INTERNATIONAL STANDARD

ISO 15709

First edition
2002-08-15

Soil quality — Soil water and the unsaturated zone — Definitions, symbols and theory

Qualité du sol — Eau du sol et zone non saturée — Définitions, symboles et théorie

Reference number
ISO 15709:2002(E)

PDF disclaimer

This PDF file may contain embedded typefaces. In accordance with Adobe's licensing policy, this file may be printed or viewed but shall not be edited unless the typefaces which are embedded are licensed to and installed on the computer performing the editing. In downloading this file, parties accept therein the responsibility of not infringing Adobe's licensing policy. The ISO Central Secretariat accepts no liability in this area.

Adobe is a trademark of Adobe Systems Incorporated.

Details of the software products used to create this PDF file can be found in the General Info relative to the file; the PDF-creation parameters were optimized for printing. Every care has been taken to ensure that the file is suitable for use by ISO member bodies. In the unlikely event that a problem relating to it is found, please inform the Central Secretariat at the address given below.

ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.ch
Web www.iso.ch

Printed in Switzerland

Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this International Standard may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 15709 was prepared by Technical Committee ISO/TC 190, *Soil quality*, Subcommittee SC 1, *Evaluation of criteria, terminology and codification*.

Introduction

This document provides background information for soil physical investigations of the unsaturated zone. It enables a better understanding of the International Standards used for the determination of soil properties and the status of the soil water (e.g. ISO 10573, ISO 11267, ISO 11274, ISO 11275, ISO 11461, etc.).

Soil comprises an intimate mix of liquids (water), gases and biota within a solid porous matrix. Water is a particularly important soil component. The state of water in a soil changes continually in response to modifications of hydraulic conditions caused by inputs of water (infiltration, upward capillary flux) and/or losses due to evapotranspiration and drainage. Saturated soils generally have a water content of 30 % to 50 % of the total soil volume. In the upper unsaturated layers quantities are smaller, but water content fluctuation with time is marked, from less than 10 % to more than 30 % by volume, depending on the soil and environment. In some cases, for example after heavy rain, in early spring, saturated conditions should also appear.

Knowledge of the quantity of water present in soil is useful. Most soil water is held in pore spaces, although certain soils, e.g. those dominated by smectites or similar minerals, can hold considerable quantities of non-easily-removable water adsorbed on mineral particle surfaces. The size and shape of a pore and the amount of water present within it determine how strongly water is held there and how easily water may flow through it. Water flow occurs in response to potential energy gradients. Therefore information as to the water retention and hydraulic conductivity properties of a soil, as well as field soil water potentials, gives much fuller understanding of soil water conditions. Which of these soil properties should be determined for a particular project will depend on the nature of the problem being studied.

Soil quality can only be defined in terms of the intended use of a soil; e.g. soil water conditions favourable for a natural wetland are not appropriate for grain production, except rice. Soil quality is particularly relevant to environmental issues as well as agricultural production. Soil water characteristics should be known, especially those where the emphasis is on

a) the availability of soil water to sustain plant growth,

b) the maintenance or modification of shallow water table conditions,

c) soil contamination caused by point, line or diffuse sources of pollution.

In addition, soil water is significant to the quality of surface and ground waters. Soil water movement is often the mechanism by which soluble pollutants are transported to surface and ground waters.

Water plays an essential role in the life of plants, directly as such and in transporting nutrients from the soil to and through the plant; it is also crucial to seed germination. Agricultural production depends upon sustaining a supply of water to crops so that water stress is minimized. Excess soil water is problematic, however, for if much of the available pore space is water-filled, lack of oxygen may limit root growth, and in extreme cases lead to plant death. Soil water availability is often significant in determining the character of the natural vegetation which grows in a given location. Maintenance of a given plant community may depend upon regular periods of water stress and/or water excess. Plant water use is driven by the atmospheric evaporative demand. The amount of water available for transpiration is determined by the physical quality of the soil, which can be quantified by several parameters including the soil water content, the water retention curve and the hydraulic conductivity of the unsaturated zone.

