Waste Management 38 (2015) 222–231

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Functional relationships for the estimation of van Genuchten parameter values in landfill processes models

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ARTICLE INFO

Article history:
Received 14 June 2014
Accepted 15 December 2014
Available online 5 January 2015

Keywords:
Landfill
Modelling
Gas
Leachate
Recirculation
Unsaturated

ABSTRACT

Numerical models of landfill processes need to be able to estimate the capillary pressure and relative permeability of waste as a function of moisture content using analytical equations such as the van Genuchten equations. The paper identifies the range of van Genuchten parameter values for use in models and proposes a formulaic relationship between these parameter values and saturated moisture content.

The concept of porous material, its behaviour under unsaturated conditions and Mualem's integral transform equation that estimates relative permeability from capillary pressure are reviewed. The application of the algebraic form of the capillary pressure function proposed by van Genuchten and its application using Mualem's transform to obtain the van Genuchten algebraic functions for relative permeability are discussed.

Functional relationships are identified between saturated moisture content and the van Genuchten parameters using a database of results from other sources. These relationships may be used in numerical modelling of unsaturated flow in landfilled waste where the saturated moisture content varies significantly as the result of compression, settlement and degradation.

A 2D numerical model simulation of leachate recirculation is used to investigate the sensitivity of the simulation to the introduction of these functional relationships. It is found that the transient liquid and gas flows across the model boundaries appear to be insensitive to whether or not the functions are incorporated into the model algorithm. However it is observed that using the relationships does have some impact on the distribution of the degree of saturation throughout the model and on the transient behaviour of the way in which the recirculation recharges the waste. However it is not thought that this impact would be sufficient to influence the design of a leachate recirculation system.

1. Introduction

The leachate and gas flow algorithms used by numerical landfill processes models depend on the specification of the functional relationships between capillary pressure, relative permeability and moisture content of the waste material being modelled. The parameter values in the algebraic equations that have been developed to represent these relationships, for example Brooks and Corey (1966), van Genuchten (1980), are calibrated from the results of laboratory tests on samples of the waste materials. Not unexpectedly these parameter values exhibit a considerable degree of variability, reflecting to a great extent the variability of the waste material itself. It has however been noted by Stoltz et al. (2012), Zardava (2012) that, in the case of the van Genuchten equation parameters, there is some evidence that the variability may be partly accounted for by the parameter values being sensitive to the saturated moisture content or porosity of the sample being tested.

In a landfilled waste material the saturated moisture content changes significantly both spatially and with time as the result of compression, settlement and degradation. The decrease in saturated moisture content with depth is particularly evident, (Powrie and Beaven, 1999). It would be of value therefore if it were possible to develop functional relationships that realistically reflect the variability between the van Genuchten parameters and saturated moisture content. This possibility is explored in this paper and a method is proposed for utilising the relationships in a landfill processes model. The sensitivity of the results of an exemplar landfill model simulation to these second order effects is explored.

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http://dx.doi.org/10.1016/j.wasman.2014.12.014
0956-053X/

Nomenclature

Symbol (units)			
d_t	pore-network throat diameter, see Eq. (2) (m)	θ	volumetric moisture content
h	pressure head, see Eq. (1) (m)	ζ	degree of saturation, $=\theta/\theta_S$
k	relative permeability, see Eq. (1)	E	superscript denoting 'effective'
K	permeability, see Eq. (1) (m/day)	G	superscript denoting gas phase
p	pressure (kPa)	L	superscript denoting liquid phase
n	van Genuchten equation parameter, see Eq. (5)	MAX	superscript denoting maximum value
m	van Genuchten equation parameter, see Eq. (5)	MIN	superscript denoting minimum value
T	surface tension of liquid, Eq. (2) (N/m)	P	superscript denoting phase. Liquid phase $P = L$, gas phase $P = L$, solid phase $P = S$
v	Darcy velocity, see Eq. (1) (m/day)	w	superscript denoting weighted value
x	co-ordinate direction	C	subscript denoting capillary pressure
α	van Genuchten equation parameter, see Eq. (5)	D	subscript denoting dry density
δ	Mualem correlation power law index, see Eq. (4)	R	subscript denoting residual moisture content or residual degree of saturation
ε	Mualem pore throat diameter power law index, see Eq. (4)	REL	subscript denoting relative value
φ	porosity, $=\theta_S$	S	subscript denoting saturated moisture content
ϕ	meniscus contact angle, Eq. (2) (degrees (°))		Note on units: force kN, mass kg, time days.
ρ	density (kg/m^3)		

2. Aims

The aims of this paper are (1) to identify the practical range of van Genuchten parameter values for use in the numerical algorithms describing fluid flow in landfill processes models and (2) to propose a formulaic relationship between these parameter values and the local saturated moisture content which is generally subject to significant variability both spatially and with time.

