Proceedings of the ISSS symposium on water and solute movement in heavy clay soils

Edited by J. Bouma and P.A.C. Raats
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Horizontal cross-section of a dry, cracked clay soil at 40 cm below surface. (Photo courtesy of the Netherlands Soil Survey Institute.)
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International Symposium on
water and solute movement in heavy clay soils
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Proceedings

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PREFACE

At the 12th International Congress of Soil Science, held in New Delhi, India in February 1982, a proposal by the Dutch Soil Science Society to host an international symposium on water movement in heavy clay soils was accepted. The symposium was to be sponsored by the International Society of Soil Science (ISSS). To further develop contacts between pedologists and soil physicists, it was decided that the symposium be organized by Commissions I (Soils Physics) and V (Soil Genesis, Classification, and Cartography) of the ISSS. Later, it was also agreed that the symposium be co-sponsored by the European Geophysical Society.

In the fall of 1982 an organizing committee was formed consisting of G.H. Bolt (Chairman), J. Bouma (Secretary), and W.A. Blokhuys, J.W. van Hoorn, P.A.C. Raats, K. Rijniersce, and G.P. Wind (members). The ISSS was represented on an ad hoc basis by its Secretary General W.G. Sombroek. Secretarial assistance was provided by Mrs. M. Rijk of the Netherlands Soil Survey Institute.

At its first meeting the organizing committee decided to expand the scope of the symposium to cover not only water but also solute movement in heavy clay soils, thus including aspects of ISSS Commission II (Soil Chemistry).

The three-day symposium was held from 21 to 29 August 1984, at the International Agricultural Centre, Wageningen, The Netherlands. Organizational aspects were handled by Mrs. L. Hotke and Mrs. E. van de Wetering. The schedule included a reception given by the Dutch Ministry of Agriculture and Fisheries, a visit to the International Soil Reference and Information Centre (ISRIC) in Wageningen and, of course, a symposium dinner. Following the symposium were two day-long excursions. The first, organized by K. Rijniersce of the IJsselmeerpolders Development Authority, was to very young clay soils in a newly-reclaimed polder. The second, to young and old riverine clays near the Rhine, was organized by M. Kooistra, J.H.M. Wüsten, V
L.W. Dekker, and J. Bouma of the Netherlands Soil Survey Institute, and
by R. Miedema and J. Versluys of the University of Agriculture,
Wageningen. Excursion guides were prepared, but they have not been
reproduced in these proceedings.

The following themes were covered in the symposium:
1. Development of structural patterns in swelling and shrinking clays;
2. Transport phenomena: water movement;
3. Transport phenomena: solute transport;

The sessions in which these themes were covered were chaired by
G.H. Bolt, W.A. Blokhuis, J.R. Philip, G.D. Towner, D.H. Yaalon, and
L.P. Wilding.

Prior to the symposium, ten individuals with particular experience in
one of the four themes were asked to submit a keynote paper of a
maximum ten pages in length. Each paper was to be presented during a
half hour period, at least fifteen minutes of which was to be devoted
to discussion. This unusual timing was possible because of the fact
that the participants had received the papers well before the symposium
took place, and had been asked to submit their comments and questions
in writing preferably before, but also during, the symposium.

Voluntary papers were also invited, to be submitted in the form of
expanded abstracts with a minimum of 2 and a maximum of 4 pages. These
were available to all participants during the symposium. To stimulate
meaningful discussions, the authors were asked to include specific
information, such as tables, graphs, and selected key references. They
were encouraged to submit the complete papers elsewhere as well.
Each expanded abstract was reviewed by a member of the organizing
committee. Preprints of keynote papers and expanded abstracts were
prepared by Messrs. T. Beekman and J. van Manen of ILRI.

The present book consists of the keynote papers, the expanded
abstracts, and the discussions during the symposium, the latter only
insofar as questions and answers were submitted in writing, to the
symposium committee. Thus, not all exchanges are reflected in these Proceedings. All authors were given the opportunity to submit corrected versions of their papers.

Heavy clay soils occupy large areas of the world. Their complex and variable structure leads to intricate patterns of water and solute movement. This book shows that the soil surveyors, experimentalists, theorists, and the scientists who are building (computer) models are, individually and jointly, facing up to the challenges that these soils present. We hope that the symposium and these proceedings will prove to be a contribution towards a more mature assessment of the problems and potentials of heavy clay soils.

The editors.
CONTENTS

THEME 1: DEVELOPMENT OF STRUCTURAL PATTERNS IN SWELLING AND SHRINKING CLAYS

Development of structural and microfabric properties in shrinking and swelling clays *
L.P. Wilding and C.T. Hallmark

Mechanics of cracking soils *
P.A.C. Raats

Mechanics of colloidal suspensions with application to stress transmission, volume change, and cracking in clay soils
J.R. Philip, J.H. Knight and J.J. Mahony

Extent and dynamics of cracking in a heavy clay soil with xeric moisture regime
D.H. Yaalon and D. Kalmar

Evolution of crack networks during shrinkage of a clay soil under grass and winter wheat crops
V. Hallaire

Cracking patterns in soils caused by shrinking and swelling
K.H. Hartge

Crack formation in newly reclaimed sediments in the IJsselmeerpolders
K. Rijniersce

A technique for the description of the crack pattern and for predicting the hydraulic efficiency of heavy soils
F. Dolezal, S. Hrín, R. Mati, J. Harmoci and M. Kutilek

Variations in hydraulic conductivity under different wetting regimes
P.B. Leeds-Harrison and C.J.P. Shipway

Structural changes in two clay soils under contrasting systems of management
L.A. Mackie, C.E. Mullins and E.A. FitzPatrick

* keynote paper
** paper submitted but not presented
Effect of Al-hydroxyde on the stability and swelling of soil (clay) aggregates
A. Muranyi and M.G.M. Bruggenwert

Change of structure and fabrics of clay alluvial soils under agriculture **
S.A. Avetjan, B.G. Rozanov and N.G. Zborishuk

Relation between the density of heavy clay soil and its moisture content **
B.G. Rozanov, N.G. Zborishuk, G.S. Kust and J.L. Meshalkina

THEME 2: TRANSPORT PHENOMENA: WATER MOVEMENT

A distribution function model of channelling flow in soils based on kinematic wave theory *
K. Beven and P. Germann

Mathematical models of water movement in heavy clay soils */**
Ya.A. Pachepsky and N.G. Zborishuk

Some theoretical and practical aspects of infiltration in clays with D = constant *
M. Kutilek

Hydraulic conductivity and structure of three Australian irrigated clays
J. Loveday and J.M. Cooper

Rapid changes in soil water suction in a clayey subsoil due to large macropores
H.H. Becher and W. Vogl

Rainfall infiltration into swelling soils
J.V. Giraldez

Field evidence for a two-phase soil water regime in clay soils
A.C. Armstrong and R.A. Arrowsmith

