Relative Importance of Factors Influencing the Permeability of Clay Soils

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ABSTRACT

An appraisal is presented of the various factors influencing the permeability of clays and their relative importance is examined. In particular, the significance of soil micro and macro-structure is discussed and the development of a hydraulic radius type permeability equation for anisotropic clays is described. This equation addresses shortcomings in the Kozeny-Carman equation developed for granular soils and is based on an idealisation of the soil structure and determination of the true 'seepage' velocity.

INTRODUCTION

An appreciation of the factors influencing permeability is an essential prerequisite to an understanding and the prediction of the migration of water borne contaminants (advection) from pollution sources. Though carefully controlled and designed laboratory and field tests are essential requirements in determining permeability, testing only tells part of the story. Test results are often only reproducible to perhaps an order of magnitude and can be misleading under changing conditions. A full appraisal of the efficacy of a clay to retard pollution migration requires the development of (i) a comprehensive permeability theory to facilitate an understanding of the role, significance and interaction of the various factors influencing permeability and to explain anomalies, as well as (ii) a predictive analysis to enable an assessment of the development of pollution plumes and the migration of pollutants.

The variability of soil permeability and the number of influencing factors means that prediction presents a complex problem but the development of an equation which sets out the relative importance and incorporates at least in simple terms the major factors which influence permeability, is of fundamental importance.

FACTORS INFLUENCING THE PERMEABILITY OF CLAY SOILS

The permeability of clay soils may be broadly categorised as influenced by the factors discussed below -

Soil Micro-Structure

Physical Properties of the Particles - It is generally accepted with justification that the finer particles have a disproportionate effect on permeability. Clays are composed of very fine plate-like particles which results in low transmission rates for fluid flow. The particle size is of great importance and clays composed of the larger particle types yield greater permeabilities than those with smaller size particles other factors being equal. Thus, kaolinite generally has a

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permeability greater than illite which in turn has a greater permeability than smectite (Mesri and Olson, 1971). The Specific Surface, which is defined as the surface area of the particles divided by the volume of the particles, is sometimes used to yield an equivalent particle diameter (Carman, 1939) for clays as well as for granular soils though clay particles are by no means unidirectional. Care should also be exercised if the Specific Surface is used to account for the frictional drag on the permeant not least because it is a non-directional term and clays generally exhibit highly directional properties and a distinct macro-structure. The Kozeny-Carman equation (Kozeny, 1927 and Carman 1937, 1939, 1956), developed for fine sands and powders, implicitly uses the Specific Surface to determine the frictional resistance to flow as well as the representative particle size and is only strictly usable for isotropic fine granular soils.

Distribution of the Particles - Ignoring soil macro-structure, the greater the degree of compaction the less the pore volume and the lower the permeability. However, the pore openings available for flow in any particular direction will be influenced by the particle configuration and shape. For example, the alignment of plate-like particles in a horizontal direction as in Fig. 1 will lead to less pore area available to transport the permeant and a more tortuous flow path in a vertical direction than in a horizontal direction. The vertical permeability will thus be less than the horizontal permeability (Lambe, 1955; Witt and Brauns, 1983; Arch et al, 1993). An ordered soil structure of this kind can result from compaction operations, be a result of natural deposition or a consequence of particle reorientation on deformation planes. Aggregation of clay platelets also influences the distribution of the pore spaces and the flow of permeant (Mesri and Olson, 1971). Though it is the distribution of the particles which controls the pore spaces and the anisotropy of fluid flow, nevertheless it is the pore spaces along which the permeant flows, and the distribution of the particles only gives a guide to the pore space characteristics.

