free moisture that is affected by both hydraulic and loading conditions.



Figure 5.1 Schematic diagram showing the pore structure of a fine-grained soil.

Cellulose, a major degradable constituent of waste refuse, is present in the form of woody material and paper fibres. The physical characteristics of cellulose contain a system of large capillaries, i.e. the lumen, which have typical dimensions about 0.5 μ m, and a system of smaller capillaries whose typical dimension is about 0.02 μ m. Clearly the physical dimensions of the pore system of cellulose are similar to those of a fine-grained soil. It might therefore be logical that the organic fraction of waste refuse retains moisture in both free and quasi-immobile states. Therefore the moisture retention of fine-grained structured soils provides a useful starting point for the analysis of the hydraulic behaviour of landfilled waste.

5.2 Extended Phase Relations in MSW

With the data on the composition of waste, McDougall et al. (2004) introduced a method of calculating the extended phase composition of landfilled waste which distinguish between solid organic and inorganic fractions, resulting in a four phase

material. The model is developed using the detailed moisture and waste composition data from Lyndhurst sanitary landfill in Victoria, Australia (Yuen, 1999).

McDougall et al. (2004) discussed that the waste arrives on site with uniform initial moisture content. Then there will be a moisture redistribution towards equilibrium moisture profile which may result in a combination of both drainage and absorption as shown in Figure 5.2. Elements of waste deposited near to the base of a site (i.e. close to the sump) will have a higher equilibrium moisture content than waste deposited at a higher elevation. Finally upon completion of infilling, the moisture profile effectively takes the shape of post capping equilibrium state. Knowledge of post capping moisture profiles have enabled variations of both density and moisture to be estimated. Figure 5.3 shows the moisture content measured in the test cell at Lyndhurst (Yuen 1999). The in-situ moisture content measurements were performed by Yuen (1999) with the use of neutron probe technique. The post capping depth dependent equilibrium moisture profile was defined by a linear function (see Figure 5.3)

$$w = 25\% + 0.03z$$

equation 5.1

where w is the gravimetric moisture content, 25% is the surface moisture content and z is the depth below the surface in metres.

The compressibility of waste varies considerably depending on composition, age and compaction effort. When the vertical stress is increased by the deposition of further waste, the porosity of the material at the base of the landfill decrease significantly. Based on the data from Beaven and Powrie (1995) and Jessberger and Kockel (1995), McDougall et al. (2004) has adapted a linear variation of one-dimensional compression modulus with the load for the Lyndhurst waste as shown in Figure 5.5,

$$E_0 = 300 + 5\sigma_v$$
 equation 5.1

where E_0 is the one-dimensional compression modulus which is defined as the ratio

 $E_{o} = \frac{\Delta \sigma}{\Delta \varepsilon}$ where $\Delta \epsilon$ is the increase in the vertical strain which results in vertical effective stress of $\Delta \sigma$ under condition of lateral displacement. The compression modulus is directly applicable to estimation of vertical settlements in the field.



Volumetric moisture content

Figure 5.2 Illustration of moisture storage over the depth of landfill



Figure 5.3 Measured moisture contents with depth for waste refuse at Lyndhurst (from Yuen (1999)) and assumed moisture relationship (from McDougall et al., (2004)).



Figure 5.4 Compression modulus with vertical stress for waste refuse from Beaven and Powrie (1995) and Jessberger and Kockel (1995), and the adapted relationship for Lyndhurst waste by McDougall et al. (2004) (from McDougall et al. (2004)).

The variation of density with depth due to self-weight can then be determined by using the as-placed bulk unit weight of waste and the compression modulus for the given stress-state. Using the initial uniform and post capping equilibrium moisture contents, the as placed bulk unit weight profile can be readily converted to stress-dependent dry unit weight profile and post-capping equilibrium moisture content dependent bulk unit weight profile. Using this procedure the bulk and dry unit weight with depth profiles was calculated for Lyndhurst Landfill as shown in Figure 5.5.

Using the detailed breakdown of waste composition at Lyndhurst given by Yuen (1999) in conjunction with the unit weight data published by Landva and Clark (1990), McDougall et al. (2004) quantified the solid organic and inorganic volume fractions, and estimated the overall solid unit weight. Materials including elementary particles that are able to absorb moisture contain both macropores and structured micropores, whereas granular media such as quartz sand comprising elementary particles that are solid and non-absorbent, contain solely macropores.



Figure 5.5 Calculated bulk and dry unit weight with depth profiles for Lyndhurst Landfill. Solid lines show cell average values reported by Yuen (1999) (from McDougall et al. (2004)).

The presence of a structured micropore system means it is difficult to measure specific weights by conventional methods thus the solid phase unit weight often refers to the unit weight of a solid particle plus the contents of its (usually saturated) micropore system. The effect of this additional weight is shown in Table 5.1. The solid phase unit weight refers to the dry unit weight of the given solid material under consideration with respect to the elementary particle volume minus the micropore volume. Table 5.1 presents the Lyndhurst waste composition data and associated unit weights. The solid phase unit weights of the individual constituents (γ_{si}) are calculated from their respective dry (γ_d) and saturated (γ_{sat}) unit weights using:

$$\gamma_{\rm si} = \frac{\gamma_{\rm d}}{1 - \left(\frac{\gamma_{\rm sat} - \gamma_{\rm d}}{\gamma_{\rm w}}\right)}$$
equation 5.4

where γ_w is the unit weight of the water. The overall solid phase unit weight γ_s , i.e. of the combined solid constituents, is given by,

equation 5.5

$$\gamma_{s} = \frac{1}{\sum\limits_{i=1}^{i=n} \frac{P_{i}}{\gamma_{si}}}$$

where P_i is the fractional composition by the dry weight of each of the n solid constituents. The data in Table 5.1 results in an overall solid phase unit weight of 13.2 kN/m³. With the unit weight of the solid phase, void ratio calculations (macroplus micro) can easily made from the dry unit weight profiles. Figure 5.6 shows the estimated variation of void ratio with depth at Lyndhurst.



Figure 5.6 Void ratio with depth at Lyndhurst Landfill (from McDougall et al., 2004).

Based on the assumption which relies on the deformation of the macropores and saturated micropores, and using the data for waste compressibility and solid phase unit weight, the phase composition for surface and base locations at the Lyndhurst have been calculated (Figure 5.7). Both micropore (immobile) and macropore (free) water phases are depicted. Three dimensional interpretations of moisture content void ratio and elevation relationship under hydrostatic conditions for Lyndhurst waste can be found in McDougall et al (2004).



Figure 5.7 Extended waste composition at (a) surface and base (b) base locations for Lyndhurst Landfill site (from McDougall et al. (2004)).

	Constituent	P _i ^a Fractional composition (dry weight)	Yai ^b (kN/m ³)	γ _{sati} c (kN/m ³)	γ _{si} ^d (kN/m³)	P _i / γ _{si} (kN/m³)	Fraction (by weight)	Fraction (by volume)
	Paper	0.12	4	12	20	0.006		
Organic	Grdn/Food/Timber	0.23	5.8	8.7	8.2	0.028	40%	0.61
	Textile	0.05	3	6	4.3	0.012	-	
	Plastic	0.09	11	11	11	0.008	•	
Tuononio	Metal	0.03	60	60	60	0.001	600	0.20
Inorganic	Glass	0.01	29	29	29	<0.001	00%	0.39
	Inert/Cover	0.47	18	20	22.5	0.021		
Total		1.00				0.076	100%	1.00

Table 5.1 Calculation of organic and inorganic fractions, and solid phase for waste constituents at Lyndhurst Landfill (from McDougall et al. 2004)

5.3 Composition and Classification of MSW Sample

Technical Classification of MSW

The essential aim of this section is to describe the MSW classification criterion which has been developed by Grisolia et al. (1995). The physical and mechanical behaviour of each waste component varies with time, as a result of stress level and with environmental conditions. Changing stress levels and environmental conditions have different effects on the waste components depending on the basic characteristics of the material. From this point of view, Grisolia et al. (1995) suggested that the solid elements that make up the waste may be categorised as follows:

Class A – Inert Stable Elements

The material that do not modify their initial composition in the intermediate term and whose characteristic strength and deformability properties do not affect the overall behaviour of the waste heap are grouped in this class. This class includes natural soils that are always present in waste, but also artificial materials such as construction debris, glass, ceramics, metals, hard plastic, also wood. The materials of this class are similar to those classified as "soil-like" in the European ETC8 report (ETC 8, 1993).