In many cases, it is the soil cover which determines recharge rates to the aquifer, as well as discharge due to plant water use, and hence maintenance of water levels. Assessment of the agricultural and environmental impact of shallow ground-water extraction is facilitated by use of soil physical and hydrogeological methods. Measurements of pore-water potentials in both the saturated and unsaturated zones, and of hydraulic conductivities, are essential to understand the direction and rate of water movement.

Pollutants, whether due to diffuse, point or line contamination, are usually transported through soil by water flow. Pollutants are usually transported from the surface by water flow. Many processes influence the fate of a particular pollutant as it moves into and through the soil. Identification of water flow pathways and flowrates is essential to determine pollutant travel times and the possibility of degradation or sorption related retardation. Water and pollutants which move beyond the unsaturated zone cause surface and/or ground water pollution. Soil physical investigations are therefore an important part of pollution studies.

Soil water is relevant to the investigations of several branches of the various soil and earth sciences, including agriculture, forestry, environmental studies, hydrology, hydrogeology and civil engineering. Each has developed its own methods of investigation, many of which overlap. In considering soil water and soil quality for environmental and agricultural purposes, the aim should be satisfactory integration of methodologies to permit the evaluation of soil quality conditions. It is important that organizations dealing with soil quality should have access to standardized methods of soil water measurement, and a standardized set of definitions, units and symbols, so that reliability of determinations is assured, and comparisons with results from elsewhere are possible.

The simplified theory of the physics of soil water in the unsaturated zone in clause 4 is broadly in line with references [3] and [5].

Soil quality — Soil water and the unsaturated zone — Definitions, symbols and theory

1 Scope

This International Standard gives a simplified theory of the physics of soil water in the unsaturated zone and defines a set of terms, quantities, units and symbols used in the field of soil physics investigation of the unsaturated zone.

This International Standard is applicable only to standards on soil physical investigations of the unsaturated zone (including swelling soils) elaborated within ISO/TC 190. This International Standard specifically excludes macropore flow.

2 Terms and definitions

For the purposes of this International Standard, the following terms and definitions, based on [8], [9] and [10], apply.

2.1 General terms

2.1.1
water content
φ_w
⟨volume fraction⟩ volume of water evaporating from the soil when dried to constant mass at 105 °C, divided by the original bulk volume of the soil

NOTE Water content is dimensionless.

2.1.2
water content
w_w
⟨mass fraction⟩ mass of water evaporating from the soil when dried to constant mass at 105 °C, divided by the dry mass of the soil

NOTE Water content is dimensionless.

2.1.3
soil water retention characteristic
$h_\mathrm{m}(\varphi)$
relation between soil water content and soil matric head of a given soil (sample)

2.1.4
hydraulic conductivity
K
factor of proportionality between the soil water flux density and the hydraulic gradient in Darcy's equation, assuming isotropic conditions, i.e. $v = -K\nabla h_\mathrm{h}$

NOTE Hydraulic conductivity is expressed in metres per second $(\mathrm{m \cdot s^{-1}})$.

2.2 Soil water potential and equivalents

2.2.1 Potential

NOTE Potential is expressed in joules per kilogram $(J \cdot kg^{-1})$.

2.2.1.1
total potential

e_t

⟨of soil water⟩ amount of work that must be done in order to transport, reversibly and isothermally, an infinitesimal quantity of water from a pool of pure water, at a specified elevation and at atmospheric pressure, to the soil water at the point under consideration, divided by the mass of water transported

2.2.1.2
pneumatic potential

e_a

amount of work that must be done in order to transport, reversibly and isothermally, an infinitesimal quantity of water identical in composition to the soil water from a pool at atmospheric pressure and at the elevation of the point under consideration, to a similar pool at an external gas pressure of the point under consideration, divided by the mass of water transported