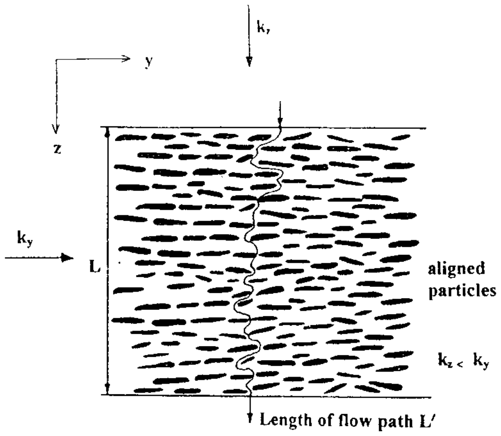

FIG. 1 TORTUOSITY AND THE EFFECT OF PARTICLE ALIGNMENT

Pore Space Characteristics - The total volume of the pore spaces is generally defined by either the porosity or the voids ratio. In the following the various equations are presented in terms of the porosity which is defined as,

$$n = \text{porosity} = \frac{\text{volume of voids}}{\text{total volume}} \tag{1}$$

For a given porosity, a small number of large pore openings will lead to greater permeability than a large number of small openings and is controlled to a large extent by the particle sizes (i.e. kaolinite with a relatively large particle size has a greater permeability than illite or smectite all other factors being equal). The porosity is non-directional and it is necessary to consider the winding path followed by the fluid flowing through the pore spaces in order to account for anisotropy. This may be done by defining the tortuosity of flow ($T \geq 1.0$) as below and illustrated in Fig. 1 where T is a statistical average for the given direction of flow through a soil.

$$T = \frac{\text{Average tortuous route followed by permeating liquid}}{\text{straight line distance}} = \frac{L'}{L} \qquad (2)$$

However, sight must not be lost of the fact that pore spaces are highly irregular in shape, vary from position to position and are interconnected with other pore spaces. A simple idealisation of the pore spaces is required in developing a permeability equation.

The mode of deposition, stress history and the chemical properties of the permeant greatly influence both the micro and macro-structure of clays and in recompacted as well as undisturbed clays the soil fabric will be a reflection of the complex stress regime comprising attractive and repulsive particle and pore fluid forces. The observations of McGowan and Collins (1975) and Collins (1984) appear to suggest that two principal levels of micro-structure dominate, namely an elementary arrangement of clay platelets and particle aggregations. Popescu (1980) identifies a cause of particle aggregation as cyclic wetting and drying and is a consequence of the development of negative pore fluid pressures and the formation of closely packed 'packets' of saturated soil surrounded by air filled voids as described by Barden and Sides (1970). These aggregations greatly influence the engineering behaviour of clays as suggested by Chandler and Davis (1973). The moisture content of a clay subject to compaction also influences both the micro and macro-structure (eg. Lambe, 1962). Aggregation influences the porosity distribution and gives rise to the presence of many small flow channels within aggregations and a small number of large flow channels between aggregations. This results in a relatively high permeability compared to a dispersed structure where the pore spaces are of more uniform size. As suggested by Michaels and Lin (1954) and Mesri and Olsen (1971) amongst others, the chemistry of the permeant also greatly influences the soil structure and thus the permeability and a number of researchers have attempted to categorise the various levels and states of particle configuration.

Soil Macro-Structure

In clays the presence of fissures, laminations and other discontinuities making up the macro-fabric present preferential seepage paths which lead to enhanced permeability in the direction of the discontinuities. Such behaviour has been reported by Leroueil et al (1992), Little et al (1992) and Hossain (1992). In analysing the permeability of such soils it is thus necessary to consider carefully the permeability through the discontinuities as a separate but additive entity to the permeability through the inter-particle pore spaces which in itself may be sub-divided into different levels of porosity and thus flow conditions.

The tortuosity of fluid flow along discontinuities is likely to be significantly less than that of inter-particle flow. Discontinuities may be viewed as representing large void spaces with an increased permeability above that of the surrounding intact soil. This is true of undisturbed as well as recompacted clays. In recompacted clays the identification of 'clod' size as being a major contributor to the presence of discontinuities or fissures (Benson and Daniel, 1990; Wright et al, 1996) goes a long way to explaining why there is often large discrepancies between in-situ permeabilities and the lower values obtained on laboratory prepared samples. Nevertheless, dry of optimum moisture content a compacted soil exhibits a fissured structure which can be expected to be present both in the field and in laboratory tests.

