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SOIL MORPHOLOGY AND PREFERENTIAL FLOW ALONG MACROPORES[1]

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ABSTRACT

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Preferential flow of water along macropores can only be characterized in quantitative terms when the flow system is functionally characterized by using tracers. Standard descriptions of soil structure do not provide adequate information. Expensive micromorphometric techniques allow specific measurements of macropores in terms of size, type, shape and continuity. Inexpensive macromorphometric techniques are attractive for field use.

Preferential flow in saturated soil involves rapid displacement of water from macropores (hydrodynamic dispersion). In unsaturated soil, flow into air-filled macropores (short-circuiting) occurs, which is followed by lateral absorption.

Examples are discussed which illustrate the use of soil morphology to characterize preferential flow along macropores: (i) empirical extrapolation of measured data on the basis of macrostructure descriptions. So far, this procedure could only be applied to breakthrough curves of soils with identical textures but very different macrostructures; (ii) using staining techniques which provide essential boundary conditions for newly developed physical flow models. The latter describe macropores in terms of size, type and shape, rather than in terms of relative volumes; and (iii) developing physical interpretations of pedological features, such as mottling patterns.

The examples are based on four case studies which deal with practical problems of soil water management. In these studies, morphological methods provided essential data, which could not have been obtained by physical methods.

INTRODUCTION

Recent soil physics research has paid much attention to the preferential flow of water along macropores in soil (Thomas and Phillips, 1979; Beven and Germann, 1980b). Different research approaches have been followed: (i) physical aspects of flow are emphasized by measuring breakthrough curves (e.g. Cassel et al., 1974) and by applying the theory of hydrodynamic dispersion (e.g. Nielsen et al., 1980); (ii) physical aspects of flow are related to

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natural porosity patterns in the soil (e.g. Anderson and Bouma, 1977a,b); (iii) staining techniques are used to demonstrate the occurrence of preferential flow patterns along different types of pores in natural soil (e.g. Kissel et al., 1973); (iv) soil structure models with schematized macropores are used to predict infiltration patterns (e.g. Edwards et al., 1979); and (v) theoretical descriptions of water flow are developed for heterogenous porous media (e.g. Kutilek and Novak, 1976). This last aspect is considered beyond the scope of this paper.

In the first and last approaches soil macropores are not characterized as such. In the other three approaches macropores are considered as discrete entities which can be defined in terms of type and number, rather than in terms of relative volumes. This procedure has also traditionally been followed in soil morphology. However, so far these morphological descriptions have hardly been interpreted from a physical point of view.

The purpose of this paper is to critically examine morphological descriptions of soil pores, emphasizing their potential for contributing towards a better understanding of preferential flow along macropores.

Flow of water is a physical process. Morphology can only provide supporting data, which may, however, be essential in obtaining a better physical characterization of flow processes in soils with macropores.

A distinction will be made in this paper between the use of: (i) macromorphological data which are easily obtained from existing soil survey descriptions; (ii) macromorphological data which functionally characterize flow systems with tracing techniques; and (iii) micromorphological data derived from thin sections which require specialized equipment and expertise.

CONCEPTS AND TERMINOLOGY

Soil physics aspects

The terminology for characterizing preferential flow along macropores needs to be better defined (Soil Sci. Soc. Am., 1978). In addition, nonmathematical descriptions are considered useful for communication purposes. Two major types of flow are relevant for the discussions in this paper and are given below.

(i) Steady flow. A hypothetical fully homogeneous and isotropic soil sample might show piston-type flow whereby the percolating water first replaces all water that was initially present, before it leaves the soil (Fig. 1A). In many soils flow is associated with a wide variety of flow velocities of water in the soil pores (Fig. 1B). These phenomena can be characterized by measuring breakthrough curves using a tracer. Breakthrough curves show the relative concentration of the tracer in the soil effluent (c/c_0) as a function of the relative volume of water which was displaced from the soil (v/v_0). In these examples, the chloride ion, which is not adsorbed by the soil, is used as a tracer and hydrodynamic tracer dispersion in single pores is ignored.