Class B – Highly Deformable Elements

Paper, plastic sheets, textiles, rubber, tires, etc. come under this class. When subjected to a load these materials have a tendency to undergo a very noticeable initial settlement, and their original shape and volume is significantly change. Moreover, some of them consist of materials having a creep behaviour so that major deformation continues in time even at constant load. The influence of class "B" material on the overall behaviour of the heap depends generally on the size of the individual elements, on the pre-treatment if any, on the presence of water and of other liquids, on the stress level, etc.

Class C – Readily Biodegradable Elements

This class groups together the materials which vary markedly in terms of constitution and consistency in dependence of the major transformations and consistency in dependence of the major transformations they may undergo in the short term, and in ordinary conditions. This is the case of vegetable products, of food and animal waste, also of the "undersieve fraction" which is mixed organic waste of diameter less than 20 mm. (Cossu and Granara, 1989). The decay of these substances induces deep changes in the material structure accompanied by shrinkage and formation of liquids and gas. The effect of the biodegradation on the heap behaviour depends not only on the amount and characteristics of the degradable material present, but also on the environmental conditions that governs the complex decay and transformation processes.

The elements of each category are presented in Table 5.2. The choice of the product classes proposed tends to emphasise the role that each different component would play in a general compressibility and strength model of the landfill.

Practical Applications

On the basis of the proposed classification, the data on the composition of municipal solid waste can easily be plotted on a triangular diagram. Grisolia et al. (1995) presented a large amount of data. The diagrams obtained distinctly reflect the type of MSW represented. The triangular diagram in Figure 5.8(a) shows the data available for the different areas of the United States. All the data points group around a well-defined area of the diagram. Figure 5.8(b) presents the data relative to the City of Rome and all data points group around in a different area of the diagram in a well defined manner. Based on the same criteria, the data coming from all over the world have been characterized. It is clearly indicated in Figure 5.9 that MSW data of a geographic origin is defined in precise zones in the triangular diagram.

Class A	Class B	Class C
Soils	Paper	Food waste
Metals	Cardboard	Yard waste
Glass	Rugs and textiles	Animal waste
Ceramics	Leather	Undersieve (Φ <20 mm)
Construction debris	Plastics and rubber	
Ash	Diaper	
Wood	Tires	

Table 5.2	Elementary	Categories	for technical	Classification


Figure 5.8 (a) MSW composition in the U.S. A. on 50 data between 1965-1995, (b) MSW composition in Rome (Italy) on 16 data between 1980-1989 (from Grisolia et al, 1995).



Figure 5.9 MSW compositions in the world on 83 data between 1960-1995 (from Grisolia et al, 1995).

Chapter 6

6. AIMS AND OBJECTIVES OF THESIS

6.1 Aims

This thesis aims to address some of the immediate research requirements for modelling landfill hydraulics. Its primary aim is to investigate the unsaturated hydraulic properties of the landfilled waste. Therefore, this leads to two principal objectives:

- To establish the moisture retention curve of landfilled waste using a modifid pressure plate apparatus
- To measure the unsaturated hydraulic conductivity of landfilled waste using onestep outflow test method of Passioura (1976).

6.2 Objectives

This chapter highlights the approach and methodology that have been employed in this thesis to accomplish the two specific aims as identified above. Each aim will be discussed in more detail below. With the purpose of achieve the above aims realistically within the resources of this thesis; the study has proceeded with the following specific objectives:

1. Development of a laboratory method to establish moisture retention properties of landfilled waste.

Perform a desk study to investigate the suitability of the most commonly used suction measurement techniques for MSW.

Development of the modified pressure plate apparatus and testing procedure. Perform initial tests on compacted silty-sand specimens to investigate the problem of air diffusion through a high air entry value porous plate.

Prepare a representative synthetic MSW sample based on waste at Lyndhurst landfill site, Australia, for which detailed moisture content and waste composition data are available (Yuen, 1999) and establish information on the composition, density and phase relations.

Establish the moisture retention curve of compacted MSW sample using modified pressure plate apparatus.

2. Establish the MSW moisture diffusivity and hydraulic conductivity using Passioura's (1976) laboratory one-step out-flow technique.

Perform a desk study to investigate the suitability of the most commonly used techniques for unsaturated hydraulic conductivity measurement techniques for MSW.

Run one step outflow determination on the same MSW sample using the modified pressure plate apparatus.

Use Passioura's (1976) one step outflow method with independently measured water retention data to predict unsaturated hydraulic conductivity. Compare the unsaturated hydraulic conductivity of MSW determined using Passioura's (1976) one-step outflow test method with that predicted using van Genuchten's model and measured moisture retention data.

6.3 Brief description of Work Devised to Meet Listed Objectives

6.3.2 Measurement of Moisture Retention Curve of MSW

There is limited information regarding in-situ distribution of moisture with depth in MSW landfills. The absorptive capacity of MSW is often characterised using the term field water capacity. However, the absorptive capacity of waste is often quoted as a single-valued parameter, which is a function of physical properties such as waste composition, density, porosity and age (El-Fadel, 1997; Yuen, 1999).

In this study, the mechanisms of moisture retention within the landfilled were investigated for the purpose of characterising the moisture distribution within MSW landfills. As a novelty the moisture retention and movement of landfilled waste are linked to those of an unsaturated soil in this thesis. In other words, moisture retention in waste is a function of its position relative to the phreatic surface whereas with a uniform field water capacity, no such variation in moisture can be accommodated.

During the early phase of the research, a desk study was carried out to investigate the suitability of a number of instruments and techniques those are available for the measurement of pore suction in soils for establishing the moisture retention curve of MSW. In MSW wide pore and particle size ranges complicate the measurement of suction. Furthermore, complex and changing leachate chemistry undermines the calibration of some of measurement techniques. This thesis has described modifications to a commercially available pressure plate apparatus for measuring the water retention curve of large specimens of 230mm diameter and 140mm height.

Using this equipment, the author determined the moisture retention curve of a synthetic waste sample, based on waste at Lyndhurst landfill site, Australia, for which detailed moisture content and waste composition data are available (Yuen, 1999). An important part of this study is to establish a synthetic waste sample in which detailed information on the composition, density and phase relations are available. This data is shown to be useful information to assess the measured moisture retention curve of the waste sample.

6.3.2 Measurement of Water Diffusivity and Hydraulic Conductivity of MSW

Despite the significance to modelling landfill hydraulics, unsaturated hydraulic conductivity of landfilled waste has never been measured in the laboratory or in the field. Experimental procedures are usually time consuming, require sophisticated equipment and substantial expertise. Most of the time, these experimental methods proposed in the literature are difficult to implement as they involve extremely low flow rates, especially high suctions. As a result many landfill researchers have focused on pore-structure models for predicting unsaturated hydraulic conductivity in which most of them are based on water retention data.

In this study, unsaturated hydraulic conductivity of MSW was measured by Passiouras's (1976) one-step outflow method. One step outflow determination was run on the same MSW sample using the same apparatus. The moisture retention curve measured for this sample was used to determine the unsaturated hydraulic conductivity. The results were compared with the van Genuchten's (1980) pore-structure model.

6.4 Summary

This chapter sets out a research program which aims to establish hydraulic properties of landfilled waste. In particular, a laboratory based research for determination of moisture retention characteristics and unsaturated hydraulic conductivity of MSW was investigated, in which most of the required equipment is available at reasonable cost. Such an investigation is original and provides useful insights to develop more realistic landfill hydraulics models.

Chapter 7. MEASUREMENT OF MOISTURE RETENTION CURVE OF MUNICIPAL SOLID WASTE

7.1 Introduction

The importance of moisture retention curve of MSW in relation to landfill hydraulics has been highlighted in previous chapters. A number of instruments and techniques that are available for the measurements of suction in soils are introduced in Chapter 2. By comparison with soils, MSW is more heterogeneous, more compressible, has wide range of particle and pore size ranges, and is biodegradable material. These characteristics complicate the measurement of moisture retention characteristics of MSW.

The principle aim of this chapter is to present a laboratory method which can be devised to investigate the moisture retention characteristics of MSW. Detailed information on the composition, density and phase relations of a compacted sample will be investigated with the method described by McDougall et al. (2004). Technical classification of the sample is provided according to Grisolia et al. (1995). Finally the measured moisture retention curve this waste sample will be presented.

7.2 Selection of Suction Measurement Technique for MSW

In MSW, wide pore and particle size ranges complicate the measurement of suction; therefore large volume samples are required. Furthermore, a complex and changing leachate chemistry through changes in osmotic soil water potential, can affect the suction measurements. For this reason, a desk study was carried by the author to investigate the suitability of the most commonly employed suction measurement

techniques for MSW. The following is the discussion of advantages and pitfalls of each of these techniques using to establish the WRC of MSW.