Infiltration of water into cracked soil
V. Novák and A. Soltész

The role of earthworm channels in water flow on a drained clay soil
J. Urbánek and F. Dolezal

Seasonal changes in soil-water redistribution processes affecting drain flow
I. Reid and R.J. Parkinson
Impact of water relations of vertisols on irrigation in Sudan (Field studies on Gezira clays)
O.A. Fadl 160

Seasonal changes of hydric and structural behaviour in clay soils with saline watertables on the coast of Languedoc, France
J.C. Favrot, R. Bouziques and Ph. Lagacherie 167

Water regime of a mole drainage experiment on a heavy clay soil of the Sologne area (France)
B. Lesaffre, M. Normand and G. Valencia 171

Soil variability and hydraulic restrictions: in the marshland of the West Central Atlantic region of France
P. Collas, L. Damour and Y. Pons 178

Simulation of the hydraulic behaviour of a plot of drained and tilled marshland
J. Duprat 185

Hydraulic and hydrological operating of a field experiment in Lorraine heavy clay soil over a period of eight years
B. Lesaffre, R. Morel, A. Kinjo, L. Florentin and F. Jacquin 191

Tritiated water movement in clay soils of a small catchment under tropical rainforest in North-East Queensland **
M. Bonell, D.S. Cassells and D.A. Gilmour 197

Factors conditioning the surface waterlogging of leached clay chernozems in Bulgaria **
M. Pencov, B. Djuminski and T. Palaveev 202

THEME 3: TRANSPORT PHENOMENA: SOLUTE TRANSPORT

Water and solute movement in a heavy clay soil *
D.E. Smiles and W.J. Bond 205

Analysis of solute movement in structured soils *
J. Skopp 220

Salt transport in heavy clay soil *
J.W. van Hoorn 229

Effect of anion exclusion on solute transport in soil
W.J. Bond 241

Evaluating a model for nitrate leaching in clay soils with macropores
R.E. White 246
Soils and solute patterns in reclaimed estuarine marshland in South-East England  
P.J. Loveland, R.G. Sturdy and J. Hazelden 252

Transport of solutes in highly structured soils  
M. Loxham 258

Solute displacement through a Rendzina  
R. Schulin, P.J. Wierenga and H. Flühler 262

Some theoretical aspects of the influence of soil-root contact on uptake and transport of nutrients and water  
P. de Willigen 268

Improvement in leaching efficiency of a silty clay loam soil through application of sand  
H.S. Sen and A.K. Bandyopadhyay 276

THEME 4: MEASUREMENT AND SIMULATION TECHNIQUES

Modelling the interaction between solute leaching and intra-ped diffusion in clay soils  
T.M. Addiscott 279

Using soil morphology to develop measurement methods and simulation techniques for water movement in heavy clay soils  
J. Bouma 298

NMR Measurement of water in clay  
R.F. Paetzold and G.A. Matzkanin 316

The time response characteristics of tensiometers in heavy clay soils  
G.D. Towner 320

The moisture characteristic of heavy clay soils  
L. Stroosnijder and G.H. Bolt 324

Computer optimization of a heavy soil drainage system by two-dimensional saturated-unsaturated water flow modelling  
N. Shopsky, I. Nickolov and E. Doneva 330

Use of the neutron probe and tensiometers to monitor gravity irrigation in soils of low permeability  
J.M. Allard and O. Auriol 334

The role of structure for the compressibility and trafficability of heavy clay soils  
R. Horn 342
The measurement of soil structural parameters by image analysis
A. Ringrose-Voase and J. Bullock

List of participants
Development of structural and microfabric properties in shrinking and swelling clays

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Abstract

Soil structure in the pedological context is the physical constitution of soil material expressed by size, shape and arrangement of solid particles and voids into secondary polyhedral assemblages of primary particles. The secondary units (peds) are separated from adjoining cohesive aggregates by natural surfaces of weakness. Surfaces of weakness include simple or compound concentration coatings (cutans) of sesquioxides, clays, organic-clay complexes, carbonates, albic materials, and/or rearrangement of in situ clay plasma by stress. In high shrink-swell clay systems, structural surfaces are commonly generated by microshear, macroshear (slickensides), or plastic deformation stresses. Microfabrics are lattisepic, vosepic, masepic, skelsepic and crystic. Several generations of structural formation and subsequent instability are evident from microfabric analysis. Size of structural units is generally smallest near the surface and increase with depth while strength of structural development is the converse. While cutanic surface features may comprise only a small proportion of the ped bulk volume, their impact on inter- and intra-ped solute and water transfer may be inordinately great. Structural units are stabilized by interparticle bonding associated with organic matter, amorphous inorganic compounds, and silicate clays. Bonding forces include polar and non-polar van der Waal forces, coulombic attractions, and organic chelation - complexation of polyvalent metals at silicate surfaces.
Pedologically, structure may be defined as the arrangement of sand, silt and clay into aggregates and the arrangement of these aggregates (including pores) into a composite pattern (Baver et al., 1972). Soil Survey Staff (1975) defines soil structure as "the aggregation of primary soil particles into compound particles, or clusters of primary particles, which are separated from adjoining aggregates by surfaces of weakness". This is essentially the concept of "pedality" as defined by Brewer (1976) and is the definition of structure to be used herein. Field pedologists have long recognized structure and its spatial variability as important attribute that directly or indirectly determines soil porosity, transfer of liquids and solutes, plant rooting volumes, and the intensity, mode and mechanisms of pedogenic development.

Pedologists qualitatively describe structure in terms of shape (type), size (class) and strength (grade) of development (Soil Survey Staff, 1975). Few advances have been made to further quantify structure for more definitive interpretations of soil management and hydrological interpretations (Bouma, 1983).

Processes responsible for structural development are physical, chemical, and biological. In cracking clayey soils, surface horizons are commonly granular, angular blocky, or subangular blocky. In subsoils prismatic, angular blocky, wedge-shaped aggregates, or compound prismatic-blocky structure occurs. Size increases with depth while grade decreases. Excellent reviews on this topic for Vertisols have been presented by Blokhuis (1982) and Ahmad (1983). Microfabrics of Vertisols and Vertic intergrades have been summarized by Nettleton et al. (1983). Baver et al. (1972) and Martin et al. (1955) have also provided extensive reviews on soil structure and aggregation. The purpose of this paper is to outline modes of structural aggregate formation, to consider means by which aggregates are stabilized and to present macro and micromorphical evidence that structure in clayey soils controls water and solute movement.
Formation of structural aggregates

Major processes in the formation of aggregates in soils are desiccation, shear failure, and biological activity.

