permeability and groundwater contaminant transport

Zimmie/Riggs, *editors*

ASTM STP 746

AMERICAN SOCIETY FOR TESTING AND MATERIALS

PERMEABILITY AND GROUNDWATER CONTAMINANT TRANSPORT

A symposium
sponsored by ASTM
Committee D-18 on
Soil and Rock for
Engineering Purposes
AMERICAN SOCIETY FOR
TESTING AND MATERIALS
Philadelphia, Pa.,
17–23 June 1979

ASTM SPECIAL TECHNICAL PUBLICATION 746
T. F. Zimmie, Rensselaer Polytechnic
Institute, and C. O. Riggs, Central
Mine Equipment Co., editors

ASTM Publication Code Number (PCN)
04-746000-38

AMERICAN SOCIETY FOR TESTING AND MATERIALS
1916 Race Street, Philadelphia, Pa. 19103

Library of Congress Catalog Card Number: 81-65838

NOTE

The Society is not responsible, as a body,
for the statements and opinions
advanced in this publication.

Printed in Baltimore, Md.
September 1981

Foreword

The symposium on Permeability and Groundwater Contaminant Transport was held on 17–23 June 1979 in Philadelphia, Pa. The meeting was sponsored by the American Society for Testing and Materials through its Committee D-18 on Soil and Rock for Engineering Purposes. The chairmen were T. F. Zimmie, Rensselaer Polytechnic Institute, and C. O. Riggs, Central Mine Equipment Co., both of whom also served as editors of this publication.

Related ASTM Publications

Behavior of Deep Foundations, STP 670 (1979), $49.50, 04-670000-38

Dynamic Geotechnical Testing, STP 654 (1978), $34.50, 04-654000-38

Dispersive Clays, Related Piping, and Erosion in Geotechnical Projects, STP 623 (1977), $40.75, 04-623000-38

Soil Specimen Preparation for Laboratory Testing, STP 599 (1976), $35.00, 04-599000-38

Manual on Water, STP 442A (1978), $28.50, 04-44210-16

A Note of Appreciation to Reviewers

This publication is made possible by the authors and, also, the unheralded efforts of the reviewers. This body of technical experts whose dedication, sacrifice of time and effort, and collective wisdom in reviewing the papers must be acknowledged. The quality level of ASTM publications is a direct function of their respected opinions. On behalf of ASTM we acknowledge with appreciation their contribution.

ASTM Committee on Publications

Editorial Staff

Contents

Introduction

A symposium was presented as the joint effort of ASTM Subcommittees D18.04 on Hydrologic Properties of Soil and Rock and D18.14 on Soil and Rock Pollution, both subcommittees of ASTM Committee D-18 on Soil and Rock for Engineering Purposes. The active members of these subcommittees, along with selected nonmember reviewers, participated in the planning and implementation of the symposium.

During the symposium, outstanding state-of-the-art presentations were made by Professors Roy E. Olson[1] and George F. Sowers.[2] These presentations were followed by brief summaries of other contributors and a panel discussion that was splendidly chaired by W. C. Walton.[3]

It should be recognized that two previous symposia have been presented on the general subject of permeability: *Symposium on Permeability of Soils, ASTM STP 163,* in 1955 and *Permeability and Capillarity of Soils, ASTM STP 417,* in 1966. A. I. Johnson[4] was chairman of the 1966 symposium and presented a glossary of groundwater terminology. This glossary has been updated and follows this introduction.

Many of the engineers and geologists who are now involved in groundwater seepage analyses and evaluation of contaminant transport problems cut their teeth in geotechnical engineering on problems of the stability of embankments and foundations. The guidelines for analysis were established by wise educators and practitioners who recognized that almost every act performed during exploration, field testing, and laboratory testing contributed to the conservative nature of the solution. It is probably a fortunate circumstance that most geotechnical engineers have at some time studied or encountered the time-of-settlement problem and thus gained some appreciation of the magnitude of error that can occur when a prediction of field seepage velocity and the related time of settlement is made on the basis of a poorly modeled laboratory experiment.

The possible magnitude and nature (which can be either conservative or unconservative with respect to the problem at hand) of errors from both laboratory and field measurements of hydraulic conductivity (permeability) is thoroughly discussed by Olson, Sowers, and other contributors. These

[1]The University of Texas at Austin, Tex.
[2]Georgia Institute of Technology and Law Engineering Testing Co., Atlanta, Ga.
[3]Upper Mississippi River Basin Commission, Minneapolis, Minn.
[4]Woodward-Clyde Consultants, Denver, Colo., chairman, ASTM Committee D-18.

analyses of error magnitudes along with some specific, recommended or otherwise cited test procedures probably represent the most significant contribution of the symposium.