2.2.1.3
gravitational potential

e_g

amount of work that must be done in order to transport, reversibly and isothermally, an infinitesimal quantity of water identical in composition to the soil water from a pool at a specified elevation and the external gas pressure of the point under consideration, to a similar pool at the elevation of the point under consideration, divided by the mass of water transported

2.2.1.4
matric potential

e_m

amount of work that must be done in order to transport, reversibly and isothermally, an infinitesimal quantity of water identical in composition to the soil water from a pool at the elevation and the external gas pressure of the point under consideration, to the soil water at the point under consideration, divided by the mass of water transported

2.2.1.5
osmotic potential

e_o

amount of work that must be done in order to transport, reversibly and isothermally, an infinitesimal quantity of pure water from a pool at the elevation and external gas pressure of the point under consideration, to a similar pool containing water, identical in composition to the soil water, divided by the mass of water transported

2.2.1.6
pore water potential
tensiometer potential

e_p

sum of matric and pneumatic potentials

NOTE In most cases e_a is zero, in which case $e_p = e_m$.

2.2.1.7
hydraulic potential

e_h

sum of matric, pneumatic and gravitational potentials

NOTE In most cases $e_a = e_o = 0$, in which case $e_h = e_t$.

2.2.2 Pressure equivalent

NOTE Pressure is usually measured with a tensiometer; it is expressed in pascals (Pa).

2.2.2.1
pressure
p
pressure equivalent of soil water potential

NOTE Subscripts as for potentials.

2.2.2.2
total pressure
p_t
amount of work that must be done in order to transport, reversibly and isothermally, an infinitesimal quantity of water from a pool of pure water, at a specified elevation and at atmospheric pressure, to the soil water at the point under consideration, divided by the volume of water transported

2.2.2.3
pneumatic pressure
p_a
amount of work that must be done in order to transport, reversibly and isothermally, an infinitesimal quantity of water identical in composition to the soil water from a pool at atmospheric pressure and at the elevation of the point under consideration, to a similar pool at an external gas pressure of the point under consideration, divided by the volume of water transported

2.2.2.4
gravitational pressure
p_g
amount of work that must be done in order to transport, reversibly and isothermally, an infinitesimal quantity of water identical in composition to the soil water from a pool at a specified elevation and the external gas pressure of the point under consideration, to a similar pool at the elevation of the point under consideration, divided by the volume of water transported

2.2.2.5
matric pressure
p_m
amount of work that must be done in order to transport, reversibly and isothermally, an infinitesimal quantity of water identical in composition to the soil water from a pool at the elevation and the external gas pressure of the point under consideration, to the soil water at the point under consideration, divided by the volume of water transported

2.2.2.6
osmotic pressure
p_o
amount of work that must be done in order to transport, reversibly and isothermally, an infinitesimal quantity of pure water from a pool at the elevation and external gas pressure of the point under consideration, to a similar pool containing water identical in composition to the soil water divided by the volume of water transported

2.2.2.7
pore water pressure
p_p
sum of matric and pneumatic pressures

NOTE 1 In most cases p_a is zero, in which case $p_\mathrm{p} = p_\mathrm{m}$.

NOTE 2 Usually the pore water pressure is measured with a tensiometer.

2.2.2.8
hydraulic pressure
p_h
sum of matric, pneumatic and gravitational pressure

NOTE In most cases $p_a = p_o = 0$, in which case $p_h = p_t$.

2.2.3 Head equivalent

NOTE Head is expressed in metres.

2.2.3.1
head
h
head equivalent of soil water potential

NOTE Subscripts as for potentials.

