Using morphological data for the simulation of water regimes in clay soils

J. Bouma

Netherlands Soil Survey Institute, Wageningen, The Netherlands

1 Summary

Formation of acid sulphate clays involves ripening processes that are often associated with formation of both vertical and horizontal cracks (planar voids) in clayey soil materials. Crack formation complicates the physical characterization of soil water regimes because vertical cracks induce bypass flow which is defined as vertical flow of free water through macropores in an unsaturated soil matrix. Horizontal cracks impede vertical unsaturated flow of water, particularly in the upward direction. Use of computer simulation techniques to characterize flow processes and the associated transport of dissolved chemical compounds, is not possible in cracked clay soils when using existing models that are based on Darcy-type flow theory. A new procedure is presented in this paper that allows simulation of water regimes in clay soils with cracks or other continuous macropores, such as channels. The model used consists of three submodels that describe: (1) Vertical infiltration at the soil surface in peds between cracks; (2) Surface ponding and flow into the cracks (bypass flow); (3) Lateral absorption of water from the partly or completely filled cracks into the unsaturated soil matrix, and (4) Upward unsaturated flow from the water table to the rootzone in soil with horizontal cracks. Soil morphological descriptions, using staining techniques, form a key element of the model. Simulation results for a Dutch heavy clay soil will be discussed to illustrate the potential of the method. Implementation of the method requires measurement of hydraulic conductivity and moisture retention curves with existing methods and use of several new macromorphological field techniques.

Résumé

La formation d'argiles sulfaté-acides implique de processus de maturation souvent associés à la formation de fentes verticales et horizontales dans les matériaux des sols argileux. La formation de fentes complique la caractérisation physique des régime hydriques des sols, en ce sens que les fentes verticales entraînent des dérivations dans l'écoulement de l'eau. On parle alors d'écoulement vertical par les macropores se trouvant dans une matrice de sol non-saturée. Les fentes horizontals empêchent l'ecoulement vertical non-saturé de l'eau surtout vers le haut. L'utilisation de techniques informatiques de simulation, en vue de caractériser les processus d'écoulement et de transport des composants chimiques dissous, n'est pas possible dans le cas des sols argileux fissurés lorsqu'on fait appel aux modèles existants, lesquels sont basés sur des théories d'écoulement de type Darcy.

La présente étude, propose une nouvelle procédure qui prévoit la simulation des régimes hydriques dans les sols argileux fissurés ou présentant d'autres macropores

continus tels que les canaux. Le modèle utilisé consiste en trois sous-modèles qui décrivent:

1. L'infiltration verticale se produisant à la surface du sol dans les agrégats entre les fentes;
2. La formation de mares en surface et l'ecoulement de l'eau par les fentes (écoulement par dérivation);
3. l'absorbtion latérale de l'eau des fentes partiellement ou entièrement remplies dans la matrice du sol non-saturé; et
4. l'écoulement ascendant non-saturé de la nappe aquifère jusqu'à la rhizosphère dans les sols présentant des fentes horizontales.

Les descriptions morfologiques des sols constituent un élément clé du modèle; se sont:

a. Le microrelief de la surface supérieure des agrégats;
b. La longueur des fentes (ou le nombre de pores tubulaires ouverts) au niveau de la coupe transversale du sol;
c. La zone de fentes verticales qui permette une infiltration latérale; et
d. La zone relative de fentes horizontales dans le sous-sol qui est remplie d'air, comme fonction de la pression hydrostatique.

Des techniques de coloration pour utilisation in situ ont été mises au point afin de déterminer les données morphologiques mentionnées dans les deux derniers points.

L'article présente les résultats des essais de simulation d'un sol argileux lourd de Pays-Bas. L'application de cette méthode nécessite la mesure de la conductivité hydraulique et des courbes de rétention de l'humidité à l'aide des méthodes existentes, ainsi que l'utilisation de plusieurs techniques macromorphologiques de terrain comme indiqué ci-dessus.