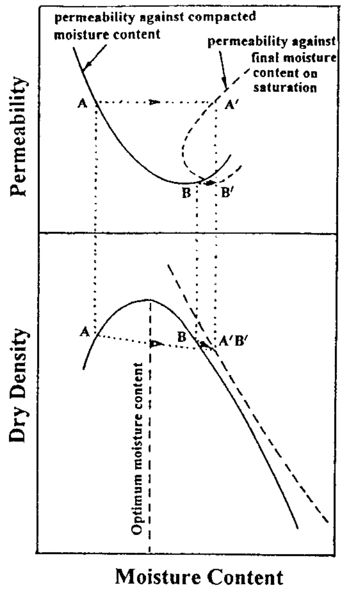

FIG. 2 TYPICAL DRY DENSITY-MOISTURE CONTENT- PERMEABILITY RELATIONSHIP FOR COMPACTED CLAY

The influence of discontinuities may be demonstrated as in Fig. 2 which is a representation of a typical 'dry density - moisture content - permeability' relationship for a compacted clay soil (eg. Day and Daniel, 1985; Murray et al, 1992). It is usual to plot the permeability against the as-compacted moisture content and dry density and the condition of a sample compacted dry of optimum with a relatively high permeability is given by A. However, the quoted permeability is usually for a saturated or near-saturated soil and in achieving this condition the sample can be expected to exhibit a degree of swelling. Thus the condition of the sample at the end of the permeability test may be represented by A'. Points B and B' represent the corresponding conditions of a sample compacted wet of optimum. Though in the final condition the two samples have the same dry density and moisture content given by the correspondence of A' and B', they have significantly different permeabilities as the flow of permeant through sample A is controlled largely by the fissured structure and the flow through the lower permeability sample B by inter-particle flow.

Physical Properties of the Permeant

In equating the forces resisting flow of permeant to those causing flow it is necessary to take account of the unit weight of the permeant (γ) and the dynamic viscosity (μ) of the permeant. Both these parameters are influenced by temperature and are also likely to be influenced by physio-chemical interaction of the permeant with the soil particle system particularly close to the particle surface (Terzaghi, 1925). In fact, Macey (1942) considered the most influential factor for the low permeability of water in clay to be the viscosity of water near the clay surface though other researchers attribute the low permeability to other permeant-soil particle effects.

The degree of saturation greatly influences the permeability. As a soil first becomes unsaturated, air replaces the permeant in the larger pores. Increase in the air content corresponds to a decrease in the pore volume occupied by the permeant and an increase in the matric suction. Permeability decreases rapidly as the air-permeant interface is drawn closer to the particles and the smaller pore spaces available for permeant flow decrease (Fredlund and Rahardjo, 1993)

Chemical Properties of the Permeant-Soil Particle System

Other factors such as the thickness of the fluid film adsorbed to the particles (double layer), inter-lamellar swelling (Mesri and Olsen, 1971) and osmotic and other physio-chemical effects (eg. the electro-osmotic counterflow effect suggested by Michaels and Lin, 1954) have a potentially major influence on the permeability and transportation of contaminant. Michaels and Lin (1954) suggest that the adsorbed liquid attached to soil particles appeared in experiments to have little effect on the permeability and suggest the major influence of the permeant was in controlling the tendency of the clay particles to disperse or to form aggregates. However, there does not appear to be unanimity of view on the influence and significance of the double layer and according to Schmid (1957) in reviewing the work of Michaels and Lin (1954), Mansur and Kaufman (1962) and Shakelford (1993) the effect is likely to be significant and reduces the size and number of pore spaces available to fluid transportation.