2.2.3.2
total head
h_t
amount of work that must be done in order to transport, reversibly and isothermally, an infinitesimal quantity of water from a pool of pure water, at a specified elevation and at atmospheric pressure, to the soil water at the point under consideration, divided by the weight of water transported

2.2.3.3
pneumatic head
h_a
amount of work that must be done in order to transport, reversibly and isothermally, an infinitesimal quantity of water identical in composition to the soil water from a pool at atmospheric pressure and at the elevation of the point under consideration, to a similar pool at an external gas pressure of the point under consideration, divided by the weight of water transported

2.2.3.4
gravitational head
h_g
amount of work that must be done in order to transport, reversibly and isothermally, an infinitesimal quantity of water identical in composition to the soil water from a pool at a specified elevation and at atmospheric pressure, to a similar pool at the elevation of the point under consideration, divided by the weight of water transported

2.2.3.5
matric head
h_m
amount of work that must be done in order to transport, reversibly and isothermally, an infinitesimal quantity of water identical in composition to the soil water from a pool at the elevation and the external gas pressure of the point under consideration, to the soil water at the point under consideration, divided by the weight of water transported

2.2.3.6
osmotic head
h_o
amount of work that must be done in order to transport, reversibly and isothermally, an infinitesimal quantity of pure water from a pool at the elevation and external gas pressure of the point under consideration, to a similar pool containing water, identical in composition to the soil water, divided by the weight of water transported

2.2.3.7
pressure head
h_p
sum of matric and pneumatic heads

NOTE In most cases h_{a} is zero, in which case $h_p = h_{\mathrm{m}}$.

2.2.3.8
hydraulic head
h_{h}
sum of matric, pneumatic and gravitational heads

NOTE In most cases $h_{\mathrm{a}} = h_{\mathrm{o}} = 0$, in which case $h_{\mathrm{h}} = h_{\mathrm{t}}$.

3 Symbols and units

g acceleration due to gravity, in metres per second squared ($\mathrm{m \cdot s^{-2}}$)

h head (head equivalent of the soil water potential), in metres of water

h_{a} pneumatic head, in metres

h_g gravitational head, in metres

h_{h} hydraulic head = $h_{\mathrm{a}} + h_g + h_{\mathrm{m}}$, in metres

h_{m} matric head, in metres

h_{o} osmotic head, in metres

h_p pressure head = tensiometer head = $h_{\mathrm{a}} + h_{\mathrm{m}}$, in metres

h_{t} total head = $h_{\mathrm{a}} + h_g + h_{\mathrm{m}} + h_{\mathrm{o}} + ...$, in metres

m mass, in kilograms

p pressure (pressure equivalent of the soil water potential), in newtons per square metre ($\mathrm{N \cdot m^{-2}} = \mathrm{Pa}$)

p_{a} pneumatic pressure, in pascals

p_g gravitational pressure, in pascals

p_{h} hydraulic pressure = $p_{\mathrm{a}} + p_g + p_{\mathrm{m}}$, in pascals

p_{m} matric pressure, in pascals

p_{o} osmotic pressure, in pascals

p_{p} pore water pressure = tensiometer pressure = $p_{\mathrm{a}} + p_{\mathrm{m}}$, in pascals

p_{t} total pressure = $p_{\mathrm{a}} + p_g + p_{\mathrm{m}} + p_{\mathrm{o}} + ...$, in pascals

t time, in seconds

v' velocity, in metres per second ($m \cdot s^{-1}$)

v soil water flux density, in metres per second ($m \cdot s^{-1}$)

w_w water content mass fraction

z vertical coordinate (positive upwards), in metres

D water diffusivity, in metres squared per second ($m^2 \cdot s^{-1}$)

K hydraulic conductivity, in metres per second ($m \cdot s^{-1}$)

NOTE $K(h_m)$ is the hydraulic conductivity as a function of h_m,
$K(\varphi)$ is the hydraulic conductivity as a function of φ.