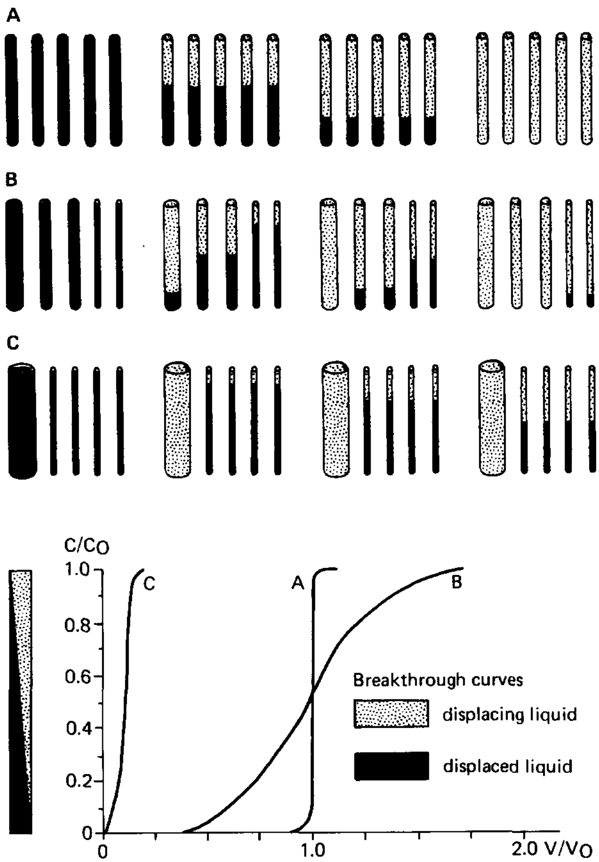

Fig. 1. Displacement patterns, as expressed by breakthrough curves, in three schematic "soils materials" (saturated flow). A, piston-type flow; B, flow in soil with a limited range of pore sizes; C, flow in soil with continuous macropores. The breakthrough curves show the relative concentration of the tracer (c/c_0) as a function of the displaced relative volume of water (v/v_0). The drawing is conceptual: relative volumes in the pipe diagrams do not quantitatively correspond with those in the graphs.

The breakthrough curve can be interpreted using the theory of hydrodynamic dispersion (e.g. Brenner, 1962; Nielsen et al., 1980). With piston-type flow the tracer concentration in the soil effluent reaches the concentration of the influent abruptly, while this process occurs more gradually in a soil with a wider range of pore sizes (Fig. 1B). The occurrence of relatively large, continuous pores may result in very rapid breakthrough of the tracer (Fig. 1C). Obviously, the concentration of the tracer in the soil effluent cannot be equal to the concentration of the influent as long as all the water initially present in the soil has not been desplaced (Fig. 1C). However, the latter displacement rate may be so slow that its dilution effect cannot be measured. The water in the fine pores is then considered to be "immobile" or "stagnant" (Van Genuchten and Wierenga, 1976). Steady flow through unsaturated soil may be due to infiltration through a surface crust or to steady application of water at a rate which is lower than K_{sat}. During steady flow the moisture content is constant, so the comments made above now apply to the water-filled part of the soil.

(ii) Intermittent flow. This occurs, for example, when water is applied to initially unsaturated soil in which at least some macropores are filled with air. The resulting flow pattern of water is a complex function of the initial moisture content of the soil and the rate of application. There is no miscible displacement from the air-filled pores. The term "hydrodynamic dispersion" is generally associated with miscible displacement of water initially present in able here — certainly not when the soil is initially dry. This process is illustrated in Fig. 2B for a soil with continuous macropores. An example was presented by Blake et al. (1973). Vertical penetration of water in air-filled voids is associated with vertical displacement of water initially present in the finer pores, when the soil is initially moist or wet. The effects of this process are illustrated in Fig. 2A for a soil with continuous macropores. An example was presented by Quisenberry and Phillips (1976). In both cases there is rapid downward movement of "free" water (having atmospheric pressure) through air-filled macropores in unsaturated soil. This phenomenon has been called "short-circuiting" (Bouma and Dekker, 1978), and "non-matrix flow" (Bouma et al., 1980a). Short-circuiting in unsaturated soil is associated with lateral movement from the larger water-conducting pores into adjacent unsaturated soil. The rate of lateral movement is a function of the application rate, the hydraulic conductivity and the moisture content of the soil (Bouma and Anderson, 1977; Bouma et al., 1978; Hoogmoed and Bouma, 1980).