2.1 Desiccation

Upon desiccation and dewatering of saturated sediments, open fabrics become denser and more compact. Edge to edge orientation of clays become face to face, and clays become oriented around sand and silt skeleton grains. Contractual forces exceed tensile strength, and polygonal fractures develop to form very coarse prismatic structure. Prisms subsequently part along bedding planes to form coarse angular or subangular blocky, and thick platy structure (Pons and Zonneveld, 1965; Mitchell, 1976; Pons and Van der Molen, 1973). Fabric reorientation is in response to contractive capillary water forces pulling particles closer together as water content decreases (Figure 1).

Figure 1. A schematic to illustrate the effect of drying on packing of moist powders. (1) capillary attraction drives particle b from initial position (discontinuous line) toward particle a; (2) contractible force of menisci m will bring adjacent particles closer together and may cause collapse of vault above c (modified from Biekerman, 1958, p. 36).
Grossman (1983) reports that once the new orientation has been assumed, wetting alone without accompanying mechanical disturbance does not restore the original fabric and its original high water content. This irreversible change in fabric organization would be expected to enhance upon increasing frequency of desiccation-rewetting cycles and with proximity to the soil surface; hence, smaller aggregates should be expected and are commonly found at or near the soil surface.

2.2 Shear Failure

Wedge-shaped aggregates in subsoils are formed by intersecting shear planes (slickensides) whenever the swelling pressures of a confined system exceed the shear strength of the soil (Yong and Warkentin, 1975; Yaalon and Kalmar, 1978; Blokhuis, 1982; Ahmad, 1983). The shear strength of a clayey soil is a function of cohesion which is dependent on bulk density, clay content, clay mineralogy and moisture content (McCormack and Wilding, 1979). Upon wetting and subsequent swelling of a dry soil, vertical and lateral stresses are generated (Figure 2A). In unconfined surface horizons, vertical stresses are relieved by upward movement. When the vertical stresses are confined and lateral stresses exceed the shear strength, failure occurs along a grooved shear plane approximately at 45° to the horizontal (Figure 2B), but in practice from 10 to 60° (Smart, 1970). In subsoils, overburden pressures confine vertical movement; upon crack closure, and when swelling pressures exceed the shear strength, the soil fails along diagonal shear planes. Often such mechanisms give rise to tilted lenticular (bicuneate) or larger wedge-shaped aggregates (Blokhuis, 1982; Ahmad, 1983). Several factors appear to determine the depth and character of such aggregates including: seasonal wetting-drying patterns, organic matter content, clay content, clay mineralogy, saturating cation species, and maximum difference in water content between wet and dry cycles. Shrinking and swelling is an equidimensional phenomenon (Yule and Ritchie, 1980). It's magnitude is positively correlated with the external surface area (size) of colloids, independent of mineralogy (Dixon, 1982; Wilding, 1984).
2.3 Biological Activity

Granular aggregates in soils are commonly formed by the mixing of organic and mineral constituents by biota particularly arthropods and annelids (Kubiena, 1970; Ugolini and Edmonds, 1983). Earthworms have often been noted for their effectiveness in developing a granular sponge-like structure in surface horizons by forming coalescent worm droppings (Kubiena, 1970).
This promotes high infiltration, high water-holding capacity and good aeration. Fibrous root systems and root, fungal and bacterial metabolites also favor formation and stability of granular structure (Baver et al., 1972; Ugolini and Edmonds, 1983). The role of roots may be to separate larger aggregates into smaller granules or to desiccate soil around the root causing shrinkage and formation of fracture planes (Baver et al., 1972).

3 Stabilization of aggregates

The stability of aggregates is a function of two factors—the relative degree of cohesion within aggregates versus adhesion among aggregates. Water-particle interactions and cementation by organic matter, sesquioxides, silica, carbonates and clay impact cohesion. Adhesive forces are dependent on surfaces of weakness that separate abutting natural aggregates and the degree of surface accommodation among peds.

3.1 Surfaces of weakness
3.1.1 Plasma concentrations

Translocation of mobile constituents (plasma) during pedogenesis often results in concentrations or coatings of plasma along ped surfaces (Figures 3A, B, C, D). The two most commonly cited processes for formation of these features are illuviation and diffusion (Brewer, 1976). Illuviated clays (argillans) that occur along ped surfaces are indicative of ped stability requiring geologic periods of time (several thousand years) to form. Illuviated argillans exhibit optical birefringence (Figure 3A) and extinction phenomena indicative of their crystallinity, continuity, thickness, orientation, packing density and distribution. They are commonly laminated indicating deposition in successive increments.
Figure 3. Thin section micrographs taken in cross-polarized light illustrating: (a) illuviated argillan along a channel void (Btg horizon, Fulton series, Aeric Ochraqualf, Ohio); (b) gysan and carbonate nodule along a planar ped void (Btky horizon, Lufkin series, Vertic Albaqualf, Texas); (c) calcan along a channel void (Bk horizon, Algoa series, Aquic Calciustoll, Texas); (d) calcan along a channel void in oxidized calcareous glacial till (C horizon, Celina series, Aquic Hapludalf, Ohio) (e) stress-oriented plasma separation around a skeleton grain in a skelsepic plasmic fabric (Bt horizon, Rumple series, Udic Argiustoll, Texas); (f) stress-oriented plasma separations along planar ped voids in a vosepic plasmic fabric (Bg horizon, Toledo series, Mollic Haplaquept, Ohio); and (g) plamsa separations in masepic plasmic fabric indicating microshear failure (A horizon, El Carmen series, Typic Pellustert, El Salvador). Bar length is equal to 2 mm. (a = argillan, c = calcan, cn = carbonate nodule, g = gysan, s = plasma separation and v = void.)
Ped instability is indicated by embedded illuviation argillans and stress-oriented plasma separations within the s-matrix (Smeck et al., 1968; Smith and Wilding, 1972; Rostad et al., 1976; Ritchie et al., 1974). Embedded argillans often outline former structural units. Ped instability appears greatest in soils that have high shrink-swell potential, high clay content, and expandable 2:1 layer clay minerals (Ritchie et al., 1974). Shrink-swell activity and ped instability may become so great in some soils as to deter formation of illuviation cutans or destroy preexisting cutans (Nettleton et al., 1969 and Smeck et al., 1981).

Other cutanic or subcutanic plasma concentrations that occur at ped surfaces include: carbonates (calcans, Figure 3C, D), gypsum (gypsans, Figure 3B), silica (silans), iron oxides (ferrans), manganese oxides (mangans), sesquioxides (sesquans) and albic materials (skeletans or albans). These cutanic features also represent surfaces of weakness because of their differential composition, texture and particle orientation with the host ped s-matrix.

3.1.2 Plasma separations (stress reorientation)

Cutans in clayey soils can also be formed by differential swelling pressure causing macro and microshear planes with translational or plastic flow deformation (Crampton, 1974; McCormack and Wilding, 1974; Wilding, 1984). Grooved and polished slickensides result from translational shear along the failure zone while plastic deformation causes reorientation as pressure faces that often lack the shiny, grooved appearance (Blokhuis, 1982).