The contributions to this volume in the area of groundwater contaminant transport reflect the tremendous increase in activity in the area of waste disposal, an area in which geotechnical engineers are now heavily involved. Permeability is only one of the many parameters required to predict groundwater contaminant transport. It is evident that there is a pressing need for the development of standards dealing with groundwater contaminant transport as related to waste disposal.

T. F. Zimmie

Rensselaer Polytechnic Institute, Troy, N.Y. 12181; symposium chairman and editor.

C. O. Riggs

Central Mine Equipment Co., St. Louis, Mo. 63147; symposium chairman and editor.

A. I. Johnson[1]

Glossary

REFERENCE: Johnson, A. I., "**Glossary,**" *Permeability and Groundwater Contaminant Transport, ASTM STP 746,* T. F. Zimmie and C. O. Riggs, Eds., American Society for Testing and Materials, 1981, pp. 3–17.

ABSTRACT: In presenting an interdisciplinary symposium on permeability and groundwater contaminant transport, there is considerable chance for lack of communication between the engineers and scientists of the many different disciplines interested in these subjects. To assist in better communication between the disciplines involved in permeability and capillarity testing of soils and rocks, a glossary and conversion factor tables are provided.

Nearly 100 terms are listed alphabetically, followed by brief definitions. Where two or more definitions are listed following a term, no significance is placed on the order of presentation. The source is indicated for each definition, and the sources are listed in the reference section following the glossary. Two tables of conversion factors also are presented to assist in conversion of the units used by the various disciplines.

KEY WORDS: permeability, groundwater, glossary

In presenting an interdisciplinary symposium on permeability and groundwater contaminant transport, there is considerable chance for lack of communication between the engineers and scientists of the many different disciplines interested in these subjects. For example, a variety of terms have been used to describe the pressure condition existing above the groundwater table, where the soil-moisture pressure is negative. The term *soil-moisture tension* seems to be favored by most soil scientists in the United States, and *soil-moisture suction* by those in Europe. Civil and petroleum engineers use *capillary pressure, pore pressure,* or *neutral stress* to designate essentially the same phenomenon. The *capillary-pressure curves* of the petroleum engineer are similar, in general, to the *moisture-tension (moisture-retention) curves* of the soil physicist, and both in turn may be used by the hydrologist to represent the moisture distribution in the unsaturated zone above the water table. Furthermore, there is no interdisciplinary standardization of units used to express either permeability or capillarity.

[1]Water resource consultant, Woodward-Clyde Consultants, Denver, Colo. 80204.

To assist in better communication between the disciplines involved in permeability and capillarity testing of soils and rocks, the following glossary and tables of conversion factors are provided. Because of the rapidly increasing interest in waste disposal and contaminant transport, it should be kept in mind that the word *liquid* could be substituted for the word *water* in many of the definitions.

Terms are listed alphabetically, followed by brief definitions.[2] Where two or more definitions are listed following a term, no significance should be placed on the order of presentation. The source is indicated for each definition, and the sources are listed in the reference section following the glossary. Several tables of conversion factors also are presented to assist in conversion of the units used by the various disciplines for expressing permeability and capillarity.

Definitions

Air-space ratio, G_a (D)—the ratio of (1) the volume of water that can be drained from a saturated soil or rock under the action of force of gravity to (2) the total volume of voids [*1*].[3]

Anisotropic mass—a mass having different properties in different directions at any given point [*1*].

Aquiclude—a formation which, although porous and capable of absorbing water, does not transmit it at rates sufficient to furnish an appreciable supply for a well or spring [*2*].

Aquifer—a water-bearing formation that provides a groundwater reservoir [*1*]; a formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs [*3*].

Area of influence of a well (L^2)—the area surrounding a well within which the piezometric surface has been lowered when pumping has produced the maximum steady rate of flow [*1*].

Artesian—synonymous with *confined. Artesian water* and *artesian water body* are equivalent respectively to *confined* groundwater and *confined* water body. An *artesian well* is a well deriving its water from an *artesian* or *confined* water body. The water level in an artesian well stands above the top of the artesian water body it taps [*3*].

Capillary action (capillarity)—the rise or movement of water in the interstices of a soil or rock due to capillary forces [*1*].

Capillary conductivity—the ability of an unsaturated soil or rock to transmit water or another liquid. As the larger interstices are partly occupied by air or another gas, rather than a liquid, the liquid must move through

[2] The abbreviations in parentheses stand for terms of measurement and are defined as follows: D = dimensionless; L = length; T = time; M = mass; and F = force.