S degree of saturation, (dimensionless)

V volume, in cubic metres

φ water content volume fraction

λ volumetric extraction speed, per second (s^{-1})

ρ_α density of the material α, in kilograms per cubic metre ($kg \cdot m^{-3}$)

ρ_a density of the soil air, in kilograms per cubic metre ($kg \cdot m^{-3}$)

ρ_b bulk density, the density of the three-phase mixture, in kilograms per cubic metre ($kg \cdot m^{-3}$)

ρ_d dry density, the density of the dried solid, in kilograms per cubic metre ($kg \cdot m^{-3}$)

ρ_s density of the solid matter (including the biological components), in kilograms per cubic metre ($kg \cdot m^{-3}$)

ρ_w density of the water (soil solution), in kilograms per cubic metre ($kg \cdot m^{-3}$)

ρ_α' partial bulk density of phase α, in kilograms per cubic metre ($kg \cdot m^{-3}$)

ρ_a' partial bulk density of the soil air, in kilograms per cubic metre ($kg \cdot m^{-3}$)

ρ_s' partial bulk density of the solid particles and the dry bulk density (neglecting the bulk density of air), in kilograms per cubic metre ($kg \cdot m^{-3}$)

ρ_w' partial bulk density of the water (soil solution), in kilograms per cubic metre ($kg \cdot m^{-3}$)

ϕ porosity, (dimensionless)

φ_α volume fraction of phase α

φ_a volume fraction of the soil air

φ_s volume fraction of the solid matter

e potential (of soil water), in joules per kilogram ($J \cdot kg^{-1}$)

e_a pneumatic potential, in joules per kilogram ($J \cdot kg^{-1}$)

e_g gravitational potential, in joules per kilogram ($J \cdot kg^{-1}$)

e_h hydraulic potential $= e_a + e_g + e_m$, in joules per kilogram ($J \cdot kg^{-1}$)

e_m matric potential, in joules per kilogram ($J \cdot kg^{-1}$)

e_o osmotic potential, in joules per kilogram ($J \cdot kg^{-1}$)

e_p pore water potential = tensiometer potential $= e_a + e_m$, in joules per kilogram ($J \cdot kg^{-1}$)

e_t total potential $= e_a + e_g + e_m + e_o + \ldots$, in joules per kilogram ($J \cdot kg^{-1}$)

4 Theory

4.1 Composition of the unsaturated zone

4.1.1 The unsaturated zone consists of three phases, labelled by a subscript α:

— the solid phase $\alpha = s$

— the liquid phase: the soil water $\alpha = w$

— the gas phase: the soil air $\alpha = a$

The biological components are part of the solid phase. The soil water is usually water including dissolved and suspended materials, the soil liquid. In the definitions of water content, however, water is only the chemical constituent H_2O, see [5]. Note that the saturated zone is a special case of the unsaturated zone. The gas phase is not present in the saturated zone, it contains only the liquid and solid phase.

4.1.2 There are two kinds of density (expressed in kilograms per cubic metre):

— the density ρ_α of the material α, which is equal to the ratio of the mass of a phase to the volume of that phase;

— the partial bulk density, ρ_α', which is equal to the ratio of the mass of a quantity of material (i.e. one phase) to the total volume occupied by this material (including other phases).

The bulk density is equal to the sum of all partial bulk densities:

$$\rho_b = \rho_s' + \rho_w' + \rho_a'$$

4.1.3 The dry bulk density equals the partial bulk density of the solid phase, ρ_s', if the mass of the soil air is neglected. It also equals the product of the volume fraction and the density of the solid phase:

$$\rho_s' = \varphi_s \rho_s$$

4.1.4 The volume fraction of a phase, φ_α ($m^3 \cdot m^{-3} = 1$), is the ratio of the volume occupied by that phase and the total volume or bulk volume. It is also the ratio of the partial bulk density and density of that phase:

$$\varphi_\alpha = \frac{\rho_\alpha'}{\rho_\alpha}$$

The porosity or pore fraction, ϕ, is the complement of the volume fraction of the solid phase:

$$\phi = 1 - \varphi_s$$

4.1.5 The water content of the unsaturated zone is often given as the water content volume fraction or volumetric water content, φ_w ($m^3 \cdot m^{-3} = 1$). This is the same as the volume fraction of the soil water, φ_w. The water content can also be expressed as the water content mass fraction, w_w ($kg \cdot kg^{-1} = 1$), or gravimetric water content. It is the same as the mass ratio of the soil water to the solid phase.