Soil morphology aspects

Soil pores can be described in terms of size, shape and arrangement, and counts can be made to express their number per unit area. Several size classifications have been proposed. The term "macropores" has different meanings. Beven and Germann (1980b) define these as pores having a radius of more than 2 mm. The equivalent pressure head in such a (cylindrical) pore will be only -1cm. Brewer (1964) reviewed different classifications and defined macropores as having a diameter of more than 75 μm. This followed a proposal by Johnson et al. (1960), who reported an apparent relationship between percolation rate and air content in soil at a pressure head of -40 cm (which corresponds to a pore diameter of 75 μm). Size as such is less important than pore continuity: small pores with a diameter of 40 μm can conduct considerable quantities of water, if they are continuous throughout a soil sample (Bouma et al., 1979a). Perhaps macropores should be defined as pores which are significantly larger than those which result from the simple

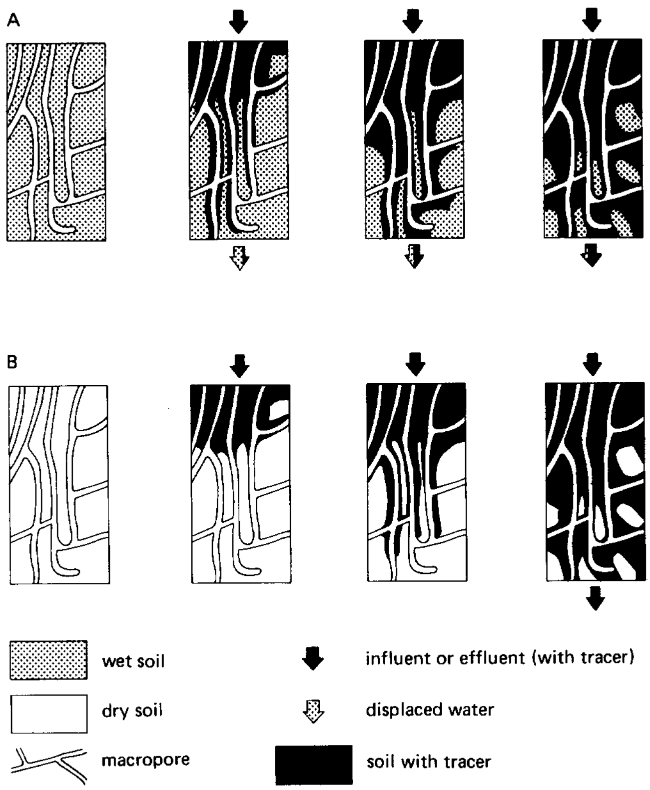

Fig. 2. The effects of short-circuiting of water along air-filled macropores in unsaturated soil after application of a limited quantity of water. When the soil is initially very moist or wet (A) there is both displacement of the initially present water (gray arrow) and preferential movement of the influent along the macropores (not shown). Short-circuiting is relatively strong as compared with conditions when the soil is initially dry or slightly moist (B); then, there is no displacement but only infiltration at the soil surface and preferential vertical movement along the macropores and associated lateral infiltration (after Bouma, 1977).

packing of the individual soil particles. Three major types of macropores are distinguished (Brewer, 1964): (i) channels have a generally cylindrical shape; (ii) planes are defined by the ratio of their principal axes; and (iii) vughs are irregular in shape. Macropores can be described in the field as seperate entities, but continuity patterns are difficult to assess in a relatively small soil sample (Johnson et al., 1960). Standard soil structure descriptions, which note size, grade and type of structure, may provide some broad information on macropore patterns between the natural aggregates ("peds") in the soil. However, such information is qualitative in nature and its reproducibility is often questionable.

