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PEDOTRANSFER FUNCTIONS FOR VARIOUS TROPICAL SOIL TEXTURES

(NURADDEEN MUHAMMAD BABANGIDA)

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PEDOTRANSFER FUNCTIONS FOR VARIOUS TROPICAL SOIL TEXTURES

NURADDEEN MUHAMMAD BABANGIDA

A project report submitted in partial fulfilment of the

requirements for the award of the degree of

Master of Engineering (Civil – Hydraulic and Hydrology)

Faculty of Civil Engineering

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To my Parents; who had to endure a whole year without a helping son. To my wife Ummul-Khair; who had to live several moments of her early marital life without a loving husband. And to my daughter Halima; who had to live her tender days and take her first step without a Father's helping hand.

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ABSTRACT

The determination of soil hydraulic properties is of paramount importance, as they are needed in many models of water and solute transport in soils. However conventional methods are quite difficult, expensive and sometimes cumbersome to use, and hence the use of *pedotransfer functions* (PTF). Most studies of PTF are for temperate soils, of which were found to be erroneous when extrapolated to tropical region. Parameters of soil water retention models of Brooks & Corey (1964), van Genuchten (1980) and Kosugi (1996) were optimised by fitting them to 191 water retention datasets, using visual *basic for applications* (VBA) & solver add-in in *Microsoft* (MS) excel. The optimised parameters were used to estimate soil water characteristics of 10 different tropical soil textures (ISSS classification), of which the Kosugi (1996) model was found to give the best prediction. Parametric PTF using *multiple linear regression* (MLR) which relates basic soil data of particle size distribution, bulk density and carbon organic to the parameters of the aforementioned water retention models was also developed. Good linear relationship was found between saturated moisture content and basic soil data for all 10 textures. The MLR model was also found to be generally good for silty soils, and sand and poor for clayey soils. Furthermore parametric PTF for clayey soils was developed using *artificial neural network* (ANN), and the model indicated some strong relationship between basic soil data and hydraulic model parameters for heavy clay, and a weaker relationship in the case of light clay.

ABSTRAK

Penentuan ciri-ciri hidraulik tanah adalah sangat penting, sebagaimana ia diperlukan dalam banyak model air dan pengangkutan bahan larut di dalam tanah. Disebabkan kaedah konvesional agak sukar, mahal dan kadang-kadang rumit untuk digunakan, *fungsi pedotransfer* (PTF) telah digunakan. Kebanyakan kajian PTF ialah untuk tanah sederhana dan tidak boleh diekstrapolasikan kepada rantau tropika. Parameter model pengekalan air tanah menggunakan Brooks & Corey (1964), van Genuchten (1980) dan Kosugi (1996) dioptimumkan dengan menggunakan model-model tersebut untuk 191 set data retensi air dengan menggunakan *visual basic untuk applications* (VBA) & solver add-in dalam *Microsoft* (MS) excel. Parameter yang paling optimum telah digunakan untuk menganggar ciri-ciri air tanah untuk 10 tekstur tanah tropika yang berbeza (pengelasan ISSS), di mana model Kosugi (1996) didapati memberi ramalan terbaik. Parametric PTF menggunakan *regresi linear berganda* (MLR) yang mengaitkan data asas tanah seperti taburan saiz zarah, ketumpatan pukal dan karbon organik bagi parameter ketiga-tiga disebutkan di atas model retensi air telah dibangunkan. Perhubungan linear yang baik telah diperoleh di antara kandungan lembapan tepu dan data asas tanah untuk kesemua 10 tekstur. Model MLR juga telah didapati secara umumnya sesuai untuk tanah berlodak dan pasir tetapi tidak sesuai untuk tanah liat. Di samping itu, parameter PTF untuk tanah liat telah dibangunkan menggunakan *artificial neural network* (ANN), dan model telah menunjukkan beberapa hubungan yang kukuh antara data mengenai asas tanah dan parameter-parameter model hidraulik untuk tanah liat berat, dan hubungan yang lemah untuk tanah liat ringan.