SOIL STRUCTURE AND FLOW CONDITIONS

Porosity and Darcy's Law

The total of the micro and macro void spaces available to transport permeant may be defined by the non-directional porosity term given by Eq. (1). The rate of fluid flow through these pore spaces in clays is low and it is reasonably assumed that flow is laminar. Under such conditions Darcy's law gives the rate of flow q as,

$$q = v.A = -k.i.A \qquad (3)$$

where, v is the approach (or discharge) velocity
k is Darcy's coefficient of permeability
i is the hydraulic gradient = $\Delta h/L$
A is the area of the flat plane under consideration

For flow through a particulate material, Darcy's law is clearly a statistical representation of the average flow conditions. Conventionally, the conceptual seepage velocity v_s is given by $q = v_s.A_v$ where A_v is the area of voids cut by a flat plane at right angles to the flow direction v. Making the assumption of an isotropic soil the seepage velocity v_s, which assumes the permeant to flow in a straight line at constant velocity, is given by -k.i/n. In analysis of flow through tubes or pipes it is logical and usual to consider a cross section at right angles to the flow direction. In analysing flow through a particulate material the use of a 'wavy surface' is proposed as a better representation of physical conditions where the wavy surface is defined as being at right angles to the flow through the individual pores. From this idea stems a prediction of the rate of flow of permeant through anisotropic soils.

Tortuosity and the 'Wavy Surface'

The tortuous route followed by a fluid passing through a soil will in general be different in different directions. Tortuosity is a function of the pore spaces and consequently the porosity of a soil. This may be illustrated by considering the 'wavy surface' of total surface area A' as in Fig. 3.

$$A' = A'_V + A'_P \tag{4}$$

where, A'_P is the area of particles and A'_V is the area of pores cut by the wavy surface.

In order to be meaningful the wavy surface must reasonably reflect the physical properties of the soil particle system and the flow of permeant. Area A is the projection of A' at right angles to the general flow direction and the wavy surface is defined by the following conditions: (i) it passes through representative particle sizes, (ii) it passes through representative pore spaces, and (iii) it is of minimum length and is at right angles to the flow through the individual pores.

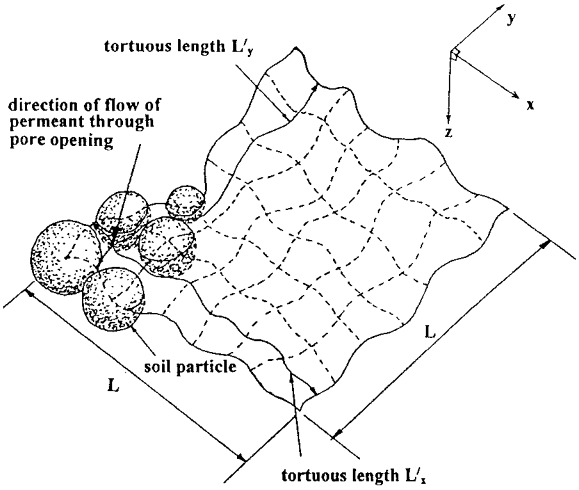

FIG. 3 ILLUSTRATION OF 'WAVY SURFACE'

Thus, the average velocity of flow v_t through the pores is given by,

$$q = v_t \,.\, A'_V \tag{5}$$

and from Eqs. (3) and (5),

$$v_t = -k.i.\frac{A}{A'_V} = \frac{-k.i}{n^*} \tag{6}$$

where, $n^* = A'_V/A$ is defined as the directional pore area ratio.

Considering the voids to be represented by a series of tortuous tubes the total volume of voids is equal to $A'_V.L'$.

$$\text{Thus,}\quad n = n^*.T = \frac{A'_V}{A}.\frac{L'}{L} \tag{7}$$

and, $$v_t = \frac{-k.i}{n} . T \qquad (8)$$

which is compatible with the suggestion of Carman (1956) from more intuitive considerations.

Available Pore Spaces

The assumption of full usage of the pore spaces as flow channels is likely to be true for granular soils but is unlikely to be the case for fine-grained cohesive soils. In fact some pores may be closed to the passage of permeant. In simplistic terms most of the physio-chemical effects may be envisaged as encompassed within these two effects. For given values of k and i in clayey soils the fluid flow velocity will be greater because of these influences. Based on the foregoing,

$$n_e = n_e^*.T = \frac{A'_{ve}}{A}.\frac{L'}{L} \qquad (9)$$

where the suffix 'e' denotes the available parameters based on the reduced pore size and numbers. The assumption is made that the tortuous flow path length is unaffected.