Detailed micromorphometric measurements allow specific definitions of macropores, using area and parameter dimensions of individual voids. The use of tracers is necessary to establish continuity patterns of the macropores, which cannot be derived from an untraced thin section (Bouma et al., 1977, 1979a).

The term "pore" is usually reserved for soil physics terminology and the term "void" suggests a morphological classification. Both terms will be used here.

CHARACTERIZING FLOW ALONG MACROPORES

Use of macromorphology

The use of macromorphology for characterizing preferential flow of water along macropores is attractive because the observation methods involved are relatively simple and cheap; also morphological descriptions of major soil series are available and ready to be interpreted physically. Of course, field descriptions of soil morphology and porosity patterns are bound to be rather qualitative and variable, and their use is therefore feasible only for contrasting types of structure with major differences. Four procedures will be discussed here: (i) use of field descriptions of soil macrostructure as carriers for physical information; (ii) use of schematized soil structure models; (iii) use of staining techniques to functionally characterize different types of macrostructure, and (iv) use of pedological features, such as mottlings, as indicators for flow along macropores.

Existing macrostructure descriptions

Measurement of physical soil properties such as hydraulic conductivity, moisture retention and dispersion coefficients is cumbersome and expensive. Methods which allow extrapolation of measured data are therefore desirable. Physical soil properties, as mentioned, are complex functions of the pore size distribution of the soil and, in particular, of three-dimensional pore size continuity. Undisturbed soil columns have significantly different breakthrough curves as compared with those for packed colums using the same soil (Elrick and French, 1966; Cassel et al., 1974; McMahon and Thomas, 1974). Structural differences within the same soil material are therefore important. Measurement of breakthrough curves and short-circuiting yielded significantly different results when comparing multiple samples from undisturbed subangular blocky and prismatic soil horizons, both of which had a silty clay loam texture (Anderson and Bouma, 1977a,b; Fig. 3). Similar results were reported by Bouma and Wösten (1979) for two clay soils with quite contrasting macrostructures, but with identical textures. These results suggest that texture alone is not adequate for correlation with differences in hydrodynamic dispersion. Texture together with structure could be used for the examples discussed. However, these are the only examples available so far. Attempts to correlate macrostructure descriptions with differences

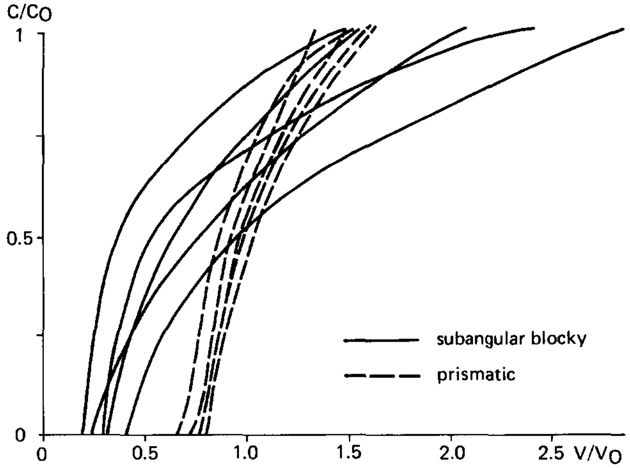

Fig. 3. Measured chloride breakthrough curves for five subangular blocky and five prismatic structures in silty clay loam soil horizons, sampled at 10 different locations (saturated, gravity flow). Curves for the two types of macrostructure are significantly different (after Anderson and Bouma, 1977a,b).

in K_{sat} and with different degrees of short-circuiting in dry clay soils have not been successful. This is due to the character of the features which govern these physical properties: size of planar necks and the number of vertical infiltration bands along ped faces are not primarily related to very broad macrostructure descriptions (Bouma et al., 1978, 1979a and recent unpublished data).