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LIST OF SYMBOLS AND ABBREVIATIONS

ANN	-	Artificial neural network
ANOVA	-	Analysis of variance
ASCE	-	American society of civil engineers
BD	-	Bulk density
CO	-	Carbon organic
GUI	-	Graphical user interface
h	-	Suction
h_B	-	Air entry value for Brooks & Corey (1964) model
h_m	-	Related to capillary pressure at inflection point for Kosugi (1996) model
ISSS	-	International society of soil science
m	-	van Genuchten’s (1980) dimensionless curve-shape parameter
MATLAB	-	Matrix laboratory
MSE	-	Mean square error
n	-	Pore size distribution index
pF	-	log (h)
PSD	-	Particle size distribution

PTF	-	Pedotransfer function
R^2	-	Coefficient of determination
R	-	Coefficient of correlation
RMSE	-	Root mean square error
SSQE	-	Sum of square error
VBA	-	Visual basic for applications
α	-	Inverse of the air-entry value for van Genuchten (1980) model
θ	-	Moisture content
$\theta(h)$, *SWRC*	-	Soil water retention curve
θ_s	-	Saturated moisture content
θ_s	-	Residual moisture content
λ	-	Pore size distribution index for Brooks & Corey (1964) model
σ	-	Dimensionless parameter which decides the effective saturation at the inflection point of Kosugi (1996) model

CHAPTER 1

INTRODUCTION

In recent years there has been a growing interest in the study of water movement in the unsaturated soil zone (vadose zone), this may be attributed to the growing concern that the underground aquifer may be contaminated due to industrial, agricultural and other urban activities.

The unsaturated soil zone or vadose zone has with time been recognised as an integral part of the hydrological cycle, as it plays an important role in many aspects of hydrology such as infiltration, plant water uptake and groundwater recharge (Simunek *et al*. 2006)

Many models, especially computer models are being created nowadays in order to simulate the transport of water and solute contaminants through the vadose zone. These models can only be successful if reliable values of soil hydraulic properties are available.

Hydraulic properties of soil such as *hydraulic conductivity* (K)**,** *soil moisture content* (θ), and *soil water pressure or matric potential* (h) must be determined in order to achieve success with many soil water and solute transport models. These properties can be obtained from 2 different approaches.

1. Measurement techniques (direct or indirect)
2. Predictive Methods

As explained by Haverkamp *et al.* (1999), the first method are for measurement of hydraulic parameters either from laboratory or field measurements, in any case they both entail precise and time consuming procedures. He further concluded that even though laboratory methods allow accurate measurement, the measurements are conducted on field samples, and the effects of cracks, stones, root holes etc., if present, are not accounted for in small scale laboratory experiments, and consequently results in error. Ultimately the result of the field measurement (in-situ) if properly controlled, leads to a more accurate result.

For both field and laboratory measurements, a number of methods exist for the measurement of the hydraulic parameters of soil. e.g. The instantaneous profile or tension disk infiltrometer for determination of hydraulic conductivity; the tensiometer or psychrometer for measurement of soil water pressure; gravimetric method for determination of soil water content to mention a few.

The second method entails the use of easily measureable soil pedological data such as particle size distribution, bulk density, porosity, organic content etc. to estimate the much more difficult hydraulic parameters of the soil. These methods are purely predictive methods. Some researchers see them as transfer functions as they transfer readily available soil data to data we require and are thus commonly referred to as *pedotransfer functions* (PTF). The major focus of this study will be on these predictive functions.

1.1 Predictive Methods

Research in the field of prediction of soil properties was pioneered in 1912 by Briggs and Shantz, however it was not until 1989 that Bouma propose the name pedotransfer functions (Wosten *et al*, 2001).

Basically PTF are theoretical models to predict soil hydraulic properties (e.g. hydraulic conductivity and soil moisture) from other readily available basic soil data (e.g. bulk density, particle size distribution).

With a pool of information about the readily determinable soil parameters lying around in many institutions all around the world, it may be rewarding to collect and analyse such data, and transfer it to what we require. As pointed out by Wosten *et al*. (2001), that the analysis of such pool of data may result in PTF, which may be good predictors of other, required soil hydraulic parameters.

Most of PTF for predicting hydraulic conductivity in the vadose zone are based on statistical pore size distributions models, such as those by Mualem (1976) & by Burdine (1953), they assumed water flows through cylindrical pores and incorporate the Darcy and Poiseville equations of groundwater flow to simulate the actual flow (van Genuchten *et al*. 1991).

The use of closed form equations as PTF requires input in the form of measured retention data, since they contain parameters that are to be fitted to the observed data in order to evaluate these fitting parameters, generally by optimization and subsequently use them to obtain other desired result.

1.2 Applicability of PTFs

PTFs may have wide range of applicability and may result in hydraulic properties of soils for larger/ wider areas compared with measurement methods, this by no means suggest that results of PTF of one location should be applied to another. Results from PTF, just like other methods (measurement techniques) are quite local only that, they may be applicable to wider area, depending on the range of soil data used for developing the function. Consequently they may not be applicable outside the location from which they were developed from (Mermud and Xu, 2006; Partha Pratim *et al*. 2008).