2 Introduction

Computer simulation models are well established tools to characterize actual and potential soil water regimes in the context of land evaluation (e.g. Belmans et al. 1984 and references therein). Special problems occur, however, when these models are applied to cracked clay soils where flow patterns are strongly influenced by both vertical and horizontal cracks (planar voids). Many acid sulphate soils have been formed in clay soils and use of traditional simulation models, assuming presence of isotropic soil, may therefore raise problems. Two approaches are being followed now in trying to model water movement in cracking clay soils: (1) varying hydraulic characteristics of the soil matrix are measured as a function of swelling and shrinkage processes. In this approach, size and continuity of planar voids are considered to be the result of these processes. (2) Morphometric characterization of both vertical and horizontal planar voids is emphasized. In this approach, the soil matrix is considered to be 'soil between the cracks'. The second approach will be discussed in this paper. A case study from the Netherlands will be presented to explain the procedures involved. Particular emphasis will be placed on water storage in cracked soil; lateral infiltration from planar voids into the soil matrix; and upward, unsaturated flow from the water table to the soil surface in clay soils with horizontal planar voids.

3 Defining subsystems of flow

Complex flow processes in clay soils with macropores can be better understood when submodels are distinguished, which can be defined by using soil morphological data for the entire soil and soil physical data for the soil matrix. Three submodels are distinguished in Figure 1:

1. Vertical infiltration at the upper soil surface between the planar voids (i_1), and downward vertical movement through the soil matrix;
2. Flow of water from the surface into the planar voids, after filling of microdepressions at the soil surface. The process of vertical movement of free water along cracks in an unsaturated soil matrix is referred to as 'bypass flow' (Bouma 1984);
3. Partial or complete filling of the macropores and lateral infiltration into the (unsaturated) soil matrix (i_2), to be characterized by flow equations (Hoogmoed and Bouma 1980; Bouma and Wösten 1984).

A separate submodel for upward unsaturated flow (i_3 in Figure 1) is needed when hydraulic gradients induce upward flow. Vertical and lateral infiltration can be characterized by Darcy's equation in combination with the continuity equation. The reader is referred to any current soil physics textbook for specific details. Computer simulation, using CSMP or other user friendly subroutines, is attractive for the applications being discussed here.

4 Methods

4.1 Bypass flow

Bypass flow can be measured by using large undisturbed cores of dry soil (Bouma et al. 1981). For Dutch conditions in heavy clay soils, cylinders have been used with a height and diameter of 20 cm. Cores include the soil surface with grass, which is closely cropped. The cores are placed in the path of a spraying gun in the field which

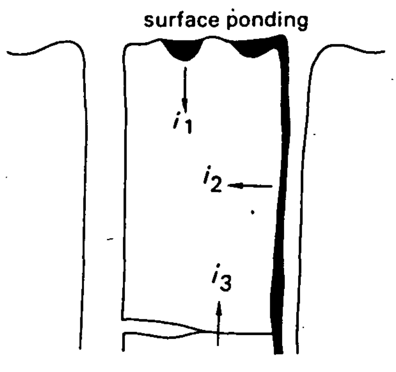


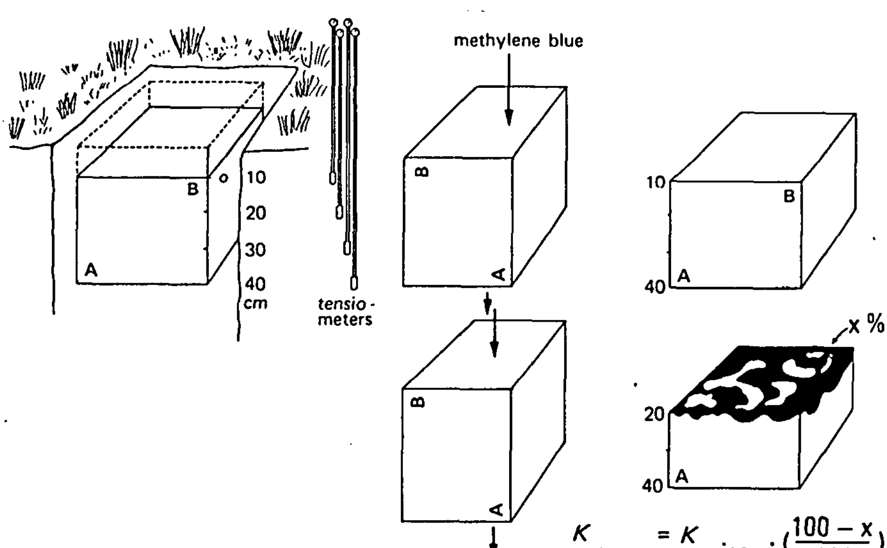
Figure 1 Schematic representation of water infiltration into cracked clay soils, showing surface ponding of water, vertical infiltration (i_1), lateral infiltration from ped faces into the peds (i_2) and upward flow (i_3).