In thin sections, microshear planes are identified by linear oriented patterns of striated clay aggregates that exhibit preferential plate orientation and optical birefringence (plasma separations, Figure 3E, F, G). Figure 4 schematically illustrates postulated stages in developing stress-oriented plasmic fabrics in high shrink-swell clayey soils.
Figure 4. Schematic stages of wetting as water front advances into blocky ped, showing postulated direction of strain and shear planes commonly found within structural units of high shrink-swell soils. Taken from Figure 5, McCormack and Wilding, 1973.

The process involves wetting a dry soil with strongly expressed prismatic-blocky structure. Differential wetting, swelling and development of microshear, first in the horizontal and then in the vertical axis, are proposed. Strong anisotropic wetting and swelling patterns are in response to the size and patterns of the structural voids (McCormack and Wilding, 1974; Ahmad, 1983). In shrinking and swelling clayey soil systems with moderate to high shrink-swell potential, microfabrics reflecting microshear and ped instability yield skelsepic (Figure 3E), vosepic (Figure 3F), lattisepic, masepic (Figure 3G), and combinations of these plasmic fabrics (Holzhey et al., 1974; Nettleton et al., 1969, 1983; Smeck et al., 1981; Blokhuis, 1982).

Crystic is also a common plasmic fabric in Vertisols (Wilding, 1984). The degree of stress-oriented soil fabric is inversely related to the
occurrence of illuviation argillans. Stress oriented plasmic fabric can also be generated by root pressure, mass movement, and ice crystal growth.

3.2 Cementation effects: Bonding of soil separates in aggregates

Bonding between particles is possible only when particles are sufficiently close for bonding mechanisms to become effective. Therefore, physical rearrangement to increase the proximity of particles may be necessary. This is accomplished by processes including flocculation, hydration-dehydration, shrinking-swelling, freezing-thawing, movement by gravity, and forces exerted by roots, earthworms, and other biota. For significant structure formation to endure, bonding must be sufficiently strong to withstand destruction from these same physical forces.

Bonding among particles is primarily attributed to organic matter, silicate clays, and amorphous oxy-hydroxy compounds of Al, Fe, and Si although cementation and engulfment of soil particles by relatively large quantities of calcite, amorphous silica (and opal), gypsum, crystalline Fe-oxide, and illuviated organic-metal compounds are known (Soil Survey Staff, 1975). Temporal to long-term bonding of soil separates is imparted by organic matter. Temporary bonding is primarily from physical entanglement of soil separates by filamentous structures of the microflora, principally fungi and actinomycetes (Swaby, 1949). Such structures are short-lived as the microbial bodies are substrate for subsequent decomposition by microbes. The bonding by polysaccharides (long chain, flexible polymers of varying content of alcohol, amino, carboxyl and phenolic groups) is more long-term than filamentous structures, but eventually they too are decomposed by microbes (Fehrmann and Weaver, 1978; Harris et al., 1963).
Evidence suggests that long-term bonding by organic matter is due primarily to microbial resistant fractions, most notably the humic acids.

The bonding of soil particles by both crystalline and amorphous Fe, Al, and Si forms is easily recognized in extreme cases (Soil Survey Staff, 1975). However, in less acute concentrations, bonding by these compounds is not readily obvious. Deshpande and co-workers (1964, 1968) found oxy-hydroxy Al compounds to be more important to aggregate stability than Fe oxides when levels were sufficiently low to preclude engulfment of the soil separates. Recent work on loamy fragipans indicates amorphous Si, Al, and Fe compounds even in low quantities are important in imparting brittleness and strength to the fragipan (Hallmark and Smeck, 1979; Steinhardt and Franzmeier, 1979).

The importance of silicate clays in bonding soil separates together has been long recognized because stable aggregate formation seldom takes place in sand or silt in the absence of these colloids. Preferential orientation of silicate clays in structural units occurs and has been observed as links between adjacent sand-silt grains (Wang et al., 1974). In fine-textured soils, the clay may occur as a dense groundmass surrounding sand and silt separates. Hydration state, exchangeable cation and soil solution salt content affect the expansion and orientation of silicate clays and undoubtedly their ability to bond within structural units.

Although organic matter, amorphous inorganic compounds and silicate clays are generally recognized as instrumental in structure development, the mechanisms of bonding are poorly understood. Greenland (1965) recognized that coulombic attractions and van der Waals forces (both polar and non-polar) were involved in the interaction of clays and organic compounds. The multiplicity of soil organic matter functional groups (i.e., carboxyl, amines, hydroxyls, carbonyls, etc.) provides for chelation-complexation of multivalent cations on crystalline silicate edges or on amorphous coatings of soil minerals.
Although the intercrystalline forces between adjacent clay particles may be sufficiently strong to account for binding in aggregate formation (Martin et al., 1955), recent work showing the amorphous nature of outer silicate surfaces suggests that bonding or polymerization across mineral grains through an amorphous phase is likely (Ribault, 1971). Such a mechanism would allow coherence of clay particles to quartz sand grains as well as between silicate clay particles.

The importance of macrovoids on saturated water movement and dissolved solutes has steadily gained the attention of soil physicists and chemists (Blake et al., 1973; Bouma, 1983; Ritchie et al., 1972; Kissel et al., 1973; and Thomas, 1970). There is also substantial evidence from a pedological perspective that water moves preferentially along ped interfaces. The evidence is based on the following observations: (1) immobilization of suspended clay that is carried in an advancing water front along structural surfaces and other macrovoids (Figure 3A); (2) ped interfaces that have higher moisture contents and lower strengths than ped interiors (McCormack and Wilding, 1979); (3) occurrence of calcans (Figure 3D), ferrans, mangans, and argillans along vertical fissures and prisms in oxidized and unoxidized sedimentary deposits 4 to 8 m below the surface (Smeck et al., 1968; Smith and Wilding, 1972; Ritchie et al., 1974); (4) occurrence of roots preferentially distributed along structural surfaces (Miller et al., 1971; Ritchie et al., 1974); (5) occurrence of albans and skeletans (albic materials) along ped surfaces (Vepraskas et al., 1974; Vepraskas and Wilding 1983a, 1984b); (6) occurrence of soluble salts (gypsans Figure 3B), and silica (silans) along structural conductive voids (Brewer, 1976); and (7) the preferential flow of water along ped surfaces and other macrovoids upon pit excavation in a saturated soil.
Soils are not homogeneous media either on a macro or micro scale. They have vertical and lateral anisotropic properties with both systematic and random spacial dependence (Wilding and Drees, 1983). At the level of a ped, zonation of plasma and skeleton grains is common. Although ped cutans may comprise less than 1 or 2% of the total soil volume, they may impart a disproportionally large environmental influence on the soil as a medium for plant growth (Miller and Wilding, 1972). The pattern and orientation of slickensides in Vertisols and associated gilgai topographic relief give rise to cyclic subsurface horizonation, with strikingly different leaching potentials between microlows and microhighs (Ritchie et al., 1972; Wilding, 1984). Ped argillans have been demonstrated to markedly reduce rates of diffusion and mass flow from the ped surface to the s-matrix (Gerber et al., 1974). This impact on water movement is due primarily to increased tortuosity, but chemical interactions may be important with solute transfer depending on the mineralogical composition of the cutan and species involved. Khalifa and Buol (1968) and Miller and Wilding (1972) conclude that argillans have deleterious effects on fine root penetration into a ped and upon nutrient uptake.