[3] The italic numbers in brackets refer to the list of references appended to this paper.

and in bodies surrounding point contacts of rock or soil particles. For water, the conductivity increases with the moisture content, from zero in a perfectly dry material to a maximum equal to the hydraulic conductivity [*4*]; coefficient which measures the extent to which a permeable medium allows flow of water through its capillary interstices, under a unit gradient of capillary potential [*2*].

Capillary fringe—the lower subdivision of the zone of aeration, immediately above the water table in which the interstices are filled with water under pressure less than that of the atmosphere, being continuous with the water below the water table but held above it by surface tension. Its upper boundary with the intermediate belt is indistinct but is sometimes defined arbitrarily as the level at which 50 percent of the interstices are filled with water [*4*].

Capillary fringe zone—the zone above the free water elevation in which water is held by capillary action [*1*].

Capillary head, h (L)—the potential, expressed in head of water, that causes the water to flow by capillary action [*1*].

Capillary migration (capillary flow)—the movement of water by capillary action [*1*].

Capillary potential—a number representing the work of moving a unit mass of water from the soil to an arbitrary reference location and energy state [*5*].

Capillary pressure—the difference in pressure across the interface between two immiscible fluid phases jointly occupying the interstices of a rock. It is due to the tension of the interfacial surface, and its value depends on the curvature of that surface [*4*].

Capillary rise (height of capillary rise), h_c (L)—the height above a free water elevation to which water will rise by capillary action [*1*].

Capillary water—water subject to the influence of capillary action [*1*] water held in the soil above the phreatic surface by capillarity; soil water above hygroscopic moisture and below the field capacity [*2*].

Centrifuge moisture equivalent—see *Moisture equivalent.*

Coefficient of permeability (permeability), k (L T^{-1})—the rate of discharge of water under laminar flow conditions through a unit cross-sectional area of a porous medium under a unit hydraulic gradient and standard temperature conditions (usually 20°C) [*1*].

Coefficient of transmissibility—see *Transmissibility coefficient* or *Transmissivity.*

Conductivity, effective hydraulic, K_e (L T^{-1})—the rate of flow of water through a porous medium that contains more than one fluid, such as water and air in the unsaturated zone, and [which] should be specified in terms of both the fluid type and content and the existing pressure [*3*].

Conductivity, hydraulic, K (L T^{-1})—replaces the term *field coefficient of permeability,* P_f. If a porous medium is isotropic and the fluid is homogeneous, the hydraulic conductivity of the medium is the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow [*3*].

Cone of depression—the depression, in the shape of an inverted cone, of the piezometric (potentiometric) surface of a body of groundwater which defines the area of the influence of a well [*2*].

Connate water—water entrapped in the interstices of a sedimentary or extrusive igneous rock at the time of its deposition [*4*].

Darcy's law—a derived formula for the flow of fluids on the assumption that the flow is laminar and that inertia can be neglected. The numerical formulation of this law is used generally in studies of gas, oil, and water production from underground formations. For example, in gas flow, the velocity of flow is proportional to the pressure gradient multiplied by the ratio of permeability times density, divided by the viscosity of the gas [*4*].

Degree of saturation—see *Percent saturation.*

Diffusivity, soil water, D—the hydraulic conductivity divided by the differential water capacity (care being taken to be consistent with units), or the flux of water per unit gradient of moisture content in the absence of other force fields [*5*].

Discharge velocity, v, q (L T^{-1})—the rate of discharge of water through a porous medium per unit of total area perpendicular to the direction of flow [*1*].

Drawdown (L)—the vertical distance the free water elevation is lowered or the reduction of the pressure head due to the removal of free water [*1*].

Effective porosity (effective drainage porosity), n_e—the ratio of (1) the volume of the voids of a soil or rock mass that can be drained by gravity to (2) the total volume of the mass [*1*]; the amount of interconnected space available for fluid transmission. It is expressed as a percentage of the total volume occupied by the interconnecting interstices [*3*].

Equipotential line—see piezometric line in Ref *1*, p. 182.

Field capacity (field moisture capacity)—(obsolete in technical work) the percentage of water remaining in a soil 2 or 3 days after the soil has been saturated and after free drainage has almost ceased. The percentage may be expressed on the basis of weight or volume [*5*].

Flow line—the path that a particle of water follows in its course of seepage under laminar flow conditions [*1*].

Flow net—a graphical representation of flow lines and equipotential (piezometric) lines used in the study of seepage phenomena [*1*].

Flow steady—steady flow occurs when at any point the magnitude and direction of the specific discharge are constant in time [*3*]. (See also *Flow, unsteady.*)

Flow, uniform—a property is uniform if, at a given instant, it is the same at every point. Thus, *uniform flow* occurs if at every point the specific discharge has the same magnitude and direction [*3*].