The water content mass fraction can be determined more easily than the water content volume fraction. The relationship between these is:

$$\varphi_w = w_w \frac{\rho_s'}{\rho_w}$$

The water content can also be characterized as the degree of saturation, S [1]. It is the ratio of the water content volume fraction to the porosity:

$$S = \frac{\varphi_w}{\phi}$$

4.2 Energy status of the soil water

4.2.1 The energy status of the soil water can be described by its potential energy. The kinetic energy of soil water can usually be neglected. Generally it is more practical to work with potentials. The potential of soil water is the energy of the soil water divided by the mass of the soil water considered. The total potential of the soil water, e_t, in joules per kilogram, can be written as the sum of potentials:

$$e_t = e_a + e_g + e_m + e_o + \ldots$$

where

e_a is the pneumatic potential, in joules per kilogram ($J \cdot kg^{-1}$);

e_g is the gravitational potential, in joules per kilogram ($J \cdot kg^{-1}$);

e_m is the matric potential, in joules per kilogram ($J \cdot kg^{-1}$);

e_o is the osmotic potential, in joules per kilogram ($J \cdot kg^{-1}$).

An equivalent of the soil water potential can be expressed as the specific energy of the soil water divided by the volume of the soil water instead of the mass. This results in the pressure equivalent of the soil water potential or the soil water pressure. The unit becomes joules per cubic metre, or pascals ($J \cdot m^{-3} = Pa$). The total soil water pressure, p_t, in pascals, can be written as a sum of pressures, as for the potentials:

$$p_t = p_a + p_g + p_m + p_o + \ldots$$

where

p_a is the pneumatic pressure, in pascals;

p_g is the gravitational pressure, in pascals;

p_m is the matric pressure, in pascals;

p_o is the osmotic pressure, in pascals.

Note that the pressure due to mechanical load on the soil is considered here to be part of p_m.

Another equivalent of the soil water potential can be expressed as the specific energy of the soil water divided by the weight (force) of the soil water. This results in the head equivalent of the soil water potential or head. The unit becomes newton metres per newton, or metres ($J \cdot N^{-1} = m$). The total soil water head, h_t, in metres, can be written as a sum of heads, as for the potentials:

$$h_t = h_a + h_g + h_m + h_o + ...$$

where

h_a is the pneumatic head, in metres;

h_g is the gravitational head, in metres

h_m is the matric head, in metres;

h_o is the osmotic head, in metres.

The pressure head, h_p, equals the sum of the matric head, h_m, and the pneumatic head, h_a. If h_a can be neglected, $h_p = h_m$.

NOTE Pressure head can be measured using a tensiometer.

The hydraulic head, h_h, is the sum of h_g and h_p. In those cases where all other heads can be neglected, $h_h = h_t$.

The relationship between the potential and the pressure and head equivalent of the potential is given by:

$$e_t = \frac{p_t}{\rho_w} = g \cdot h_t$$

where g is the acceleration due to gravity. Note that the pressure equivalent of the potential depends on ρ_w. In those cases where ρ_w cannot be considered constant (e.g. due to salt or temperature gradients) one shall use potentials or heads.

Potential differences of soil water due to temperature gradients are usually neglected and therefore not explicitly mentioned in the total potential and its equivalents. However, it should be verified whether temperature gradients can be neglected.

4.2.3 The water retention characteristic gives the relationship between matric head h_m and water content volume fraction φ. This relationship usually displays hysteresis.

4.3 Transport of soil water

4.3.1 The volumetric soil water flux density ($m^3 \cdot m^{-2} \cdot s^{-1} = m \cdot s^{-1}$), $\vec{v}$, equals the volume divided by time and area. It equals also the product of the average velocity of the soil water ($m \cdot s^{-1}$), v', and the water content φ, so $\vec{v} = \varphi \cdot v'$.