Many PTF have been developed for temperate regions. Soils of the tropical region are known to exhibit different water characteristics from those of temperate regions due to differences in temporal variations. Significant differences between PTF of the tropical and that of the temperate soils have been reported. (Hodnett & Tomasella 2002; Tomasella *et al.* 2003; Partha Pratim *et al*. 2008)

Many parametric PTF have been developed over the years, some of the most frequently used have been the models of van Genuchten (1980) and Brooks and Corey (1964) (Havercamp *et al*. 1999).

Amongst many of PTF models only a few are equipped to estimate both unsaturated hydraulic conductivity (K) and soil water retention (θ), notably are those of van Genuchten(1980), Brooks and Corey (1964), and Kosugi (1996) models.

1.3 Statement of the Problem

Many soil properties can be determined from laboratory or field measurement with minimum effort and time but still there are other very important properties that require lots of time, effort and resources to determine from similar measurements, this result in the development of a way of determining or estimating these properties with least of resources and time; and hence the pedo-transfer functions (PTF). However even with this advancement, study on PTF for tropical soils is still lacking.

1.4 Aim and Objectives

1.4.1 Aim

To estimate the water retention characteristics of tropical soils using various PTFs.

1.4.2 Objectives

1. To evaluate parameters of Brooks and Corey (1964), van Genuchten (1980) and Kosugi (1996) water retention functions using *visual basic for applications* (VBA) and solver add-in, in *Microsoft* (MS) excel.
2. To develop PTF for various tropical soil textures using *multiple linear regressions* (MLR).
3. To develop PTF for selected soil textures, using *Artificial Neural Network* (ANN).

1.5 Scope and Limitations

1.5.1 Scope

1. The study entails use of three (3) different PTF, i.e. the van Genuchten (1980) Brooks and Corey (1964), and Kosugi (1996) functions.

1.5.2 Limitations

1. The study is limited to samples extracted from Askari *et al.* (2008) and that from Tessens & Jusop (1979).
2. Because of limited number of datasets on many samples, PTF using ANN are developed only for heavy clay and light clay soil textures.

1.6 Overview of Methodology

1. Data extraction, classification and grouping for parameter evaluation and formulation of the PTFs.

2. Optimization using VBA and solver add-in in MS excel to obtain fitting parameters of the Brooks and Corey (1964), van Genuchten (1980) and Kosugi (1996) water retention functions.

3. Development of PTF using multiple linear regressions, with the aid of *matrix laboratory* (MATLAB) application.

4. Development of PTF using *artificial neural network* (ANN), using MATLAB.

CHAPTER 2

PEDO-TRANSFER FUNCTIONS

2.0 Introduction

The numerical modelling of water and solute transport through the unsaturated (vadose) zone is of significant importance at present, especially due to the growing number of pollutants percolating through the vadose zone and ultimately ending up in the groundwater. In any numerical model that simulates transport in the vadose zone two important fundamental functions have been identified, viz the soil moisture retention function and unsaturated hydraulic conductivity function (Veerecken 1995; Haverkamp *et al.* 1999; Durner and Fluhler 2005; Mermud & Xu 2006).

The *soil moisture retention curve* $\theta(h)$ describes relationship between *volumetric soil water content* θ and the soil capillary pressure, and the *unsaturated hydraulic conductivity curve* $K(\theta)$ describes relationship between the volumetric soil water content and the hydraulic conductivity K of the soil.

2.1 Hydraulic properties of Soils

Hydraulic properties of soils affect flow behaviour within a soil. In many basic and applied aspects of soil, water, nutrient, and salinity management research, there's need for in-depth knowledge of the hydraulic properties of soil (van Genuchten *et al.* 1999). Almost all models require that hydraulic properties must be parameterized in closed-form expressions for application in the models, and thus the need for proper and accurate approximation of parameters of the parametric function used in the model.

There are a number of these parametric models that are readily used these days in many mechanistic models of water transport in soil. These functions describe none other, than the 2 most important aforementioned soil hydraulic functions.

Based on the two fundamental characteristics identified earlier, the main soil hydraulic properties used in flow model are the *soil water content* (θ), *soil water pressure* (h) and *soil hydraulic conductivity* (K), and between them they combine and give rise to the $\theta(h)$ and $K(\theta)$.