7.2.1 Direct Measurement Techniques

There are two direct suction measurement techniques; tensiometers and pressure plate apparatus. In direct measurement techniques, the soil water system is in hydraulic contact with the body of water, usually by the use of a water-wetted porous plate. Kelvin's equation can be used to determine the equivalent pore diameter (D) of the porous ceramic plate (or porous cup) at the specific matric suction. Kelvin's equation is given below:

$$P = \frac{4T_s \cos \alpha}{D}$$
 equation 7.1

where P is the pressure difference between air and water interface $(u_a - u_w)$,

 T_s is the surface tension of the wetting fluid,

and α is the contact angle of fluid interface to solid.

The contact angle, α , between the air and water interface and the solid particles can be assumed to be zero. Surface tension of water is 72.75 x 10⁻³ N/m at 20⁰ C. Therefore, the equivalent pore diameter corresponding to the air water interface is given by:

$$D = \frac{4T_s}{(u_a - u_w)} \quad \text{equation 7.2}$$

Using the above equation, the pore diameter of 500 kPa air entry porous plate is calculated as 0.582×10^{-6} m. Considering the hydrated diameter of the most common ions (such as Al⁺², Cl⁻¹, K⁺¹, Ca⁺, and Mg⁺²) vary between (1- 2) x 10⁻⁹ m (Mitchell, 1993), it is believed that dissolved chemical salt molecules are small enough to pass through the ceramic plate so no osmotic potential develops between the sample and the water change measuring system.

Matric suction measurements with a conventional tensiometer have a limitation of 100 kPa. Suction probe is able to measure suctions up to 1500 kPa, however, large

amount of ions found in leachate is a source of cavitation nuclei which can increase the possibility of suction probe to loose saturation during measurements of suction greater than 100 kPa. Also a good contact between the coarse MSW and small surface of tensiometer probe is difficult to establish. The limited contact with the liquid phase may restrict the moisture flow and can cause the probe to have large reading oscillations (Villar and Compos, 2002).

7.2.2 Indirect Measurement techniques

Filter paper method is the most common indirect measurement technique as it has many advantages over the other indirect methods because of its simplicity, its low cost, its ability to measure a wide range of suctions (Leong et al, 2002). There are several aspects of filter paper and other indirect methods which must be identified before using it to measure water retention characteristics in MSW. These are:

- Range and accuracy
- Calibration
- Effects of salt and organic and inorganic ions.

The accuracy of the filter paper method is dependent on the moisture-suction relationship of the filter paper; therefore, calibration procedure of the filter paper is important. The calibration curve can change over time as the organic and inorganic ions concentrations in leachate change with different age and conditions of MSW within the landfill. Furthermore, a different calibration curve is required as the composition of landfilled waste varies, from site to site and with time. There is published experimental evidence supporting this concern. Ridley and Edenmosun (1999) compared matric suction measurements, using filter paper and suction probe, on a silty clay prepared using a 0,25 molar solution of sodium chloride. They concluded that the equilibrium water content of the filter paper reduces when there is salt present in porous medium. This is shown in Figure 7.1.

Ridley et al (2003) presented the difference between measurements using suction probe and measurements using filter papers on samples removed from the ground.

Figure 7.2 shows measurements of suction made on samples of London Clay taken from a site investigation in Leigh-on-Sea, Essex. Measurements were made with filter papers placed in contact with the samples and with suction probes. The measurements from the filter papers gave very high suctions and would have suggested that there was a high excess in-situ suction most probably caused by dessication. However, the measurements with the suction probe were much smaller and lay close to the expected in-situ stress profile, suggesting that there was no excess in-situ suction. Moreover, the moisture content profiles were consistent with the area of Essex in which the investigation took place suffered considerable flooding early 1950s when sea breached the costal defences. This could have resulted in a large quantity of salt being deposited in the soil and the suctions estimated by the filter paper being too high.



Figure 7.1 Comparison of filter paper matric suction measurements and suction probe measurements on a silty clay which is prepared using a 0.25 molar solution of sodium chloride (From Ridley et al., 2003).



Figure 7.2 Comparison of the filter paper matric suction measurements and suction probe measurements on a natural soil from a region with high in-situ salt deposits (from Ridley et al., 2003).

Ridley et al. (2003) also discussed that it is essential to maintain intimate contact between the specimen and the filter paper. In places where the specimen and the filter paper are not making contact the transfer of moisture will occur partly through the vapour phase and the time to reach equilibrium will increase. A good contact between the coarse MSW and filter paper is difficult to establish. This limited contact with the liquid phase may restrict the moisture flow and can cause delay of moisture equilibrium which can lead to errors.

7.3 Modified Pressure Plate test

The pressure plate apparatus has several advantages over the other methods for establishing the water retention properties of MSW. The main advantages of this method are:

- It is a direct method, no calibration is required
- It can measure matric suction up to 1500 kPa.

• It is unaffected by soluble salts and organic and inorganic ions in leachate.

A commercially available pressure-plate extractor has been modified to establish the water retention curve of a large sample over suction ranges of 0-500 kPa. This suction range is particularly relevant for the simulation of leachate recirculation in MSW. In the pressure-plate apparatus, a pressure difference is maintained between the pore air pressures, u_a , controlled using a compressor, and the pore water pressure, u_w , which is at atmospheric pressure, by the surface-water interface in a saturated high-air entry value.

The drying moisture retention curve is measured by first saturating the specimen, and then applying u_a in a series of increments to achieve different suction values (ψ). Each increment in u_a causes water to be expelled from the specimen until the water content in the specimen is in equilibrium with the value of ψ that has been established. Additional increments in u_a are applied only after outflow from the specimen has ceased. The volume of water expelled during each increment is measured to define the water content corresponding to each suction increment. When the soil is nearly dry or sufficiently dry for the problem being analysed, the wetting moisture retention curve can be measured using the same procedure, except u_a is incrementally decreased.

Conventionally, in the pressure plate apparatus, the sample is removed and the volume of the water expelled at each suction increment is measured by weighing. Since a good hydraulic contact between the porous plate and the specimen is difficult to make when specimen is replaced on the plate, a number of identical specimens are used with one being removed for each weighing and then discarded.

The particle and pore size distribution of MSW means that multiple specimens in a standard pressure plate apparatus are out of the question, however, the pressure plate test can be modified to make volumetric measurements of the expelled water on one large 250 diameter specimen. The water volume change in the specimen with each pressure increment is measured continuously using a burette connected to the pipe which carries water discharge from the ceramic disc. There is an advantage with this

technique, that is, equilibrium of water content in the specimen with the applied matric suction can be visually confirmed. However, this method has a shortcoming. Gas can dissolve and diffuse through the liquid in the ceramic and come out of solution in the water volume measuring system. The presence of the gas in the measuring system will distort measurements of the volume of water expelled from the sample.

A further modification to the basic set-up can be made to allow the volume of diffused air to be removed and measured by attaching an air-trap between the pressure chamber and the graduated burette. The layout of the experimental set-up is shown in Figure 7.3. (a) and (b). A liquid circulation system, driven by the peristaltic pump, is used to move pockets of air, which accumulate adjacent to the ceramic plate, to the air-trap. Liquid free of bulk air then flows back into the pressure plate cell where it re-joins the liquid discharge pipe through a y-piece mounted inside the pressure plate adjacent to the ceramic plate. To remove the diffused air in the air trap, the valve on the air-trap is opened until the air is flushed out by the water from the burette. The difference of burette readings before and after the air removal is equal to the air diffused.



Figure 7.3 a) Schematic diagram of the experimental set-up and b) detail of the circulation device in the pressure cell.

7.4 Initial Test

Although the experimental set-up described in section 6.4 will be used to establish the water retention properties of MSW, a number of initial tests have been run to investigate the problem of air diffusion through a high air-entry value porous plate and the performance of the modified water and air volume measuring system. These tests were performed on a compacted silty-sand specimen of 98 mm diameter and 35 mm height. The hysteretic water retention curve obtained for this specimen is shown in Figure 7.4 including main drying curve (MDC), main wetting curve (MWC) and a primary wetting curve (PWC) as defined section 2.2. The volume of water expelled from the specimen and diffused air at various matric suctions during drying test are presented in Figure 7.5. The air-trap was used to remove the air from the measuring system regularly every 24-48 hours to determine the change of volume of water in the specimen between the two successive suctions. Equilibrium is assumed to have been established when the level of water in the burette drops to the same point after allowing air to diffuse for 24 hours. This indicates that the movement of water expelled from the specimen at the applied matric suction has ceased. It may be noted that the volume of diffused air collected in the air-trap became significant only after the air pressure was elevated to 90 kPa. The dashed line in Figure 7.5 shows the level of the water expelled from the specimen with the increased matric suction after removal of diffused air.