Schematized structure models and staining techniques

Flow through tubes and plane slits can be mathematically described (e.g. Childs, 1969). A schematization of complex three-dimensional soil-pore patterns in terms of an interconnected system of tubes and plane slits would allow calculation and prediction of various soil physical properties. Such structure models were proposed by Dixon and Peterson (1971) and Bouma and Anderson (1973). In these models macropores are defined in terms of type, size and number. Infiltration into schematized pore systems has been mathematically analyzed by Scotter (1978), Edwards et al. (1979) Bevin and Germann (1980a,b), and Germann and Beven (1980a,b). The link between these schematized models and real porosity patterns should be established. Tracing techniques, to be applied to undisturbed samples or in situ, must be used for this purpose. These techniques have already been widely applied to demonstrate deep penetration of water along continuous macropores in natural soil (Aubertin, 1971; Ritchie et al., 1972; Blake et al., 1973; Kissel et al., 1973; Ehlers, 1975; De Vries and Chow, 1978). The techniques can also be used in a quantitative manner by providing input data for the schematized structure models discussed above. Confining attention to macromorphology, two relevant case studies will be discussed.

(i) Infiltration into clay soil with continuous macropores. Rainwater will move rapidly downwards along continuous vertical cracks in clay soils, even when applied at relatively low intensities (Bouma and Dekker, 1978; Bouma et al., 1978). These authors sprayed a solution of methylene-blue in water on 40 plots of 0.5 m^2 each, using different intensities and quantities. At first, infiltration of water occurs vertically into the upper surface of the peds (prisms) (i_1) (Fig. 4). Flow into the cracks (cf) starts as soon as the application rate exceeds the infiltration rate (at time t_1 for intensity i_a). High application rates (i_b) result in earlier crack flow than low rates. Crack flow may not occur at very low application rates (i_c). Surface ponding of water is ignored in this simplified example.

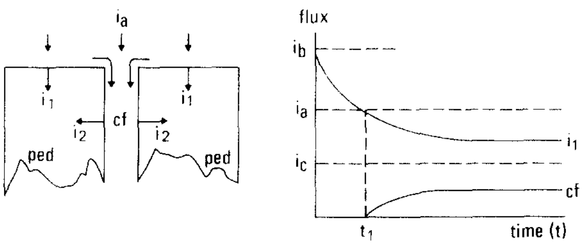

Fig. 4. Schematic diagram of infiltration into cracked clay soil (see text).

Flow into the cracks occurred only along shallow bands on vertical faces of the prisms. The total width of all bands per 10 cm depth interval below the plot was called the contact area *S*. *S* was a function of the applied flow regime and was about 1—2% of the conceptual contact area considering the total surface of the vertical prism faces in the 0.5 m^2 plot. Deep penetration of water in the cracks was primarily due to the small *S* value. At higher *S* values complete lateral adsorption would occur within a few centimeters depth. This conclusion was reached by using a simulation model for flow into cracked clay soil. The model applies existing flow theory for vertical and lateral infiltration into the peds (Hoogmoed and Bouma, 1980). *S* values derived from independent soil morphological observations form essential boundary conditions for the physical flow system, as they govern lateral infiltration into the peds and, therefore, the vertical depth of penetration of water into the cracks. Without tracing, *S* values cannot be obtained from standard profile descriptions.