Flow, unsteady—*unsteady,* or *nonsteady, flow* occurs when at any point the magnitude or direction of the specific discharge changes with time. (See also *Flow, steady.*) The word *transient* is used in reference to the temporary features of unsteady flow. Thus, in unsteady flow, the specific discharge, the head, and perhaps other factors consist of a steady component plus a transient component [*3*].

Flow velocity (of water in soil)—the volume of water transferred per unit of time and per unit of area normal to the direction of the net flow [*5*].

Fluid potential, ϕ ($L^2 T^{-2}$)—the mechanical energy per unit mass of a fluid at any given point in space and time with regard to an arbitrary state and datum. Loss of fluid potential incurred as the fluid moves from a region of high potential to one of low potential represents loss of mechanical energy which is converted to heat by friction [*3*].

Free water (gravitational water, groundwater, phreatic water)—water that is free to move through a soil or rock mass under the influence of gravity [*1*].

Free water elevation (water table, groundwater surface, free water surface, groundwater elevation)—elevations at which the pressure in the water is zero in relation to the atmospheric pressure [*1*].

Gravitational water—water which moves into, through, or out of the soil under the influence of gravity [*5*].

Groundwater, confined—groundwater under pressure significantly greater than atmospheric, its upper limit is the bottom of a bed of hydraulic conductivity distinctly lower than that of the material in which confined water occurs [*3*].

Groundwater, perched—unconfined groundwater separated from an underlying body of groundwater by an unsaturated zone. Its water table is a *perched water table.* It is held up by a *perching bed* whose permeability is so low that water percolating downward through it is not able to bring water in the underlying unsaturated zone above atmospheric pressure. Perched groundwater may be either *permanent,* where recharge is frequent enough to maintain a saturated zone above the perching bed, or *temporary,* where intermittent recharge is not great or frequent enough to prevent the perched water from disappearing from time to time as a result of drainage over the edge of or through the perching bed [*3*].

Groundwater, unconfined—water in an aquifer that has a water table [*3*].

Head, static, h (L)—the height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point. The static head is the sum of the elevation head, h_e, and the pressure head, h_p; that is, $h = h_e + h_p$. (See *Head, total.*) Under conditions to which Darcy's law may be applied, the velocity of groundwater is so small that the velocity head, $h_v = v^2/2g$, is negligible. *Head,* when used alone, is understood to mean static head. Inspection of the equation $\phi = gh$, shows that the head is proportional to the fluid potential; therefore, the head is a measure of the potential [*3*].

Head, total, H (L)—the total head of a liquid at a given point is the sum of three components: (1) the *elevation head,* h_e, which is equal to the elevation of the point above a datum, (2) the *pressure head,* h_p, which is the height of a column of static water that can be supported by the static pressure at the point, and (3) the *velocity head,* h_v, which is the height to which the kinetic energy of the liquid is capable of lifting the liquid. Thus, the total head can be expressed as

$$H = h_e + h_p + h_v = z + \frac{1}{g}\int_{p_a}^{p} \frac{dp}{p} + \frac{v^2}{2g}$$

where p_a is atmospheric pressure [*3*].

Homogeneity—synonymous with uniformity. A material is homogeneous if its hydrologic properties are identical everywhere. Although no known aquifer is homogeneous in detail, models based upon the assumption of homogeneity have been shown empirically to be valuable tools for predicting the approximate relationship between discharge and potential in many aquifers [*3*].

Hydraulic conductivity, K—the proportionality factor in Darcy's law as applied to the viscous flow of water in soil, that is, the flux of water per unit gradient of hydraulic potential. If conditions require that the viscosity of the fluid be divorced from the conductivity of the medium, it is convenient to define the permeability (intrinsic permeability has been used in some publications) of the soil as the conductivity, expressed in g^{-1} cm^3 s multiplied by the viscosity in poise [*5*].

Hydraulic diffusivity, T/S or K/S_s (L^2 T^{-1})—the *hydraulic diffusivity* is the conductivity of the saturated medium when the unit volume of water moving is that involved in changing the head a unit amount in a unit volume of medium. By analogy with Maxwell's nomenclature in heat conduction theory (thermometric conductivity), it may be considered potentiometric conductivity. Similar diffusivities, having dimensions L^2 T^{-1}, characterize the flow of heat and of electricity by conduction and the movement of a dissolved substance in a liquid by diffusion. The parameter arises from the fundamental differential equation for liquid flow in a porous medium. In any isotropic homogeneous system the time involved for a given head change to occur at a particular point in response to a greater change in head at another point is inversely proportional to the diffusivity. As a common example, the cone of depression affects moderately distant wells by measurable amounts in a short time in confined groundwater bodies for which the diffusivities are com-