Table 7.1 van Genuchten soilmoisture parameters

	MDC	MWC
θr	0.060	0.060
$\theta_{\rm s}$	0.340	0.340
α	0.055	0.10
n	2.80	2.20
m	0.643	0.545
The second second second	Contract of the second second	

Figure 7.4. Water Retention Curve of Compacted Silty-Sand Specimen.



Figure 7.5. Cumulative outflow (ml) of moisture expelled from the sandy silt sample versus elapsed time (minutes) before and after diffused air is removed from the measuring system.

A series of suction increases were applied to an initially saturated sample to measure the MDC. Upon reaching the θ_r , applied suction was decreased. The resulting MDC and MWC data, shown in Figure 7.4, were collected over a period of four months. van Genuchten parameters fitted to experimental data for the main curves are given in Table 7.1. The sample was dried to 30 kPa suction, and then re-wetted to 15 kPa. The drying process, beginning from a saturated state, follows MDC, but the reversal at 30kPa is well below θ_r so subsequent wetting follows a PWC.

The soil used in this study is compacted sandy silt, which has a relatively low matric suction range compared to fine-grained soils of high clay content. Table 7.2 summarises some properties of the soil. Suction equilibrium in the specimen was assumed to have been reached when the change in moisture volume was less than 0.2 ml/day, which corresponds to a change of 0.0009 cm3/cm3 in the sample.

Specific gravity (Mg/m ³)	2.68
Dry unit weight (kN/m ³)	17.25
Void ratio	0.52
Sand content (%)	0.43
Fines content (%)	0.57

Table 7.2 Properties of the test soil

Diffused air measurements from a different test (Figure 7.6) are consistent with a Fickian diffusion process and the constant coefficient of air permeability over the pressure gradient range in question, i.e. there is a linear relationship between the volume rate of diffused air and the air pressure gradient applied.



Figure 7.6. Rate of Diffused Air through High Air-Entry Value Porous Plate

7.5 MSW Sample Preparation

The physical, mechanical, and hydraulic behaviour of MSW is more complex than that of the most soils. The initial composition of a typical MSW involves many components with different properties. It is usually difficult to extrapolate the results obtained from one situation to another because of this difference in initial composition. Grisolia et al. (1995) presented a standard MSW classification criterion which may help in predicting the hydro-mechanical behaviour of MSW. A brief description of this method will be presented in this section. The MSW sample compacted in laboratory for studying its suction characteristics with modified pressure plate apparatus will be classified using this method.

In a typical MSW three distinct phases present – solid, liquid, and gas. The volume of these phases usually varies with depth of the landfill. There is also a need to distinguish between the immobile moisture in micropores and free liquid in large drainable macropores. An extended phase description of MSW which distinguish the immobile micropore moisture which is retained in solid organic fraction of MSW and free moisture that is retained in large macropore system of MSW at low suction values is necessary. McDougall et al. (2004) described a practical method of back-calculating the in-situ phase composition of waste with depth using cell-averaged mass, volume and moisture data. The in-situ phase calculations are based on the data obtained at the Lyndhurst sanitary landfill in Victoria, Australia. The phase composition is extended to distinguish between the organic and inorganic fractions of the solid phase and immobile and free moisture fractions of the liquid phase. Description of this method will also be presented in this section. The phase composition of the compacted MSW sample will be established with this method. This will provide some benchmark information on the moisture retention properties.

7.5.1 Pressure Plate Sample

In this study, a laboratory scale waste sample was prepared, which has similar initial composition to waste in Lyndhurst landfill site. The sample was compacted in a retaining ring of 230 mm diameter and 140 mm of height with dry density equal to the cell averaged density of Lyndhurst waste. The side and top view of the compacted

pressure plate sample are shown in Figure 7.7 (a) and (b). Table 7.3 presents the fractional composition and associated mass of the individual components of the sample. The sample was compacted to the mould using a modified proctor hammer in three layers with 25 blows for each layer. Prior to compaction, 880 grams of water has been added to the sample to ease the compaction. Then the sample was placed in a tray and saturated by adding water from the top surface of the sample. Water was infiltrated through the sample creates a water table at the base of the sample. Figure 7.7 (a) shows the saturated sample with a water table at the base. At three different times within 24 hours period, total 3000 grams of water was added to the sample in this way. In addition to this, 2000 grams of water was sprayed to the top surface of the sample with a wash bottle in next 24 hours. This ensures that moisture is absorbed by the sample and not infiltrate to the base through large pores which does not have moisture retention properties.

Later the sample was covered with cling film to prevent evaporation. After this, sample was allowed to take in moisture from the base. The mass of the sample was monitored for 48 hours to ensure that the sample was saturated to the highest moisture content as possible. Mass of the sample was stabilised at 5631 grams which corresponds to volumetric moisture content of 40%.

In order to measure the fully saturated volumetric moisture content, θ_s and porosity, n, sample was sealed with a few layers of cling film and placed on a scale. Then the sample was inundated with water. The fully saturated mass of the sample was measured as 6678 grams. This information provides to calculate the total voids of the sample as 3373 cm³ which gives the porosity of the sample as 0.58. After the cling film at the base was removed, sample was put into the tray again until moisture content is stabilised again. When the moisture content of the sample is approximately equal to the same volumetric moisture content before the sample was inundated, it is placed in the pressure plate apparatus.



Figure 7.7 Compacted pressure plate sample (a) side view (b) top view

Technical classification of the pressure plate sample and Lyndhurst waste is given in Figure 7.8 according to Grisolia et al (1995). The overall solid phase unit weight (γ_s) of the sample is calculated as 13.3 kN/m³ as shown in Table 7.4. The phase composition of the sample is shown in Figure 7.9. Calculation of phase volumes using this method shows excellent agreement with volumes and weights of the individual components of actual sample. Measured porosity is equal to the total volume of voids calculated for a unit volume of compacted sample. The total porosity, n, of the sample can also be estimated on the basis of the measured dry density and specific gravity of solids (G_s) using the following equation:

$$n = 1 - \frac{\rho_{dry}}{G_s \rho_w}$$

equation (7.3)

Where ρ_w is the density of water ($\approx 1 \text{ gr/cm}^3$). The specific gravity of solids is 1.33 gr/cm³. The resulting total porosity is 0.574 which has a very good comparison to the measured porosity (0.58) and calculated porosity (0.574) according to McDougall et al (2004). Calculating the weight of the organic and inorganic components of the sample using the extended phase composition also provides good agreement with actual weights of the sample.

	Constituents	Composition (% by dry mass)	Dry mass in sample (kg)	Contribution to water content (kg)	Fraction (% by dry mass)	
ORGANIC	Paper	12	0.390	0		
	Food	13	0.435	0.360		
	Timber	5.5	0.180	0	43	
	Garden	9	0.295	0.265		
	Textile	3.5	0.115	0		
INORGANIC	Plastics	6	0.200	0		
	Metal	3	0.100	0	57	
	Glass	2	0.060	0		
	Inert/cover	46	1.530	0 (Oven dried)		
Water added to sample before compaction (kg)				0.880		
TOTAL		100	3.305	1.505		

Table 7.3 Constituents of pressure plate sample



Figure 7.8 Technical classification of pressure plate sample according to Grisolia et al (1995).



Figure 7.9 Extended phase composition of the waste sample similar in composition with the Lyndhurst waste prepared in laboratory for pressure plate test.

Table 7.4 Calculation of organic and inorganic fractions and solid phase for waste constituents of pressure plate sample.

	Constituent	P _i ^a Fractional composition (dry weight)	γ _{di} b (kN/m ³)	γ _{sati} c (kN/m ³)	γ _{si} ^d (kN/m ³)	P _i / γ _{si} (kN/m ³)	Fraction (by weight)	Fraction (by volume)
	Paper	0.120	4	12	20	0.006		
Organic	Grdn/Food/Timber	0.275	5.8	8.7	8.2	0.034	43%	0.64
	Textile	0.035	3	6	4.3	0.008		
Inorganic	Plastic	0.060	11	11	11	0.005	57%	0.36
	Metal	0.030	60	60	60	0.001		
	Glass	0.020	29	29	29	<0.001		
	Inert/Cover	0.470	18	20	22.5	0.020		
Total		1.00				0.075	100%	1.00

7.6 Moisture Retention Curve of MSW and Discussion7.6.1 Moisture Retention Data

The moisture retention curve of MSW has been obtained using the modified pressure plate apparatus up to a maximum suction of 200 kPa. The moisture content suction data for the pressure plate sample is presented in Figure 7.10. The resulting moisture retention curve data were collected over a period of seven months. The sample was treated with bactericide before the pressure plate test to inhibit biodegradation, therefore, moisture retention properties of MSW sample will not change with time. van Genuchten water retention function provides a good description of the moisture content-suction data and it is commonly used in simulating unsaturated moisture flow through porous media. Therefore, it is considered in this study to fit the experimental data of MSW sample. Van Genuchten parameters for the measured water retention data are given in Table 7.5. It should be noted that although there is a good general fit over greater part of the suction range, the saturated moisture content is shown at a suction of 0.1 kPa as a matter of practicality. Unfortunately, this data point cannot be measured using the pressure plate apparatus and the saturated moisture content was determined by inundation of the sample as explained in section 7.5. The difficulty in establishing this part of the moisture retention curve for MSW should be noted as a limitation of the method.