Flow through Tubular Pores

In the following it is assumed that the pore spaces are represented by circular tubes. This does not detract from the analysis but is a convenient representation and the equations derived hold true for other shaped pore spaces.

Taking, $$d_{ve} = \alpha.d_v \qquad (10)$$

then, $$A'_v = \frac{\pi}{4}.d^2{}_v.N_v \text{ and } A'_{ve} = \frac{\pi}{4}.d^2{}_{ve}.N_{ve} \qquad (11)$$

where, d_v = a representative pore diameter
d_{ve}= the available representative pore diameter
α = pore size reduction factor ($0\leq\alpha\leq1$)
N_v and N_{ve} denote the total and available number of pore openings respectively.

Based on Eq. (6), it can be shown by suitable substitution that the average fluid flow velocity v_{te} through the available pore spaces is given by,

$$v_{te} = \frac{-k.i}{n^*_e} = \frac{-k.i}{n}.\frac{T}{\alpha^2.\beta} \qquad (12)$$

where $\beta = \frac{N_{ve}}{N_v} \leq 1.0$

The foregoing equations are applicable to any direction of permeant flow through a material which may be signified by adopting the suffices 'x, y, and z' for any three orthogonal directions. As the tortuous flow path will tend to be a minimum within the restrictions of the particulate system and on average the tortuous flow paths L'_x, L'_y and L'_z in the three orthogonal directions will be at right angles, it is considered reasonable from the previous definition of a wavy surface to adopt its length as L'_x and width as L'_y for flow in the z direction as shown in Fig.3.

PERMEABILITY PREDICTION

Eq. (13) has been developed from the foregoing and the principles of flow through pipes (Poiseuille, 1841); it thus constitutes a hydraulic-radius type model. The development of the equation (Murray et al, in preparation) is not presented herein but takes into account the prime factors influencing permeability and includes factors to account for anisotropy and interconnected flow channels, shortcomings within the Kozeny-Carman and other similar permeability equations (Murray, 1995). The equation may however be simplified to the Kozeny-Carman equation.

$$K_z = \frac{\alpha_z^4}{8.s_0\,\varepsilon_z} \cdot \frac{\beta_z}{N_z} \cdot \frac{n^2}{T_z^3} \qquad (13)$$

where,

K_z is the absolute permeability in the z direction = $k_z.\mu/\gamma$

s_0 = pore shape factor

= π for circular inter-particle pore openings and $2(\Gamma+1)$ for rectangular openings possibly representing fissures ($\Gamma \geq 1$)

where Γ = aspect ratio = $\dfrac{\text{gross length of opening}}{\text{gross width of opening}}$

For inter-particle flow -

N_z = total number of pore opening in z direction per unit area of flat plane (N_{vz}/A)

$$= \frac{4}{\pi} \cdot \frac{(T_x.T_y.T_z - n)^2}{n.T_z} \cdot \frac{1}{d_p^2}$$

where d_p is a representative particle size

ε_z = transverse pore area factor accounting for interconnecting pores = $1 - \dfrac{(n_{ex} \pm n_{ey})}{2.T_x.T_y.T_z}$

where $n_{ex} = \alpha_x^2.\beta_x.n$ and $n_{ey} = \alpha_y^2\ \beta_y.n$

(other parameters are as defined previously)

A number of the factors in Eq. (13) are inter-related but the equation may be used to yield an indication of the significance of the factors influencing the permeability of clays, as well as the difficulties of permeability prediction, as outlined below:

(i) The equation agrees with the general perception that inter-particle permeability is controlled by the square of some representative particle size and consequently the square of some representative pore diameter. A major difficulty is identifying an appropriate representative particle size for the fine plate-like particles which make up a clay.