Losses of soluble nutrients from the root zone will be enhanced by a water front that moves preferentially along structural voids and short circuits the s-matrix during the wetting phase in cracking clay soils (Bouma, 1983; Kissel et al., 1973; Thomas, 1970). This likewise has important implications on the suitability of soils as a media for disposal for toxic and non-toxic wastes. Conversely, leaching, weathering and nutrient transfer out of the s-matrix will be retarded by short circuit water movement through cracks of clayey soils. This is evidenced by ped interiors that are calcareous while superjacent ped exteriors have been leached of carbonates.
Summary

In clayey, high shrink-swell soil systems, ped interfaces and Biological macrovoids represent the major avenues of water movement. Strongly anisotropic wetting, swelling and shear patterns in these soils govern structural type, stability and preferential water and solute movement.

REFERENCES


Deshpande, T. L. D. J. Greenland, and J. P. Quirk. 1968. Changes in


Discussion

T.M. Addiscott:
I was interested in your comment on the effects of cutans, etc. on intraped diffusion. Are such effects likely to differ much between peds from uncultivated horizons and those at the surface, where fresh surfaces are produced by breakage during cultivation?

Author:
Most of the cutans, which consist of coatings with modified physical, chemical, or biological properties on ped surfaces are in subsoils and would only be important in cultivated surface horizons if these subsoil materials were incorporated into the surface by plowing eroded soil areas or where soils had thin surface horizons naturally. However, cutans resulting from rearrangement with preferred orientation parallel to the surface of the aggregates are common in many clayey surface horizons as a consequence of both natural and tillage-induced plastic deformation and perhaps desiccation.

J. Bouma:
You list six types of observations from which evidence is deduced that water moves preferentially along ped faces. You do not mention staining tests which have been applied by several investigators, who found stains exclusively on ped faces. Is there a particular reason for not mentioning this approach?

Author:
No. It is really an oversight in the paper and should be added to the list. Certainly dyes and solutions of CaSO$_4$·1/2H$_2$O (plaster of Paris) are direct means to demonstrate water movement along ped faces and via biological macrovoids. We have used dye methods to monitor the movement of organic toxic wastes through clay liners which have failed. In our paper we have put the emphasis on observations related to natural pedogenic transfers.

H.F.M. ten Berge:
Associated with diurnal temperature waves in the topsoil are 'waves' of moisture content. A damping depth for moisture can be defined as
PD/\pi, where P is the period (one day) and D is the soil water diffusivity. Do you expect that a causal relationship exists between, on the one hand, this damping depth and the amplitude of the water content and, on the other hand, the size of the peds?

Author:
I would expect a causal relationship of this kind to exist, but not induced by diurnal temperature waves. I believe the time scale involved is too short to result in maximum fluctuation in water content necessary to result in tensile stress failure. The rate of water transmission from the matrix of a clayey soil is slow. This, coupled with the break in capillary pore continuity associated with the 'dust mulch' or 'self mulching' effect near the soil surface, would make the rate of desiccation a long-term event of the order of weeks or months.

H.F.M. ten Berge:
Under the climatic conditions where Vertisols may occur, diurnal fluctuations in topsoil temperature may cover 50°C or more. Do you expect that these diurnal temperature waves play an important role in crack formation?

Author:
No. Our experience, and that reported in the literature, indicate that crack formation upon entering the drying cycle requires weeks or months to initiate. It is, again, a long-term process relative to diurnal changes.

D.H. Yaalon:
Which micromorphological feature would you consider as best evidence of turbation in Vertisols? Have you observed in thin sections indications of surface material falling into cracks?

Author:
As I reported on the genesis of Vertisols at the International Soil Classification Workshop in the Sudan two years ago, I am not a strong proponent of the pedoturbation model for these soils. In fact, based on organic carbon, carbonate, and salinity profiles, I do not believe they strongly churn. This suggests to me that most of
the physical activity in these soils is upward or downward thrust along the slickenside planes that act as fault zones and avenues for preferential root growth, and water and solute movement. Thus no unique micromorphic features can be attributed to Vertisols that are not also recognized in other orders of soils that shrink-swell and crack to a more limited extent. Occasionally, microscopically and macroscopically, one observes partial crack infilling that looks similar in thin section to other tubular infillings. Again, these features are not unique to Vertisols. Evidence of sepic fabrics with plasma separations are most indicative of high shrink-swell and microshear properties.

D.H. Yaalon:
Please note that on Figure 2 the shear plane angle is not 45°, while theoretically it should be 45° minus the angle of internal friction/2, which essentially accounts for differences in particle arrangements and their mineralogy.

Author:
Your comment is well taken and, in fact, true. However, in this model I had assumed the angle of internal friction was quite small because the skeleton grains are sufficiently widely spaced that they do not interlock, and the effect of clay mineralogy was not considered.

G.P. Wind:
It has been observed in the Netherlands that in heavy clays under grassland high-quality drainage (deeper drains, spaced closer together) causes smaller clods and smaller cracks than low-quality drainage. Can you explain this?

Author:
I believe the explanation for this phenomenon lies in the fact that deeper drains with closer spacing lower the water table more uniformly across these areas. This favors larger and more frequent fluctuations of the water content near the soil surface. Both of the latter processes should enhance the development of smaller structural units with greater stability, as noted in our paper.
How thick are the cutans on ped surfaces, and how far does moisture penetrate into the ped matrix?

Author:
Cutan thickness varies with the pedogenic processes under which a soil has developed, the depth in a soil, and whether one is considering a plasma concentration (coating) or plasma separation (stress orientation) feature. Plasma concentrations may range from 10 μm or less to several millimeters, while plasma separations are invariably thin (5-10 μm). In the latter case, plasma separates (micelles) may assume parallel orientation with the planar void surface at 100 μm or slightly deeper into the s-matrix.

No suitable answer can be given to the second part of your question, except that obviously the ped surfaces are the most dynamic zones, while ped interiors are the most static regions to water and solute movement.