There is a subsequent reduction of moisture content in the sample just after the seal (cling film) is removed. The moisture content stabilises at static equilibrium where suction head is equal to the height of the sample. Moisture content-suction data corresponds to 40% and 1.4 kPa (140 mm), respectively at this condition. Note that the sample is now in contact with the saturated porous plate with the air pressure equal to atmospheric pressure. Since the larger portion of the macropores does not have water retention properties, a distinct air entry pressure cannot be measured at which the sudden drainage of the macropores occurs.

After this, the air pressure is elevated step-wise to 5 kPa, 10kPa, 30 kPa, 100 kPa and finally 200kPa. Figure 7.11 shows the discharge rate (ml/day) and time to

achieve equilibrium for pressure plate test on MSW sample. As the matric suction is increased to higher values such as 100 kPa and 200 kPa, the moisture content decreases apparently asymptotically towards moisture content value of 13 - 14 %. This is one of the key features of the moisture retention curve and indicates that residual moisture content is approached at which further removal of moisture requires vapour migration. Therefore, the drying test was terminated when suction equilibrium is achieved at 200 kPa.







Figure 7.10 Moisture retention curve of compacted waste sample obtained using modified pressure plate apparatus.

Times Required for Equilibration

Klute (1986) and Wang and Benson (2003) described the equilibrium conditions as no outflow of water from the soil for at least 24 hours. Klute (1986) indicates that equilibrium conditions using a pressure plate occur in a 20-30 mm high soil specimen within 2 to 3 days for most soil types. Chao (1995) reported that time required to achieve equilibrium for measurements using clays ranged from 20 to 25 days. Miller (1996) reported that 7 to 14 days is required for equilibrium using clays. Burger and Shackelford (2001) indicate that equilibrium is achieved for measurements using pelletised diatomaceous earth material at approximately 8 days for the lower suction of 100 kPa using a pressure plate. They also discussed that equilibrium is not attained within 14 days for higher suction of 230 kPa. The author observed equilibrium conditions of a compacted silty sand specimen of a 98 mm diameter and 35 mm height during measurement of main drying curve using modified pressure plate apparatus. Time required to achieve equilibrium for low suction values of 0-30 kPa ranged from 2 to 3 days. 5 to 7 days are required for relatively higher suctions of 30-80 kPa. Equilibrium is not attained within 7 to 8 days for higher suction values of 130-280 kPa. Outflow from the sample did not cease and continue to drain at rates 0.2 mL/day, which corresponds to a change of 0.009 cm³/cm³ in the sample. When this discharge rate was reached, it was assumed equilibrium and air pressure is elevated to the next suction value. Time required for equilibrium during wetting test was longer that during test at the same magnitude of suction.

The data in Figure 7.11 indicate that suction equilibrium in MSW is achieved at approximately 25 days for the lower suction values of 5 kPa, but it is not attained within 62 days for the higher suction values of 30 kPa. Moisture in the macroscopic region between individual waste particles drains rapidly while the water in the microporosity region within each waste particle is most likely held more strongly due to smaller pores and more complicated flow paths for water flow. Additionally the water phase may become discontinuous around an individual waste particle and limiting the outflow water from within the waste. At higher suctions of 100 kPa and 200 kPa, relatively lower discharge rates are observed, as shown in figure 7.11.

It can be concluded that one of the limitations of the use of pressure plate apparatus to measure the moisture retention characteristics of MSW is that long times are required to reach suction equilibrium at high suctions. These comparatively long equilibrium times should be related to two major reasons:

- low unsaturated hydraulic conductivity that occurs generally at high suctions in any porous medium at low degree of saturation and,
- the longer drainage path (height of sample) in MSW sample compared to soil samples used in pressure plate tests.



Figure 7.11. Rate of discharge (ml/day) versus time (days) data of MSW sample using modified pressure plate apparatus.

7.6.2 Interpretation of Moisture Retention Data of MSW Sample

Links between the following will be established;

- measured moisture retention properties of the MSW sample;
- the in-situ moisture content measurements with neutron probe technique in the test cell at Lyndhurst (Yuen, 1999);
- the extended phase composition based on the surface and base locations of Lyndhurst waste; and
- the pressure plate sample.

Results of these analyses will be interrelated as pressure plate sample is compacted to the cell average dry density of Lyndhurst waste and has similar composition.

Post-Capping Moisture Profiles in MSW Landfills

When the moisture retained in MSW is in hydrostatic equilibrium, the moisture retention curve represents the equilibrium moisture content with depth profile. Without the external climatic effects, the moisture content profile changes instantaneously to its post-capping equilibrium state upon completion of infilling. Knowledge of the post-capping moisture profile at Lyndhurst provides a reference data to interpret the results of measured moisture retention curve (Figure 5.3) with the modified pressure plate apparatus. Therefore, the measured moisture retention curve will compared with the with the post-capping depth-dependent equilibrium moisture profile of Lyndhurst test cell.

Comparison of Saturated Moisture Content

It has been shown in section 7.5 that the calculated saturated moisture content of the pressure plate sample (according to McDougall et al., 2004) has an excellent agreement with the measured saturated moisture content. The volumetric moisture content corresponds to porosity when porous material is fully saturated. There is variation in waste density with depth, therefore, measured saturated moisture content of the sample cannot be directly related to in-situ moisture measurements at the base of Lyndhurst landfill.

On the other hand, there is a consistent comparison between the calculated saturated moisture content (McDougall, et al., 2004) and in-situ measured moisture contents at the base of at Lyndhurst test cell. The saturated moisture content value of pressure plate sample has a good correlation with the calculated saturated moisture contents at surface and base locations of Lyndhurst waste.

Residual Moisture Content

Based on the in-situ measurements, the post-capping depth dependent equilibrium moisture profile of Lyndhurst waste was represented as by a linear function (eq 6.3) in which the surface moisture content (gravimetric) was assumed as 25% (McDougall et al., 2004). When the moisture retained is in hydrostatic equilibrium, the moisture retention curve can be considered as an equilibrium moisture content. From this standpoint, it can be proposed to set this surface moisture content equal to the relatively immobile moisture retained by the solid organic fraction of MSW in a wide range of hydraulic and loading conditions. The measured retention curve exhibits a similar behaviour to this assumption. At high pore suctions of 100-200 kPa moisture equilibrium has apparently asymptotic behaviour which corresponds to 25 % gravimetric moisture content at cell average density in Lyndhurst waste.

Air-Entry Suction

Author has already discussed to the difficulties of establishing the saturated moisture content in MSW and the consequences for the air entry value (related to α). At the start of the pressure plate test, the volumetric moisture content of the waste sample was only 40%.

In practice, drainage of the larger pores in MSW (of the order of millimetres) will occur at even lower suctions than the elevation head of sample height. Presence of these large macro pores which has no or very low water retention mechanisms may suggest that moisture retention curve of MSW is bimodal shape in which the data corresponding to low suctions cannot be measured. The measured retention data is fitted with bimodal van Genuchten function consistent with Smetten and Kirkby (1990) (equation 2.26) is shown in Figure 7.12. This figure only aims to illustrate that MSW sample has very low water retention mechanisms in large pores and there is no measured data point within macro pore region.



Figure 7.12. Moisture retention data of pressure plate sample modified to account for the macropores.

Table 7.6 Van Genuchten bimodal curve-fir parameters for compacted MSW sample.

	fi's	0.58	
	θj	0.425	
Macro-porosity region	Ψj (kPa)	0.4	
	α	12	
	n	5	
Micro-porosity	θj	0.425	
region	Ψj (kPa)	0.4	
	θr	0.12	
	α'	0.350	

7.7 Summary

This chapter describes a laboratory test programme devised to establish the moisture retention characteristics of a compacted waste sample. The results indicate

- the moisture retention in landfilled waste is a function of its position to phreatic surface, i.e. fully saturated condition at the base of the landfill
- complications due to leachate chemistry are minimised using modified pressure plate apparatus
- extended phase composition established according to McDougall et al. (2004) has excellent agreement with the actual sample volumes.
- there are difficulties of establishing the saturated moisture content in MSW using pressure plate apparatus due to presence of large pores of order of millimetres
- Presence of these large macro pores, which have no or very low water retention mechanisms may suggest that moisture retention curve of MSW is bimodal shape.