3. Background

The flow algorithms of numerical models of landfill processes are usually based on the hypothesis that the transport of gas and liquids through waste deposits, such as municipal solid waste (MSW) and mechanically and biologically treated waste (MBT) in landfills, has characteristics similar to those observed in naturally occurring porous materials such as soils and fissured rocks (Moody et al., 1992; Tate and Rodwell, 1995; El-Fadel et al., 1996; McDougall et al., 1996; McCreanor and Reinhart, 1999; Lobo et al., 2002; White et al., 2004; Kindlein et al., 2005; Bente, 2011). Specifically, it appears that the saturated and unsaturated flow of gas and liquid may be quantified by using Darcy's Law, Eq. (1), together with appropriate relative permeability functions, see for example (Powrie and Beaven, 1999; Stoltz et al., 2010), and that the capillary pressure/moisture content characteristic, $p_C(\theta)$, of waste materials plays a similar role to those found in natural materials (see sources referenced in Table 1).

$$v_x^P = -k_{REL}^P(\theta)K_x^P\frac{\partial h^P}{\partial x} \quad (1)$$

Powrie and Beaven (1999), Stoltz et al. (2010) have also noted that the waste porosity ϕ, which is equal to the saturated volumetric moisture content θ_S, is related to compression, settlement and waste degradation, and that this impacts on the values of waste permeability so that in general, the saturated permeability reduces with porosity (saturated moisture content).

The pore space geometry of a porous material is often conceptualised as a collection of variable sized pores connected into a network by narrow throat like channels in which the throat diameters are small in comparison with the pore sizes. The concept is extended further by assuming that, when a pressure is applied to a sample, such as in a hanging column or pressure plate apparatus, the pores drained are those connected by pore throats that have a throat diameter d_t for which the pressure difference across a gas/liquid interface within the throat can overcome the surface tension forces. The relationship between this pressure difference, the capillary pressure $p_C = p^G - p^L$, and d_t is usually assumed to be the Young–Laplace equation, Eq. (2),

$$p_C = \frac{4T\cos\varphi}{d_t} \quad (2)$$

where p^G and p^L are the pressures in the gas and liquid phases in the pore network; T is the surface tension, which for a water/air interface is about 0.07 N/m; and φ is the contact angle between the liquid meniscus and the surface of the pore throat.

Thus the application of a small capillary pressure of 1 kPa would drain all of those pores connected to a network in which the pore throats were greater than 0.28 mm (for $\varphi = 0°$). As the capillary pressure increases more drainage paths with smaller pore throat diameters are mobilised and a greater fraction of the pore space is drained resulting in a reduction of the moisture content θ. Whilst the relationship $p_C(\theta)$ exhibits some hysteresis depending on whether or not the material is draining or imbibing, it can be seen from Eq. (2) that its inverse $\theta(p_C) = \theta(d_t)$ represents a geometric characteristic of the waste pore space geometry since it gives the fraction of the pore volume connected by throats with diameter d_t.

The slope of this characteristic was used by Mualem (1976) to provide a weighting factor to obtain a weighted average throat diameter, $d_t^w(\theta)$ for the region of the pore space that was saturated by a moisture content of θ. Conceptually when $p_C(\theta)$ becomes very large, θ tends to a residual moisture content, θ_R, defined as the minimum moisture content achievable by the application of a capillary pressure. The variable θ may thus be conveniently replaced by ς_E, the effective degree of saturation defined as:

$$\varsigma_E = \frac{\varsigma - \varsigma_R}{1 - \varsigma_R} \quad (3)$$

Note that ς_E lies in the range zero to 1. ς_E falls to zero when the actual degree of saturation, $\varsigma = \theta/\theta_S$, reaches the residual degree of saturation, $\varsigma_R = \theta_R/\theta_S$, and becomes 1 when $\theta = \theta_S$.

Mualem (1976) identified two distinct approaches for obtaining the functions $k_{REL}^P(\theta)$ or $k_{REL}^P(\varsigma_E)$ for use in Eq. (1). The first involves the direct measurement of $k_{REL}^P(\varsigma_E)$, which is extremely difficult, (Lam et al., 1987). The second is an indirect method in which $k_{REL}^P(\varsigma_E)$ is obtained from $p_C(\varsigma_E)$ (which is more readily measured,