(ii) Upwards fluxes in clay soils. Upward fluxes from the water table to the root zone are very important for compensating the precipitation deficit in the Dutch growing season. Measurement of hydraulic conductivity curves

in sandy soils allowed good estimates of these fluxes (Bouma et al., 1980b). However, results in clay soils were poor (Bouma and De Laat, 1981). This was due to the formation of horizontal cracks during drying of the clay. The measured K curve is representative for the peds but not for the entire soil. Fluxes have the dimension of $m^3\ m^{-2}\ s^{-1}$, implying flow across the entire cross-sectional area. Obviously, vertical flow is not possible across a horizontal crack. A staining technique was developed for field use which allows an estimate of the relative horizontal surface area which is occupied by these cracks. This area is a function of the pressure head. A block of soil (30 cm × 30 cm × 30 cm) is carved out in situ and is covered with gypsum on five sides. After removal from the pit, the bottom surface is also covered and the block is put on one of its side-walls. A solution of methylene-blue in water is poured through the block in its new position (these surfaces were two opposite side-walls in the original pit). Natural ped faces are then exposed at a given level by gently removing the peds and the stained area is counted. If this is x% of the 900 cm^2 exposed surface, a "reduced" K value (K_r) is defined as

$$K_r(h\text{=-y cm}) = K_m\ (h\text{=-y cm}) \times \frac{100\text{-}x}{100}$$

Here, K_m is the hydraulic conductivity at the actual pressure head in the block of soil. The latter is measured with tensiometry. K_m is measured with standard techniques and it representative for the peds only. Several blocks are tested in identical soils with different pressure heads. Each test yields one K_r value (Fig. 5). The degree of reduction of K_m may be different for different macrostructures and the new technique can be used to characterize different types of structures in swelling clay soils. As such, the technique is an example of using soil macromorphology for obtaining crucial boundary conditions for physical flow processes in soil with macropores. Without tracing, such data cannot be derived from standard soil structure descriptions.

Pedological features

Pedological features are recognizable units within a soil material which are distinguishable from the enclosing material, for example because of a different concentration of some soil component (Brewer, 1964). Some features can be used as indicators for preferential flow along macropores. Coatings of clay along the walls of larger pores may function as such, but mottling patterns are particularly suitable. Preferential flow along macropores in unsaturated soil may result in reduction of iron in the walls of the pore (neo-alban) and oxidation at some distance of the pore (quasi-ferran) as water moves into the aerobic soil matrix. This type of mottling was observed in the field (Veneman et al., 1976) and was reproduced in the laboratory (Vepraskas and Bouma, 1976).

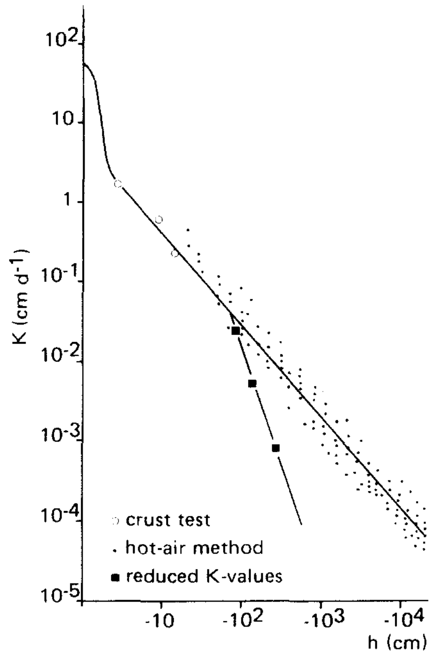

Fig. 5. Measured hydraulic conductivity (K) for a heavy clay soil. The reduced K values are due to the formation of horizontal cracks upon drying. Cracks reduce the cross-sectional surface area which is available for vertical upward flow. The reduced area was estimated using a staining technique (after Bouma and De Laat, 1981).

Use of micromorphology

The use of micromorphology for characterizing preferential flow of water along macropores is attractive because the pores can be measured very accurately in terms of size, shape and number. However, the picture obtained applies only to a thin section of 0.02 mm thickness and the techniques involved are expensive and require advanced technology and expertise. The latter is also true when polished blocks rather than thin sections are used (e.g. Dorronsoro et al., 1978a). Recently, techniques have been perfected to prepare large (8 × 15 cm) thin sections using freeze-drying techniques in clay soils which avoid shrinkage upon drying (Jongerius and Heintzberger, 1973). Also, electronic equipment is now available to automatically measure soil porosity features (Jongerius, 1974; Bullock and Thomasson, 1979; Dorronsoro et al., 1978b). However, a clear focus of research is needed to avoid a flood of non-informative data. Functional characterization of the pore system, using dyes or other tracers, is needed to focus research on relations between micromorphological porosity features and dynamic physical characteristics. As stated earlier, the latter are a function of three-dimensional pore continuity patterns which cannot be derived from a non-stained two-dimensional image of a thin section. Tracing techniques are essential in establishing continuity patterns.