Chapter 8

8. LABORATORY OUTFLOW TECHNIQUE FOR MEASURMENT OF MSW WATER DIFFUSIVITY AND HYDRAULIC CONDUCTIVITY

8.1 Introduction

Pore-structure models, such as van Genuchten-Mualem model, predict the unsaturated hydraulic conductivity from the saturated conductivity and moisture retention function. These models establish a macroscopic hydraulic conductivity as a function of an effective saturation, based on an integration of the volume of saturated pores and their contribution to flow according to Poiseuille's equation. Considerable success has been achieved with this approach in the case of inert soils.

In contrast, MSW is more heterogeneous and more compressible than soils and is biodegradable, which leads to a changing phase composition and pore structure. A moisture retention curve for a representative waste sample has been presented in Chapter 6. However, it has not yet been shown that pore structure models lead to a meaningful prediction of unsaturated hydraulic conductivity in MSW.

One aim of this study is to introduce the use of pressure plate outflow technique for estimation of MSW moisture diffusivity and unsaturated hydraulic conductivity. The unsaturated hydraulic conductivity of MSW determined using this predictive approach of van Genuchten-Mualem will be compared with that obtained using Passioura's (1976) one-step outflow test method.

8.2 Soil Water Diffusivities and One-Step Outflow Experiments

Laboratory outflow experiments are simple to perform and have been extensively used as a means of determining hydraulic diffusivity in soils. The method is based on the relationship between the volume of water expelled from an initially saturated sample following a step-wise gas phase pressure increment, or series of increments (Gardner, 1956, 1962; Kunze and Kirkham, 1962; Miller and Elrick, 1958). Originally, for reasons of accuracy, the gas pressure was changed in small increments so that the diffusivity, $D(\theta)$, may be assumed to be constant over each pressure increment. This approach required many time-consuming measurements for small changes in soil suction to define the entire $D(\theta)$ curve thereby limiting the usefulness of the method.

Gardner (1962) improved this method by replacing the requirement of several equilibrations with a single step change in gas pressure increment. This procedure for obtaining the soil water diffusivity has since been termed the "one-step" method (Doering, 1965; Gupta et al., 1974). Gardner (1962) used the separation of variables technique to solve the diffusion equation for flow of water in soil sample. By assuming $D(\theta)$ to be constant over the length of the sample, he showed that diffusivity may be calculated from the instantaneous rate of outflow, average volumetric moisture content, and the dimensions of the sample.

Doering (1965) further simplified Gardner's (1962) outflow method without loss in accuracy. However, Gupta et al., (1974) reported that, using Doering's analysis, estimates of the diffusivity function were not in good agreement with the measured data. Gupta et al., (1974) introduced additional modifications to the outflow method so that an assumption of uniform diffusivity over the sample length is not needed, but the computations required to calculate $D(\theta)$, however, were too complicated for routine use at that time (Passioura, 1976; Jaynes and Tyler, 1980).

Passioura's contribution (1976) was to simplify the computations by assuming that the rate of change in moisture content, $\partial \theta / \partial t$ is approximately uniform over most of the sample at any given time. Passioura's method offered an estimation of soil hydraulic

diffusivity for more routine use. The tests require no expensive or sophisticated instrumentation, being performed in the pressure plate apparatus (Green et al., 1998). Initial results were encouraging. Jaynes and Tyler (1980), using a Buchner funnel, compared Passioura's method to an in-situ crust method with satisfactory results. They presented the unsaturated hydraulic conductivity, $K(\psi)$ of three soil: Plainfield Sand, Ringwood Silt Loam, and Plano Silt Loam, which was measured using one-step outflow method of Passioura (1976). Comparison of these $K(\psi)$ values with values previously measured in situ for the same soils with the crust test has a satisfactory agreement. Jaynes and Tyler (1980) showed that Passioura's one-step outflow method also yields satisfactory results near saturation. The $K(\psi)$ values measured for Plainfield Sand and Ringwood Silt Loam with one-step outflow procedure are shown in Figure 8.1 (a) and (b). Passioura's method was also used by Borcher et al. (1987) on undisturbed samples of a fine-grained soil. van Dam et al. (1990) also found that combining one step outflow method with independently measured water retention data provided unsaturated hydraulic conductivities that were in good agreement with other laboratory methods.

8.3 Passioura's Method: Theoretical Background

The method is based on the assumption that the rate of change of water content, $\partial \theta / \partial t$, is approximately uniform over most of the draining soil sample at any given time.

Neglecting gravity, the nonlinear partial differential equation of water flow in onedimension is,

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left(D(\theta) \frac{\partial \theta}{\partial x} \right)$$
 equation 8.1

where x is a coordinate dimension, t is time, and $D(\theta)$ is the soil water diffusivity.



Figure 8.1 The 95% confidence interval for the mean hydraulic conductivity as a function soil water pressure potential measured in situ and the curves measured with one-step method for three samples (a) PF1, PF2, PF3, of the Plainfield Sand (b) R1, R2, R3, of the Ringwood Silt Loam (from Jaynes and Tyler, 1980).

In Passioura's one-step outflow method, an initially saturated soil sample (θ_i) is subjected to an increment of gas pressure at the upper surface (x = L, where L is the height of the sample). The outflow is measured at the base (x = 0) until the soil water content reaches an equilibrium with the gas pressure. It is assumed that volumetric water content at x = 0 is reduced to the final water content (θ_f) instantly, i.e. at the onset of outflow. The initial and boundary conditions of such a system are given as:

 $\theta = \theta_i \qquad \qquad 0 \leq x \leq L \qquad t = 0$

 $\theta = \theta_{f}$ x = 0 t > 0 equation 8.2 $\frac{\partial \theta}{\partial x} = 0$ x = L t > 0

Passouira goes on to identify three main stages of outflow, as shown in Figure 7.2. The first stage (I) is controlled by the ceramic plate and its resistance to flow at x = 0; the cumulative outflow (Q) during this stage is proportional to the time, t. Outflow rate then decreases as a reducing soil diffusivity controls the flow and the soil water content at the bottom end (x = 0) of the sample reaches θ_f . This is the second stage (II) in which the soil sample behaves as a semi-infinite column, and Q is linear function of \sqrt{t} (Crank, 1956; Passioura, 1976). When this linear relation ceases, stage III of the outflow starts and the boundary condition at the top end of the soil (x = L) begins to influence the flow. Moisture content (θ_L) decreases and the cumulative outflow curve is no longer linear with respect to \sqrt{t} . This is the stage when the assumption of a uniform rate of change of water content over most of the soil column is used to determine D(θ_L).



Figure 8.2 Cumulative outflow versus \sqrt{t} , showing the three stages of outflow.

Passioura (1976) presented the rate of change of water content, $\partial\theta/\partial t$ (normalised with respect to $\partial\theta^*/\partial t$) as a function of x/L and the mean water content θ^* . He obtained the curves by numerically solving the flow equation (8.1) subject to boundary conditions given equation (8.2) with D(θ) as an exponential function of θ . Passioura proved that $\partial\theta/\partial t$ varies slightly with x providing x is not close to zero and providing θ is not close to θ_i or θ_f . This is shown in Figure 8.3 and proves that Doering's (1965) method which is based on a constant D(θ) is valid.

Passioura (1976) shows that diffusivity at x = L, $D(\theta_L)$ can be calculated from the experimental outflow data using,

$$D(\theta_{L}) = \frac{dF}{dW} \frac{L^{2}}{2}$$
 equation 8.3

where the diffusivity is measured in cm^2/min , L is the sample height (cm), F is the rate of outflow (cm³/min) and W is the volume of water remaining in the soil at any time (cm³). Note that whilst the diffusivity is defined at x = L, the outflow data relate to sample-average moisture contents. It is therefore necessary to determine the moisture content at x = L in order to define strictly the diffusivity.



Figure 8.3 the rate of change of water content, $\partial \theta / \partial t$ (normalised with respect to $\partial \theta^* / \partial t$) as a function of x/L and the mean water content θ^* . (from Passioura, 1976).

Since $\partial \theta / \partial t$ is independent of x during the third stage of outflow, the difference between θ_L and the mean water content θ^* , denoted by δ , is constant.

Passioura also shows that when $\theta_L >> \theta_f$, δ is given by,

$$\delta = \theta_{\rm L} - \theta^* = \frac{0.61}{\rm B} \qquad \text{equation 8.4}$$

where B is obtained from the slope of the $\ln[D(\theta_L)]$ vs θ^* curve at $\theta^* = (\theta_i + \theta_f)/2$.