Comment by F.F.R. Koenigs at end of symposium

Wilding’s concept of the origin of slickensides is based on lateral compression and subsequent failure of the soil mass by the expansion on wetting of dry material fallen into vertical cracks. But according to Yaalon, no substantial amounts of material are falling into cracks. So another approach is needed and, for that, one might start from the wet end. As far as I have seen, the best lenses (lentiform, 2 m wide units delineated by slickensides) are found in drying lake deposits of montmorillonite clay. Of these, those with a known history and especially those which have been reclaimed fairly recently are of most interest. In case of the deposits of the Tisza River (in Hungary and Rumania, reclaimed 200 years ago) only slickensides and lenses are found and no vertical cracks or prisms. The volume loss after drainage will be of the order of 70%. The resulting horizontal tensile stresses can cause failure planes (see the following paper by Raats). The lenses delineated by these planes slump and slide over each other thus causing the slickensides.

I close with three comments on related matters: 1. Philip pointed out that stress relief near a crack is accompanied by a rise of the soil along the edges of the crack. This has often been observed. 2. Hartge demonstrated the importance of friction with underlying layers. If the friction is small, then the soil can travel considerable distances without cracking. I have observed that filterpaper may be torn, and that a sintered glass plate may break. 3. The tensile strength is the crucial parameter for crack formation. It is recommended that measurements of this parameter are made in the near future.
Abstract

The deformation gradient tensor of the solid phase is the central concept in the description of swelling and shrinkage of soils. The appearance of slip surfaces and cracks is governed by relationships among the stress tensor and parameters characterizing the strength of the soil. An analysis of the perturbation of stress induced by a crack gives some insight in spacings, angles of intersection, and depths of cracks.

1 Deformation of the solid phase

A description of the motion of the solid phase of a soil gives the places occupied by any parcel \( \chi_S \) of the solid phase in the course of time \( t \) (Raats, 1984a):

\[
\tilde{x} = \tilde{x} [ \chi_S, t ]
\]  

(1)

As labels for the parcels \( \chi_S \) one may use their locations \( \chi_o \) in the reference configuration at some reference time \( t_o \). Differentiation of (1) with respect to \( t \) and \( \chi_S \) gives, respectively, the velocity vector \( \dot{\chi}_S \) and the deformation gradient tensor \( F_S \):

\[
\dot{\chi}_S = \frac{\partial \chi}{\partial t} \bigg|_{\chi_S}, \quad F_S = \frac{\partial \chi}{\partial \chi_S} \bigg|_{t}
\]  

(2)
The determinant of $\mathbf{F}_s$ for a parcel $\chi_s$ compares the volume currently occupied by the parcel to the volume occupied in the reference configuration. It can be related to a concept more familiar in soil science by considering the isotropic, homogeneous swelling of a cube with current edge $l$ and edge $l_0$ in the reference configuration. Then

$$\det \mathbf{F}_s = (1/l_0)^3,$$

and the coefficient of linear extensibility, $\text{COLE}$, can be defined by:

$$\text{COLE} \equiv \frac{1 - l}{l_0} = (\det \mathbf{F}_s)^{1/3} - 1$$

For isotropic, homogeneous shrinkage of a cube, the negative of $\text{COLE}$ is defined as the coefficient of linear contractibility, $\text{COLC}$.

The measures of deformation $\text{COLE}$ and $\text{COLC}$ are mainly useful to describe the volumetric aspects of isotropic homogeneous deformations. By contrast, the deformation gradient tensor $\mathbf{F}_s$ can be used to describe all aspects of any continuous deformation. Not only $\text{COLE}$ and $\text{COLC}$, but numerous other concepts describing various aspects of deformations can be derived from $\mathbf{F}_s$ (Truesdell and Toupin, 1960). In particular, it can be shown that the deformation at any point may be regarded as resulting from a translation, a rigid rotation of the principal axis of strain, and stretches along these axis.

The deformation gradient tensor $\mathbf{F}_s$ plays a key role in the description of movement of water in deforming soils (Raats, 1984a, b). Disregarding the influence of gravity, so that the gradient of the pressure head $h$ is the only driving force, and using the solid phase as a reference, the product of the volumetric water content $\theta$ and $\det \mathbf{F}_s$ can be shown to satisfy a nonlinear, inhomogeneous diffusion equation (Raats, 1984b):

$$\partial (\theta \det \mathbf{F}_s)/\partial t|_{\chi_s} = \partial \{\mathbf{D} \partial (\theta \det \mathbf{F}_s)/\partial \chi_s\}/\partial \chi_s$$

with the transformed diffusivity tensor $\mathbf{D}$ given by
and in turn $D$ related to the hydraulic conductivity $k$ by:

$$D = k \frac{d}{dh} \left( \det F_s \right)$$

As a special case, it can further be shown that for flow in the axial direction of a swelling and shrinking, thin, porous rod (6) reduces to (Saats, 1969):

$$\Theta = (\det F_s)^{-1} \frac{2n-1}{2} D$$

Figure 1 shows plots of (8) for purely axial deformation ($n=1$), purely lateral deformation ($n=0$), deformation for which the effects of the axial and lateral deformations upon the diffusivity cancel each other ($n=\frac{1}{2}$), isotropic deformation ($n=\frac{1}{3}$), and also for $n=\frac{2}{3}$. The value $n=\frac{1}{2}$ separates two opposite trends. For $n < \frac{1}{2}$ swelling causes $\Theta/D$ to increase and shrinking causes $\Theta/D$ to decrease. For $n > \frac{1}{2}$ swelling causes $\Theta/D$ to decrease and shrinking causes $\Theta/D$ to increase.

Figure 1. Transformed diffusivity tensor for flow of water in the axial direction of a swelling and shrinking, thin porous rod

The case of purely axial deformation has been studied in great detail, yielding valuable results with regard to equilibrium of water, steady upward and downward flows of water, adsorption and infiltration of
water, and sedimentation and filtration of slurries (Philip and Smiles, 1982). But in many cases there is a need for a 2- or 3-dimensional stress-strain theory (Miller, 1975). Even splitting of parcels $\chi_s$ must be dealt with: shrinkage may lead to cracks (Corte and Higashi, 1960; Neal et al., 1968; Blokhuis, 1982) and swelling may lead to slip surfaces (Krishna and Perumal, 1948; De Vos et al., 1969). Tension cracks may also be induced by penetrating roots (Barley et al., 1965) and the passage of wetting fronts (Dexter, 1983; Parlange and Sawhney, 1976).

In the next Section two crack-slip failure criteria are discussed briefly. In Section 3 a theory for stress perturbation due to the presence of cracks is summarized.