The water balance at a point x, y, z and time t can be written as the continuity equation:

$$\frac{\partial \varphi}{\partial t} = -\vec{\nabla} \cdot \vec{v} - \lambda$$

$\vec{\nabla}$ is the differential vector operator (m^{-1}) and $\vec{\nabla} \cdot \vec{v}$ is the scalar product of the two vectors. λ is a sink or a source, e.g. the volumetric extraction speed ($m^3 \cdot m^{-3} \cdot s^{-1} = s^{-1}$) by plant roots (extracted volume of water divided by the bulk volume and time).

4.3.2 The flow of water in homogeneous and isotropic media can be described by Darcy's equation, if the osmotic and pneumatic heads can be neglected. The flux density $\vec{v}$ is proportional to the gradient of the hydraulic head [1], $\vec{\nabla} \cdot h_h$, with the hydraulic conductivity ($m \cdot s^{-1}$), K, as the factor of proportionality:

$$\vec{v} = -K\vec{\nabla}h_h = -K\vec{\nabla}h_m - K\vec{\nabla}h_z$$

Darcy's law is only valid for laminar flow. This is usually the case in soils.

The hydraulic conductivity characteristic gives the relationship between K and h_m and between K and φ. Hysteresis is less important in the relationship between K and φ. However, the relationship between K and h_m has hysteresis if the relationship between h_m and φ has hysteresis.

4.3.3 The determination of the water retention characteristic is relatively simple. However, the determination of the hydraulic conductivity characteristic is rather difficult [2], [4]. Therefore, there is much interest in predicting the conductivity characteristic from the retention characteristic [7]. The conductivity models of Mualem [6] and Burdine [1] are often used. These models are often combined with the empirical relation between h_m and φ of Van Genuchten [7].

Bibliography

[1] BURDINE, N.T. Relative permeability calculations from pore-size distribution data. *Trans. ASME,* **198** (1953), pp. 71-78

[2] GREEN, R.E., AHUJA, L.R. and CHONG, S.K.. Hydraulic conductivity, diffusivity, and sorptivity of unsaturated soils: Field methods. In: A. Klute (ed.), *Methods of Soil Analysis, Part I, Physical and Mineralogical Methods*, Agronomy Monograph No. 9, 2nd edn., pp. 771-798, Amer. Soc. Agron., Madison, WI, USA, (1986)

[3] HILLEL, D. *Fundamentals of Soil Physics.* Academic Press, New York, 413 pp., 1980

[4] KLUTE, A. and DIRKSEN, C. Hydraulic conductivity and diffusivity: Laboratory methods. In: A. Klute (ed.), *Methods of Soil Analysis, Part I, Physical and Mineralogical Methods,* Agronomy Monograph No. 9 (2nd edn) pp. 687-734, Amer. Soc. Agron., Madison, WI, USA, (1986)

[5] KOOREVAAR, P., MENELIK, G. and DIRKSEN, C. Elements of Soil Physics. *Devel. Soil Sci.,* **13**. Elsevier, The Netherlands, (1983), 228 pp.

[6] MUALEM, Y. A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resource Res*., **12,** (1976) pp. 513-522

[7] VAN GENUCHTEN, M.Th., LEIJ, F.J. and LUND, L.J. (eds). *Indirect methods for estimating the hydraulic properties of unsaturated soils.* Proc. International Workshop, October 1989. University of California Press, Riverside, CA, USA, (1993)

[8] Anonymous. *Glossary of soil science terms*. Soil Science Society of America, Madison, WI, USA (1997)

[9] BOLT, G.H., IWATA, S., PECK, A.J., RAATS, P.A.C., RODE, A.A., VACHAUD, G. and VORONIN, A.D. *Soil Physics Terminology.* Report of the second terminology committee of Commission of the International Society of Soil Science (ISSS 1973-1975) **49** (1976), pp. 26-36

[10] ROSE, D.A. Soil water: Quantities, units and symbols. *J. Soil Sci.,* **30** (1979), pp. 1-16

ICS 13.080.40

Price based on 11 pages