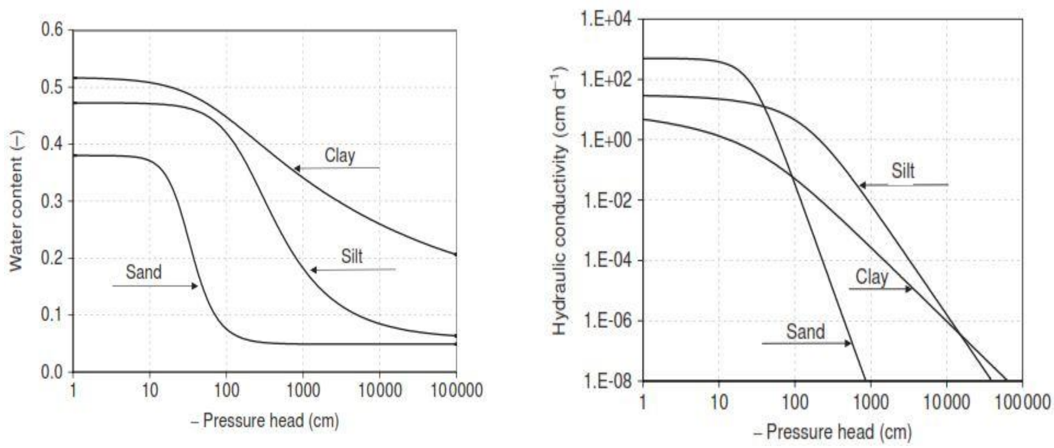
In many literatures and investigations such as van Genuchten (1980), Durner and Fluhler (2005), Haverkamp *et al*. (1999), Stankovich and Lockington (1995), and many others, led to the general expectation about the shape of the $\theta(h)$ and $K(\theta)$ curve for various soil types, which describes the complete moisture retention characteristics and capabilities of that soil. See Figure 2.1.

The $\theta(h)$ is generally a highly nonlinear S-type curve, it describes the ability of a soil to store or release water. At times the hydraulic conductivity function is expressed in terms of soil water pressure, if expressed in terms of volumetric moisture content, then it is strongly nonlinear and generally results in a power function (Haverkamp *et al*. 1999; Durner and Fluhler 2005).

2.1.1 Soil Water Retention Curve and Hydraulic Conductivity Curve

As highlighted above, these two curves represent the two most important soil hydraulic properties (moisture content and hydraulic conductivity) more than anything. The *soil water retention curve* (SWRC) generally represented as $\theta(h)$ and referred in many other literatures as “water retention characteristic curve” , “soil moisture characteristics curve ”, “water characteristic curve” or “pF curve” to mention a few, these terms are also interchangeable used in the course of this literature. Typically the SWRC can be determined from a certain hydraulic process, by simultaneously monitoring the *moisture content* θ and the corresponding *soil suction or pressure h.*

The SWRC Figure 2.1 (a), gives the relationship between the soil water content and the pressure in the soil. Due to the hysteretic effect of water filling and draining the soil pores, different curves may be obtained from the same soil sample, i.e. wetting and drying curves. Likewise the hydraulic conductivity curve Figure 2.1 (b) can be determined from hydraulic process by taking head gradient measurements.



(a) (b)

Figure 2.1: Soil water retention curve (a) & Hydraulic conductivity curve (b) (adopted from Durner & Fluhler 2005)

Because many ground water numerical simulation models require the input of various parameters that govern water flow, the soil water retention curve is expressed in some simple parametric form.

Many functions that describe the water retention in this simple parametric form are available, based on combination of the dependable parameters (θ and *h)* and some independent and fitting variables. Notably amongst such relationships are those proposed by Brooks and Corey (1964), van Genuchten (1980), and Kosugi (1996). Water retention model of Brooks & Corey is given below;

$$\theta = \theta_r + (\theta_s - \theta_r)\left(\frac{h_B}{h}\right)^{-\lambda} \qquad (2.1)$$

Where h is pressure head (generally in cm H_2O) which is negative if expressed as pressure, however it assumes a positive value when referred as matric potential or suction, furthermore it is sometimes for convenience expressed as a log value of h, and called pF value, because it may reach some very high values of more than 15000 cm H_2O.

θ is volumetric water content expressed either in percentage or $cm^3\ cm^{-3}\ H_2O$.

θ_s is saturated water content (maximum amount of water that can be held by the soil expressed either in percentage or $cm^3\ cm^{-3}\ H_2O$), also called field capacity, or porosity in some cases, but in truth this is generally known to be less than porosity due to entrapped air in the voids. It's typically between 5%-10% less than porosity (van Genuchten *et al*. 1991).

θ_r is residual water content, or wilting point, i.e. the immobile water content that can be found within a dry soil profile, expressed either in percentage or $cm^3\ cm^{-3}$ H_2O.

h_B is a dimensionless number that represents the air entry value, sometimes also referred to as pressure scale parameter and λ is the pore-size distribution index.