2 Two crack-slip failure criteria

At any point within the soil the force upon any surface through that point is determined uniquely by the normal to that surface. By using the balances of momentum and moment of momentum, it can be shown that the forces upon all surfaces through any point are determined fully by the symmetric stress tensor field $T$. If $\rho$ is the bulk density, $\gamma$ the gravitational force, and $\alpha$ is the acceleration, then

$$\text{div } T + \rho \gamma = \rho \alpha$$

In dealing with soils, force balances can be written for each of the phases and for the soil as a whole. The symmetry of $T$ implies that, at any point, $T$ is completely determined by three principal stresses $T_1$, $T_2$, and $T_3$ associated with the principal directions $n_1$, $n_2$, and $n_3$. Given $(T_1, T_2, T_3)$ and $(n_1, n_2, n_3)$ at a point the normal stress $T_n$ and the shear stress $T_s$ on any plane through that point can be calculated or determined graphically by Mohr's circle diagram.

By analogy with friction between separate bodies, in 1773 Coulomb formulated a simple criterion for slip failure of a granular material (Jaeger and Cook, 1979). According to Coulomb's criterion slip failure will
occur if on any plane the shear stress $\tau_t$, the normal stress $\tau_n$, the angle of internal friction $\psi$, and the shear strength $\sigma_s$ satisfy

$$|\tau_t| - (\tan \psi) \tau_n > \sigma_s$$

If the soil is partially saturated and $\tau_n$ is not an effective but a total stress, then $\sigma_s$ includes a cohesive component due to capillarity. Coulomb's criterion can also be expressed in terms of the major principal stress $\tau_1$ and the minor principal stress $\tau_3$:

$$\tau_1 - \nu \tau_3 > \sigma_c$$

The flow value $\nu$ and the compressive strength $\sigma_c$ appearing in (11) are given by

$$\nu = \tan^2 (\pi/4 + \psi/2)$$

$$\sigma_c = 2\sigma_s \tan (\pi/4 + \psi/2)$$

Figure 2. Two failure criteria
A plot of (11) is shown in Figure 2A. It can be shown that, according to Coulomb's criterion, slip failure may occur in two planes passing through the principal direction \( n_2 \) and making angles of \((\pi/4 - \psi/2)\) with the principal direction \( n_1 \).

In Fig. 2A the intercept on the \( \tau_1 \)-axis is the compressive strength \( \sigma_c \). The intercept \(-\sigma_c/\nu\) on the \( \tau_3 \)-axis could be interpreted as the tensile strength, were it not that cracks normal to the \( n_3 \)-direction occur at some value \( \tau_3 > -\sigma_c/\nu \). To account for this, in 1961 Paul proposed to introduce the tensile strength \( \sigma_t \) as an additional parameter and replace the slip failure criterion (11) by the combined crack/slip failure criterion (Jaeger and Cook, 1979; see also Figure 2A):

\[
\begin{align*}
\tau_3 &< -\sigma_t & \text{if } \tau_1 < \sigma_c - \nu \sigma_t & \quad (14) \\
\tau_3 &< (\tau_1 - \sigma_c)/\nu & \text{if } \tau_1 > \sigma_c - \nu \sigma_t & \quad (15)
\end{align*}
\]

At \( \tau_1 = \sigma_c - \nu \sigma_t \) the Coulomb/Paul (CP) criterion predicts simultaneous occurrence of cracks normal to the principal direction \( n_3 \) and slip surfaces passing through the principal direction \( n_2 \), making angles of \((\pi/4 - \psi/2)\) with the principal direction \( n_1 \). Nadai (1931, pp. 330-331) described an experiment of W. Riedel in which tension cracks and shearing slip surfaces indeed occurred simultaneously. Hartge and Rahle (1983) attempt to distinguish cracks and slip surfaces on the basis of angles between faces of structure elements.

An alternative theory, relating the tensile strength to the growth of pre-existing, minute cracks, was introduced by Griffith in 1921 and further developed by Irwin and by Orowan in the fourties and fifties (Irwin, 1958). On the basis of an analysis of the stress distribution near tips of such cracks, Griffith derived the failure criterion (Figure 2B).

\[
\begin{align*}
\tau_3 &< -\sigma_t & \text{if } \tau_1 < 3\sigma_t & \quad (16) \\
\tau_3 &< \{\tau_1/\sigma_t + 4 - 4 \left[ 1 + \tau_1/\sigma_t \right] \} \sigma_t & \text{if } \tau_1 > 3\sigma_t & \quad (17)
\end{align*}
\]

- 28 -
The tensile strength can be shown to be a function of the energy $G$ associated with the creation of new crack surfaces (Griffith) and/or plastic deformation near the tips of the cracks (Irwin and Orowan), the length $2\lambda$ of the cracks, Young's modulus $Y$ and Poisson's ratio $\nu$ of the soil, and a factor $\alpha$ of order unity depending on the geometry and boundary conditions.

$$\sigma_t = \alpha \left\{ \frac{G}{\lambda} \frac{Y}{(1 - \nu^2)} \right\}^{\frac{1}{2}} \quad (18)$$

For $\tau_1 < 3\sigma_t$, the Griffith/Irwin/Orowan (GIO) criterion predicts cracks normal to the $n_3$ direction. At $\tau_1 = 3\sigma_t$, a gradual change of the orientation of the failure surfaces sets in. By contrast the CP criterion predicts an abrupt change at $\tau_1 = \sigma_c - \nu\sigma_t$.

The GIO criterion implies a value 8 for the ratio of compressive and tensile strengths. According to Farrell et al. (1967) measurements of this ratio range from 3 to 13. They attribute this wide variation to anisotropy, sample preparation, and changes in geometrical configuration under different test conditions. Recently Hettiaratchi and O'Callaghan (1980) presented a mechanics of unsaturated soils incorporating both the GIO failure criterion and the so-called critical state theory. They emphasize the dependence of the mechanical properties upon the water content.

3 Stress perturbation due to presence of cracks

The GIO failure criterion is concerned with the initiation of macro-cracks by growth of randomly oriented pre-existing minute cracks. To understand the spacing, width and depth of macro-cracks, an analysis is required of the perturbation of the original tensile stress field due to the presence of macro-cracks. Lachenbruch (1961, 1962) made such an analysis and applied it to cooling joints in lava and ice-wedge polygons in permafrost. The analysis is based on the linear theory of elasticity. Lachenbruch himself suggested that a drying mud, despite its plasticity, can be expected to conform to the theory in at least a qualitative way.
Such use of the theory of elasticity is rather common in soil mechanics (Koolen and Kuipers, 1983).

It is worthwhile to point out that the application of Lachenbruch's theory to ice-wedge polygons is of interest to soil scientists in its own right. In soils that were once subject to permafrost conditions, relicts of ice-wedges occur widely as wedges filled with foreign material, usually finer than the host material (Christensen, 1974, 1978; de Cans, 1983). Their presence is sometimes revealed by polygonal plant growth and ripening patterns, most clearly in cereal during dry summers. Christensen found that the available water capacity and rootability are the primary causes of the differences in crop growth.