When θ_L approaches θ_f , D(θ) tends to a constant value throughout the sample and the relation $\theta_L = \theta^* + \delta$ breaks down. In this case, Passouira suggested using the relation obtained by Gupta et al. (1974).

$$\delta = \frac{\theta_{\rm L} - \theta_{\rm f}}{\theta^* - \theta_{\rm f}} = \frac{\pi}{2}$$
 equation 8.5
A graphical method is used to obtain θ_L values corresponding to the calculated $D(\theta)$ values based on equations (8.4) and (8.5). Plotted as a function of θ^* and smoothed in the region where the two lines meet.

 $K(\theta)$ values corresponding to the calculated $D(\theta)$ values are then determined using the measured water retention curve and the conventional relation

$$K(\theta) = \frac{\partial \theta}{\partial \psi} D(\theta) \qquad \text{equation 8.6}$$

8.4 Materials and Test Methods

One-step outflow test requires no expansive or sophisticated instrumentation and could be used to calculate $K(\theta)$ using simple computer techniques. The test was run on the modified pressure plate apparatus described in Chapter 7 and used for measuring the moisture retention curve of a synthetic waste sample based on waste at Lyndhurst landfill site, Australia. The same sample was used for one-step outflow test. The moisture retention curve measured for this sample is used to determine $K(\theta)$ values corresponding to the calculated $D(\theta)$ values using the relation given in equation (8.6).

After the moisture retention curve determination, the sample was resaturated as described in Section 7.5. Then the sample was placed in the pressure plate apparatus and the water level in the burette levelled to the bottom of the sample. The air pressure in the pressure plate was set to 100 kPa in one step increment. The outflow was recorded at 15 minutes interval for the first 6 hours with increasing time intervals thereafter. The outflow test was continued for more than 2.5 months to reach moisture equilibration with the applied air pressure. Trapped air was removed as described above during the outflow measurements. The volume of moisture expelled from the sample during the outflow experiment after removal of experiment is shown by the dashed line in Figure 8.4.



Figure 8.4. Cumulative outflow (ml) of moisture expelled from the MSW sample versus elapsed time (days) before and after diffused air is removed from the measuring system.

8.5 Calculation Steps

A spreadsheet template was compiled for the routine calculation of the one-step outflow data following Passiura 1976). The following steps are required too complete the calculation:

- 1. Copy the values of θ_i , θ_f (initial and final water contents), length of the core (L) and core volume (V) from the first part of the template files (ONESTEP) to a new worksheet (WORKING).
- 2. Copy the outflow data (cumulative outflow Q (cm³) from the second page of the template files (called OUTFLOW) to the WORKING sheet.
- 3. Calculate the square root of time and add as a new column.
- 4. Plot Q versus t^{0.5} and find the time when the stage III starts, i.e. the time when the linear relation between Q and t^{0.5} ceases.

- 5. Discard any measurement points where outflow change is zero.
- 6. Calculate the volume of water remaining in the soil (W) at each time step from:
- 7. Calculations start from the equilibrium (last) entry; $W = \theta_f * V$
- 8. At each time step (i) then working backwards, $Wi = Wi+1 + \Delta Qi$
- 9. ΔQ is found by differencing the Q entries (e.g. $\Delta Q2 = \Delta Q3 \Delta Q1$).
- 10. Calculate the rate of outflow F (cm3 h-1) by dividing the differences in Q by the differences in time (t) (e.q. F2 =(Q1 Q3) / (t1 t3).
- 11. Using the data from stage III only, try fitting the different functions (polynomials, power law, or exponential) to F-W data. Graph the results and choose the function which gives a better fit. This is important as the curve must be monotonic.
- 12. Using the function from step 8, calculate the fitted F values for each value of W.
- 13. Calculate dF/dW from fitted F values using central differencing, i.q., $(dF/dW)^2 = (F1 F3)/(W1 W3)$.
- 14. Calculate D from D = dF/dW * (L2/2).
- 15. Add a column for lnD.
- 16. Calculate $\overline{\theta} = W/V$ for each entry.
- 17. Plot lnD versus $\overline{\theta}$. Find the slope of this curve at the point $\overline{\theta} = (\theta_i + \theta_f)/2$. Call the slope B. Then calculate $\delta = 0.61/B$.
- 18. Calculate θ_i values as $\theta_i = \overline{\theta} + \delta$.
- 19. Calculate $\theta_k = \theta_f + \frac{\pi}{2} \times (\overline{\theta} \theta_f)$

- 20. Plot θ_j and θ_k versus $\overline{\theta}$ on the same graph.
- 21. From this graph we derive θ_L versus θ . Smoothing in the region where the two lines meet can be done by drawing a line between midpoints of them. Find the intersection point of the two lines (θ_j and θ_k versus θ). Then find the mid points of lines past the intersection point (θ m₁, and θ m₂). A line is drawn between these two points (Figure 6.4).
- 22. For each $\overline{\theta}$ enter θ_L from 18 following the rules:

23. If $\theta > \theta m 1$	=>	$\theta_{\rm L} = \theta + \delta$	read off the θ_j line
24. If $\overline{\theta} > \overline{\theta} m2$	=>	$\theta_{\rm L} = \theta_{\rm f} + \frac{\pi}{2} \times \left(\overline{\theta} - \theta_{\rm f} \right)$	read off the θ_k line
25. If $\overline{\theta} m 2 < \overline{\theta} < \overline{\theta} m 1$	=>	$\theta_{\rm L} = a \overline{\theta} + b$	calculated in step 17.

- 26. Where a and b are the slope and intercept of the line calculated in step 18.
- 27. This completes the $D(\theta_L)$ versus θ_L calculation.
- 28. To determine $K(\theta)$ versus θ , first copy the soil water characteristics data to the working sheet.
- 29. Taking natural log of suction (ψ) and water content (θ), Find the slope [d(ln ψ)/d(ln θ) of the moisture retention curve at each entry using forward differencing (consecutive entries) (refer to example calculation in appendix 1).
- 30. For each θ_L value, find the corresponding (ψ) value by linear interpolation on the natural log scale, using values in step 22. The slope of the moisture retention curve is determined using forward differencing (consecutive entries) (refer to example calculation in appendix 1).

8.6 Results and Discussion

As the saturated hydraulic conductivity of our waste sample was not measured, a range of K_S values based data obtained by Beaven (2000) for a typical UK waste was used in the van Genuchten hydraulic conductivity model, equation (2.23) and (3.26). Figure 8.5 shows $K(\theta)$ for the compacted waste sample measured by Passioura's method and that predicted by the van Genuchten function. The results show that van Genuchten's predicted $K(\theta)$ and experimental $K(\theta)$ do not match over the entire moisture content range. Measured and predicted $K(\theta)$ show a good agreement at low moisture content (high suction) if K_S is taken to be about 5×10^{-4} m/s. This value is consistent with saturated hydraulic conductivities found in a crude household waste under this low level of loading, e.g. Beaven (2000), suggesting that the mechanism of flow at low moisture content in waste is referable to the type of unsaturated flow analysis used in more conventional soils.

At higher moisture contents, the agreement between measured and predicted hydraulic conductivities diverges. This may be attributed to the presence of very large pores in waste. We have already alluded to the difficulties of establishing moisture contents at very low suctions in MSW, in effect of defining an air entry value (related to α). In fact, at the start of the outflow test, the volumetric moisture content of the waste sample was only 40%. We should recall that the van Genuchten pore structure model was devised for more conventional soils and may therefore assume a pore structure and pore size distribution that is inappropriate for waste.



Figure 8.5 Unsaturated hydraulic conductivity of MSW. One-step outflow tests results compared with van Genuchten predictions using data from Table 1 and K_s values of $1x10^{-4}$ m/s and $1x10^{-5}$ m/s.

8.7 Conclusion

Passioura's (1976) one-step outflow method has been used to determine unsaturated hydraulic conductivity in compacted MSW. It is a laboratory method using only readily available equipment. The experimental results have been compared with predictions from van Genuchten's (1980) hydraulic model. The measured and the predicted $K(\theta)$ values do not agree over the entire range. Good agreement is obtained at low moisture contents, suggesting that the mechanism of flow at low moisture content in waste is referable to the type of unsaturated flow analysis used in more conventional soils. At high degrees of saturation the agreement is poor. It would appear that the relationship between the air entry value, α , and its role in depicting the start of desaturation needs to be revised for materials with very large pores such as MSW.