(ii) Adoption of a shape factor $s_0 = \pi$ for circular pore spaces and a rectangular pore size as a representation for fissures should make it possible to examine the influence of inter-particle flow and fissuring as separate but additive components of overall permeability though careful selection of the other parameters in Eq. (13) would be necessary. However, this simplistic view masks the difficulty of interpretation of the influence of the variable porosity associated with flow through and around aggregations where these influence the micro-structure.

(iii) The transverse pore area factor ε_z is derived as a proportion of the tortuous flow path length in the direction of flow and has a value between 1 and 1-n which indicates that taking account of the interconnection of flow channels and reduction in frictional resistance potentially increases the permeability by a factor of 2.0 or so.

(iv) The equation confirms the previous assertion that the permeability is inversely proportional to the number of void openings per unit area N_z. That is, for a given porosity n, the smaller the number of pore openings the greater the permeability.

(v) Also illustrated is the potentially large physio-chemical effects of reduction in pore size $0 \leq \alpha \leq 1$ and closure of some of the pores $0 \leq \beta \leq 1$. α affects all pores and has a potentially large effect noting it is to the power of 4 in the numerator of the equation and also affects ε_z in the denominator of the equation. For saturated flow β will be controlled by closure of the smaller pores such as within aggregations. However, for unsaturated flow it is the larger voids that are likely to be filled with air and the smaller voids are likely to carry the permeant. This illustrates that β may not adequately describe on its own the blockage of pores in soils with variable pore sizes and that inter aggregation flow and flow between aggregations should be treated separately.

(vi) If the equality $n_{ex}=n_{ey}=n_{ez}$ is adopted, which is not an unreasonable assumption, then $\alpha^2.\beta$ is a constant irrespective of the flow direction, and ε is a constant for the material. On this basis, for a clay with no major discontinuities, noting that both ε_z and N_z are functions of tortuosity, the equation may be developed to show that $k_x.T_x^2 = k_y.T_y^2 = k_z.T_z^2$. This relationship is consistent with the suggestions of Witt and Brauns (1983) and Arch and Maltman (1990). Consequently a typical clay deposit with a permeability in the horizontal direction 10 times greater than in the vertical direction can be expected to have a tortuosity in the vertical direction of around 3 times that in the horizontal direction.

CONCLUDING REMARKS

An equation is presented which highlights the relative importance of the factors influencing the permeability of clay soils. The potential use and shortcomings of the equation have been discussed. There is great difficulty in assigning values to a number of the parameters and a realistic prediction of permeability for a clay soil is not attempted. Further investigative work is needed before realistic predictions of permeability can be made.

NOTATION

A	Cross-sectional area of flat plane
A'	Total area of wavy surface
A_v	Area of pores cut by flat plane
A'_p	Area of particles cut by wavy surface
A'_v	Area of pores cut by wavy surface
A'_{ve}	Available area of pores cut by wavy plane
d_p	Representative particle diameter
d_v	Representative pore diameter
d_{ve}	Available representative pore diameter
i	Hydraulic gradient
K	Absolute permeability
k	Darcy's coefficient of permeability
L	Length (straight line distance)
L'	Tortuous length of flow path
N	Number of pore openings per unit area N_v/A
N_v	Number of pore openings
N_{ve}	Available number of pore openings
n	Porosity
n_e	Available porosity
n^*	Directional pore area ratio
n^*_e	Available directional pore area ratio
q	Rate of flow

s	Cross-section shape factor
T	Tortuosity
v	Approach (or discharge) velocity
v_s	Seepage velocity
v_t	Average velocity of flow through tortuous tubes based on gross pore size
v_{te}	Average velocity of flow through tortuous tubes based on available pores spaces
x,y,z	Suffices attached to vector quantities to indicate properties in three orthogonal directions
α	Pore size reduction factor
β	N_{ve}/N_v
γ	Unit weight of permeant
Δh	Loss of total head
μ	Dynamic viscosity of permeant
Γ	Aspect ratio of a fissure (length to breadth)
ε	Transverse pore area factor

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