Lachenbruch (1961, 1962) derived two exact solutions for stress fields near cracks in infinite media with, respectively, a step function and a linear function initial stress distribution. From these exact solutions he developed approximate solutions for tension-cracks at the surface of semi-infinite media. The approximate solutions are based on an iterative procedure by which, in the solutions for infinite media, the normal stresses upon the planes of symmetry normal to the cracks are eliminated and at the same time the walls of the cracks are kept stress free.

For the step function initial tensile stress distribution, Figures 3A and B show the relief of the principal stress in the soil surface and normal to the crack as a function of the distance from the crack. The stress relief is expressed in units of the initial tensile stress $P$ and, not surprisingly, in these units varies from full relief of $-1.0$ at the crack to vanishing relief of $0$ at large distance from the crack. The parameter on the curves is the ratio of stress depth $a$ and crack depth $b$. Figure 3A shows that, for a given crack depth $b$, the width of the zone of stress relief is strongly dependent upon the depth distribution of the initial tensile stress. Figure 3B shows that, for a given stress depth $a$, the width of the zone of stress relief increases as the crack depth $b$ increases up to a certain limit. Multiplication of the stress relief normal to the crack by Poisson's ratio ($< 1$) gives the stress relief parallel to the crack. The nature of the anisotropy causes a
Figure 3. Stress relief at the soil surface due to a crack (inserts show the geometries and boundary conditions)
growing crack to orient itself normal to a pre-existing crack. Figure 4 shows a typical pattern of cracks with predominantly orthogonal intersections. The arrows indicate the directions in which the cracks were growing. These directions can be inferred not only from time-series of photographs but also from characteristic markings on the walls of the cracks. Euler's theorem, relating the numbers of vertices, edges, and faces of any convex polyhedron, implies some simple properties of averages of parameters characterizing random crack patterns (Gray et al., 1976; Raats, 1984c). For instance if all junctions of edges are of the types \( \triangle \) and \( \gamma \), then the average number of edges and vertices per polygon is 6.

Figure 3C shows the result for a linear stress distribution. It can be used to account for the influence of the self-weight of the soil.

According to both the CP and GIO theories a crack will be initiated at the soil surface as soon as \( \tau_b \leq \sigma \). At the ('mathematical') tip of a crack the stress will be infinite. At any finite distance from the tip
the maximum stress occurs in the plane of the crack. This stress can be expressed in terms of the radial distance \( r \) from the crack tip and the crack-edge stress intensity factor \( \kappa \) by:

\[
\tau_{\text{max}} = \kappa (2r)^{-\frac{1}{2}}
\]  

(19)

For the step function and the linear function initial tensile stress distribution the crack-edge stress intensity factor \( \kappa \) is of the form

\[
\kappa = \gamma \left[ \frac{a}{b} \right] \sqrt{b} \text{ P or Q}
\]  

(20)

Figure 5 shows the normalized crack-edge stress intensity factor \( \gamma = \kappa / (\sqrt{b} \text{ P or Q}) \) as a function of the stress/crack depth ratio \( a/b \). The \( x \) for an infinite body are exact while the \( * \) for a semi-infinite body are approximate. The latter are for the step function at \( a/b = 1 \) in good agreement with exact results of Wigglesworth and Irwin (Barenblatt, 1962). Lachenbruch (1961, 1962) shows how Equations (19) and (20) and Figure 5 in combination with the tensile strength given by equation (18) can be used to estimate the depths of unstable propagation and of arrest of cracks.

Figure 5. Crack-edge stress intensity factor (part A corresponding to Figure 3A, B and part B corresponding to Figure 3C)
Concluding remarks

Building upon experience with rigid unsaturated soils, the last two decades brought some progress with movement of water in deforming soils. Separately, classical soil and rock mechanics has recently inspired some progress with the mechanics of the solid phase of natural soils. Further progress might be expected from appropriate combinations of the separate disciplines soil physics, soil and rock mechanics, and, last but not least, modern continuum mechanics.

Acknowledgement

I wish to thank G.H. Bolt and C. Dirksen for their constructive criticism.

References


Discussion

D.H. Yaalon:
Could you explain the meaning of the arrows parallel to the cracks in Figure 4? Do they indicate propagation (growth) from a linear or point source? In a random tensional stress field there will be primary and secondary cracks, the latter tending to form at right angles to the primary cracks (cf. Hartge and Rahte, 1983). Hence, the mean number of edges per polygon is 4 to 5, as the figure clearly shows. Hexagons are an exception.

Author:
The meaning of the arrows is given in the text. The directions of crack growth were inferred from successive photographs. Among the sites where cracks originate are the edges of the sample and air bubbles in the mud. If collinear edges of polygons are counted as single edges, then, as the fraction of orthogonal intersections

- 36 -
approaches unity, the number of edges per polygon approaches 4 (cf., Gray et al., 1976). However, if one regards the edges issuing from an orthogonal intersection as separate edges for each of the three adjoining polygons, then the average number of edges per polygon is 6.

S. van der Zee:
Numerical values of the parameters found in the failure criteria are obtained by loading a soil sample in specific ways, implying the application of an external force. However, cracking seems to be more of a pulling apart mechanism than of a compression mechanism. For sand, the moment of failure of a core will occur sooner when pulled apart than in the case of compression. Possibly this is also the case for clayey material. Should not, then, the apparent cohesion (cohesion plus water suction) be a better criterion for cracking of soil, in which case the normal stress due to compression is excluded?

Author:
I agree that, when cracks form, the material is being pulled apart. Figure 2 shows how, in a sense, crack failure overrules slip failure. Just as the shear strength $\sigma_s$ (and thus the compressive strength $\sigma_c$), the tensile strength $\sigma_t$ includes a component due to capillarity. The Griffith/Irwin/Orowan criterion even implies a definite value 8 for the ratio of compressive and tensile strengths.

S. van der Zee:
In Griffith's model, breakage of soil is characterized by elastic behaviour until breakage occurs. Afterwards fractures are found and separation of soil occurs, but no plastic flow. Is this rigid-matrix model applicable to clayey soil with a higher ability to deform, thus showing more plastic behaviour? Is clay, on the verge of cracking, dried to an extent that it does show rather elastic behaviour?

Author:
Griffith's original theory is concerned only with elastic behaviour. Irwin and Orowan extended the theory to include plastic deformation near the tip of the crack.
H.P. Blume:  
What influence do variations in soil temperature have upon forming cracks? You showed soils with sand-filled cracks from Germany and Denmark. In our opinion these cracks are not formed by variations in water content, but by temperature variations during summer and winter times in the ice age. If 0.1-mm-thick cracks of a frozen soil will be filled by wind-blown sand, and this will be repeated for hundreds of years, sand-filled cracks with a diameter of 20–30 cm can be formed. Perhaps the same process will work in soils of the hot deserts by changes in soil temperature between day and night, summer and winter.  

Author:  
The cited papers by Christensen and Lachenbruch are indeed mainly concerned with the process of thermal contraction accompanying freezing.