Chapter 9

9. CONCLUSIONS AND RECOMMENDATIONS

Modelling moisture transport and leachate generation processes in MSW landfills using saturated-unsaturated flow theory was first proposed in early 1980's. The accuracy of the saturated – unsaturated flow models is dependent on the validity of the fundamental hydraulic properties of the porous medium. One of the main challenges to the simulation of flow behaviour in a landfilled site has been the characterisation of the unsaturated hydraulic properties of MSW. This study has produced one of the first comprehensive information on how moisture retention curve and unsaturated hydraulic conductivity of MSW can be obtained. The first part of this chapter summarises the findings of this study, and finally, a number of topics for future investigation are recommended in section two.

9.1 Summary of the Findings

In the early chapters of this thesis, a case was made for the comprehensive investigation of the unsaturated hydraulic properties of landfilled waste. A laboratory program has been undertaken to establish the moisture retention characteristics and unsaturated hydraulic conductivity of MSW. The findings of the previous chapters are summarised below under the specific objectives of thesis aims.

9.1.1 Moisture Retention Characteristics of MSW

A review of published work on landfill hydraulics modelling and the fundamental hydraulic properties which was used to establish the landfill hydraulic models was accomplished in Chapter 4. At the beginning of this study, there exists a very limited research dealing with moisture retention characteristics of MSW. Therefore, successful

modelling of moisture movement within a landfill using unsaturated flow theory was constrained by a lack of understanding of the nature of moisture retention in landfilled waste.

One major aim of this thesis was to highlight the role of the moisture retention curve in landfill hydraulics and then present a laboratory method by which the water retention properties of MSW can be measured. The summary of the work carried out and findings are discussed below.

Importance of Moisture Retention Curve

It is an empirical fact that MSW is capable of retaining considerable amount of moisture within micropores and macropores throughout the depth of landfill. The absorptive capacity of MSW is often characterised using the term "field water capacity". Field water capacity is defined as the amount of moisture that a porous medium can retain against downwards gravity drainage after a period of rain or leachate recirculation. In waste, the difference between the initial moisture content and its field water capacity is referred to as the absorptive capacity. Leachate is discharged when the moisture content in waste exceeds its field water capacity. However, the field water capacity of waste is often quoted as a single-valued parameter, which is a function of physical properties such as waste composition, density, porosity and age (El Fadel, 1997; Yuen, 1997).

However, author believes that field water capacity of MSW is more properly defined as the moisture content in hydrostatic equilibrium with the current hydraulic boundary conditions which will vary with elevation. It is obvious from the fundamental nature of moisture retention curve describing the moisture distribution above the leachate at mound at the base of landfill (phreatic surface). The amount of moisture retained in a unit volume of MSW at equilibrium under field conditions depends on the elevation of this unit volume above the phreatic surface. Over time, moisture contents are modified by precipitation during infilling phase and/or leachate recirculation. At any elevation, once the gravity drainage has materially ceased, a certain amount of moisture is retained in the landfilled waste. This equilibrium moisture distribution is dictated by the moisture retention curve. Consequently, absorptive capacity is the difference between the current and equilibrium moisture content, which also varies with elevation.

In addition, moisture retention curve contains valuable information within it and is of primary importance in understanding the movement of moisture within the landfilled waste. The slope of the curve represents the storage characteristics of MSW. The slope of the moisture retention curve indicates the amount of moisture taken on or released by the MSW as a result of change in pore suction.

Experimental Program

The conventional laboratory methods have practical limitations for determination of pore suction of MSW. During the early phase of the research, the suitability of a number of instruments and techniques those are available for the measurement of pore suction was investigated for establishing the moisture retention curve of MSW. Determination of pore suction of waste requires a method that takes into consideration of the complications due to waste pore and particle size range and leachate chemistry. Standard pressure plate apparatus was modified to take account of these complications offers an acceptable solution and allows for as large a sample as possible. By observing certain limitations, the method was successfully applied to establish the moisture retention curve of a non degrading synthetic waste sample based on waste at Lyndhurst landfill site, Australia, for which detailed moisture content and waste composition data available.

The modified pressure plate test allows volumetric measurements of the expelled moisture on a large 230 mm diameter specimen over suction ranges of 0-500 kPa. There is an advantage with this technique, that is, equilibrium of water content in the specimen with the applied matric suction can be visually confirmed.

The moisture retention properties of the sample waste under a range of hydraulic pressure potentials are being studied using the modified pressure plate apparatus. The measured moisture retention data is presented in Chapter 6 together with a functional interpretation of the data using van Genuchten's expressions. In general, waste moisture moisture retention data showed that compacted sample behaves similar to unsaturated soils which suggests moisture retention in waste varies with its position to the phreatic surface. With uniform field water capacity concept, no such variation in moisture can be accommodated.

Equilibrium moisture contents were established during the test for 5 kPa, 10 kpa, 30 kPa, 100 kpa, and 200 kPa, respectively. At high matric suction values, such as 100 kPa and 200 kPa, the moisture content decreases apparently asymptotically towards the moisture content value of 13-14 %.

Moisture retention data suggests that dual porosity exists in landfilled waste. Larger portion of the macropores does not have water retention properties, therefore, a distinct air entry pressure cannot be measured at which the sudden drainage of the macropores occurs.

Two main limitations were observed during the experimental work:

- 1. The saturated moisture content of compacted waste was determined by inundation. There is a difficulty of establishing initial desaturation part of the moisture retention curve.
- 2. The resulting moisture retention curve data were collected over a period of seven months.

9.1.2 Unsaturated Hydraulic Conductivity of MSW

In order to consider flow in both the saturated and unsaturated zones of a landfill, the saturated and unsaturated hydraulic conductivity of the landfilled waste must be known at all points in both the saturated and unsaturated zones within the landfill. The saturated hydraulic conductivity of MSW can be obtained using the standard laboratory and field procedures. However, direct measurement of the unsaturated hydraulic conductivity was never been attempted until the beginning of this study. Unsaturated hydraulic conductivity of MSW was evaluated based upon its moisture retention characteristics.

One objective of this study was to compare unsaturated hydraulic conductivity values for MSW measured by Passioura's (1976) one-step outflow test method with predictions using van Genuchten's (1980) pore-structure model. This is a laboratory based model for

the determination of unsaturated hydraulic conductivity in which the required equipment is available at reasonable cost.

The results showed that the measured and the van Genuchten predicted unsaturated hydraulic conductivity values do not agree over the entire range

Good agreement can be obtained at low moisture contents. This suggests that the mechanism of flow at low moisture contents in waste is similar to that in soil.

There is a poor agreement at high degree of saturation. This is attributed the difficulty of measuring retention properties of large pores at low suction values and the applicability of the van Genuchten model to such a material.

9.2 Recommendations for Further Work

Based on the results of experimental work carried out for this thesis, a number of opportunities for future research have been identified.

9.2.1 A Dataset for Unsaturated Hydraulic Properties of MSW

Generally, all that is required for landfill hydraulic modelling purposes is an estimate of unsaturated hydraulic properties of landfilled waste. However, laboratory testing can be expensive and time consuming for each modelling application, particularly for large unsaturated MSW sample.

A database can be established for experimentally measured moisture retention curves and unsaturated hydraulic conductivity of MSW sample compacted with different composition and dry densities. MSW samples should be classified according to the method of Grasiola et al. (1995). MSW samples should be prepared in a method to cover different zones in the triangular diagram in Figure 5.9. This will provide the modeller to select the most comparable dataset for the modelling of a particular landfilled waste in which the geographical origin, density and composition is known.

The proposed experimental testing is suggested to cover the impact of different compaction effort on moisture retention and unsaturated hydraulic conductivity in waste, particularly to the effect of dual porosity nature of the material.

9.2.2 A New Dual Porosity Model

One-step outflow experiments on MSW have highlighted the difficulty of defining moisture retention and conductivity properties in dual porosity systems, i.e. over a range of suctions in which distinct micro- and macro-pore domains are present. It was concluded from these tests (Kazimoglu et al., 2005) that hydraulic conductivity at low moisture contents is adequately represented by predictive functions such as van Genuchten's (1980), however, at high moisture contents, the agreement between the experimental data and predicted hydraulic conductivities is lost.

Recommended study explores the constitutive and numerical consequences of extending van Genuchten's moisture retention curve function to capture the retention and conductivity properties in a dual-porosity material. Each pore domain is defined by a van Genuchten function with associated parameters. In dual porosity material, two van Genuchten functions are combined to describe the complete moisture retention curve. This formulation can depict the very large pore sizes in waste refuse and requires the introduction of only three additional parameters. Moreover the soil water capacity, i.e. the derivative of the moisture retention curve, is calculated as before thus only relatively simple modifications to model codes are required.

Chapter 10

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