Undisturbed, saturated samples of clay soils were therefore percolated with a solution of methylene-blue in water until the effluent had the same color intensity as the influent (Bouma et al., 1977, 1979a). Thin sections were made of the soil afterwards and they showed that stains did not occur in the soil matrix but only in macropores; also, stains on the walls of these pores were intermittent, demonstrating the effects of "necks" in the flow system (Fig. 6). The number and dimensions of the stained pore fragments could not be used as such to estimate K_{sat} because the values obtained were far too high (Bouma et al., 1977). A pore continuity model was developed which allowed an estimate of the size of the pore necks for planar voids and channels. The use of this neck size for all stained pores resulted in good calculation results (Bouma et al., 1979a). This example illustrates the specific use of morphological information which cannot be obtained by other methods.

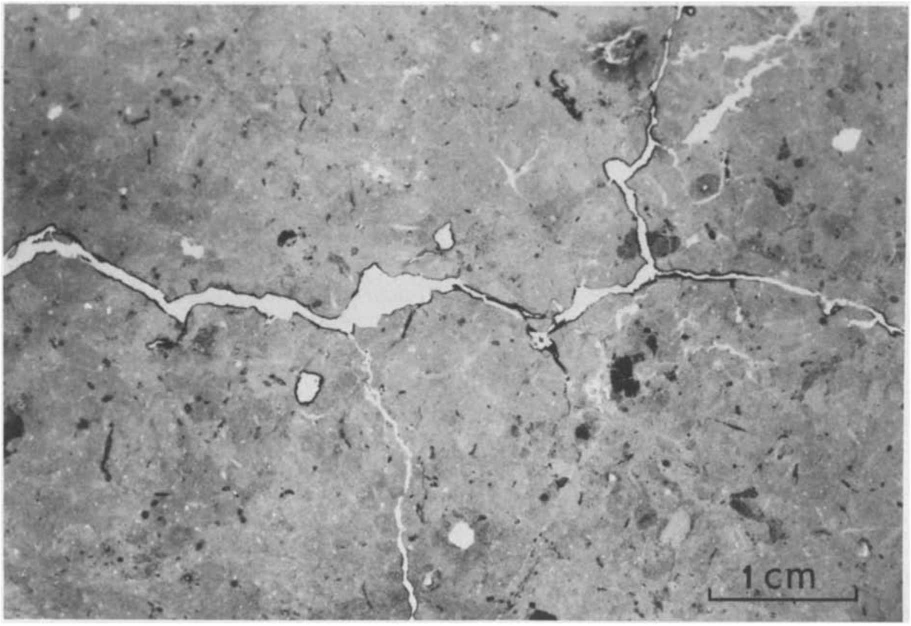

Fig. 6. Thin-section image of a freeze-dried clay sample which was percolated with methylene blue to indicate preferential flow patterns along macropores. Planar voids ("cracks") are intermittently stained, indicating the effect of "necks" in the natural three-dimensional porosity pattern. Some channels ("rootholes") are stained, others are not, suggesting that the latter are not vertically continuous. The observed patterns were used to calculate K_{sat} (Bouma et al., 1979a).

Physical procedures for calculating K, using moisture retention curves, do not allow distinction of different types of pores, nor can they distinguish the very small pore volumes that are occupied by the active macropores. The use of matching factors when calculating K_{sat} with moisture retention data does not solve the problem but illustrates the inadequacy of the physical method.

The staining technique described was also used to predict the initial breakthrough of chlorides when measuring breakthrough curves of clay soils (Bouma and Wösten, 1979).

The micromorphometric calculation methods for K_{sat} and for initial breakthrough are not intended to replace physical measurements, which are much cheaper. However, these techniques can be used to analyze field problems, as will be illustrated with two examples.

(i) Perched or real water tables in clay soils. Free water levels in some Dutch clay soils were found simultaneously in shallow and deep boreholes. The shallow levels did not indicate the presence of perched water tables, as was initially expected. Their occurrence was explained by preferential flow of water into the shallow boreholes. Flow, as indicated by stains and chloride tracing, followed planar voids which intercepted the vertical walls of the borehole. Boreholes usually had their bottoms inside peds which allowed only slow drainage into the surrounding soil, which was and remained unsaturated, as evidenced by in situ tensiometer measurements (Bouma et al., 1980c).

(ii) Flow along different types of macropores. Flow of water into tile drains of a heavy clay soil followed only the planar voids (cracks) and not the channels (rootholes). This conclusion could be reached by analyzing thin sections after application of in situ staining techniques (Bouma et al., 1981). Planar voids are formed by drying. The observation suggests that desiccation of the soil, due to lowering of the water table by tile drainage and improved water management, can be used to increase the number of planar voids and K_{sat}. Emphasis on channels would have resulted in different conclusions as to the most desirable management.

Field variability and macropores

Field variability of physical data is often very large, creating major interpretation problems. Part of the variability in soils with macropores may be due to poor measurement procedures and inadequate standards by which the obtained results are being judged. These procedures and standards are based on the Darcy flow theory which assumes that soils are rigid, homogeneous and isotropic (Klute, 1973). These assumptions do not usually apply to soils with macropores. Predictions of soil moisture regimes are therefore often unsuccessful (see the example by Bouma and De Laat, 1981). Some other problems and possible solutions are broadly discussed in five examples. The reader is referred to the publications cited for additional details.

(i) Only very large undisturbed samples yield representative values when measuring K_{sat} of clay soils with macropores. The auger-hole method may yield unrepresentative results due to puddling of the hole, while the use of small cores yields very high values with a high variability due to unrepresentative continuity patterns. Field variability is strongly reduced by using cores with a volume of 10 l (Bouma, 1979; Bouma et al., 1979b).

(ii) Soils with macropores always exhibit a strong drop in K near saturation. K_{sat} of some Dutch clay soils was 50 cm/day, while K at h=-5 cm was only 1 cm/day (see Fig. 5). The drop is, of course, due to emptying of macropores. Many existing unsteady methods for measuring K_{unsat} do not allow determination of K_{unsat} at pressure heads higher than, say, -15 cm. Often, independently obtained values for K_{sat} are connected with those determined with unsteady methods for h values lower than, say, -15 cm. Thus, unrealistic values are obtained for K_{unsat} near saturation and these may not explain observed moisture conditions in the field. Steady-state methods, such as the crust test, should therefore be used in soils with macropores to obtain K_{unsat} values near saturation.

(iii) As already discussed, preferential flow along macropores may fill unlined boreholes when these end inside (unsaturated) peds. Thus, the occurrence of perched water tables may be incorrectly suggested (Bouma et al., 1980c). The use of piezometers or tensiometers will avoid problems.

(iv) Measurement of in situ moisture contents with neutron or gamma probes yields average values for a given volume of soil. These values do not reflect preferential patterns of water infiltration as discussed earlier. Selective gravimetric sampling of soil in a soil pit will provide more relevant information.

(v) Extraction of soil water with suction cups, which may or may not intercept continuous macropores, often results in variable data (e.g. Shaffer et al., 1979). It is advisable to excavate the cups at the end of the experiments and to observe macropore patterns near the cups. Staining or tracing before excavation is necessary. Thus, sub-populations can be distinguished among the data, which reduces the interpretation problems.

Field variability can be reduced if the effects of macropores on flow are considered when measuring basic physical data, when monitoring soil profiles in situ, and when developing flow models for prediction purposes.

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