is commonly used for sprinkling irrigation. In general, sprinkling conditions should correspond to local practices. The mass of the soil filled cylinder is determined before and after sprinkling and the stove dry mass is measured at the end, thus allowing calculation of physical constants such as bulk density and moisture contents. Sprinkling intensities and duration should be measured independently. The volume of water that leaves the column is measured as a function of time, thus allowing an estimate of bypass flow which can be expressed as a percentage of the applied quantity of water. Many measurements can be made in a short time and the effects of using different durations can be easily evaluated. Thus, irrigation efficiencies can be improved because movement of water beyond the root zone often presents a loss of precious irrigation water and surface applied chemicals (Dekker and Bouma 1984).

4.2 Horizontal cracking

Vertical planar voids may result in bypass flow. However, soil shrinkage also causes the formation of horizontal cracks which strongly impede upward flow of water in unsaturated soil (Bouma and De Laat 1981). A method was devised to stain air filled horizontal cracks at different moisture contents and corresponding (negative) pressure heads. A cube of soil (30 cm × 30 cm × 30 cm) is carved out in situ (Figure 2). The cube is encased in gypsum and is turned on its side.

The upper and lower surfaces are opened and two sidewalls of the turned cube are closed. Methylene blue in water is poured into the cube and will stain the air filled cracks. The surface area of these stained cracks is counted after returning the cube



$$K_{macro} = K_{micro} \cdot \left(\frac{100 - x}{100}\right)$$

Figure 2 Schematic representation of the method for measuring the area of air-filled horizontal cracks as a function of the pressure head.

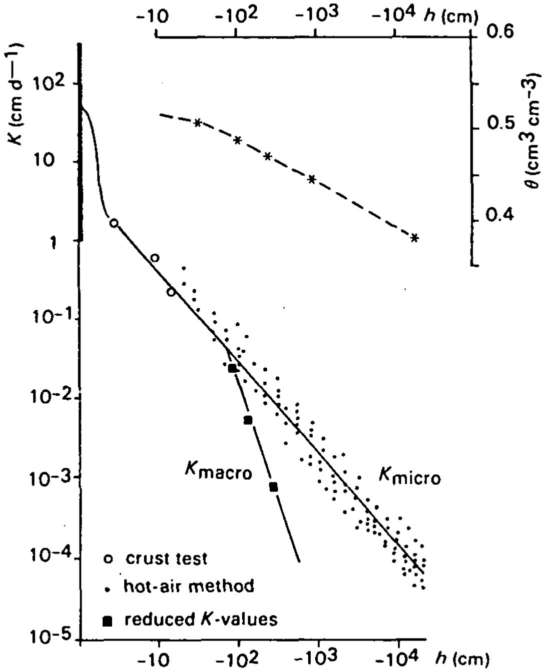


Figure 3 K curve for a heavy clay consisting of the regular curve (k_{micro}) which defines water movement in the peds and a K_{macro} curve which is used to define upward, unsaturated flow from the water-table. Three cubes of soil were used to obtain the three reduced K values that are indicated.

to its original position. A separate cube is needed for each (negative) pressure head. The K-curve for the peds (Figure 3) is 'reduced' for each pressure head measured in a cube. When, for example, 50% of the horizontal cross sectional area is stained, K_{unsat} for upward flow is 50% of the K_{unsat} at the same pressure head in the peds.

5 Results

Two types of results will be discussed: (1) Simulation of the water regime in the growing season, and (2) Simulation of infiltration during sprinkling irrigation or ponding in dry or slightly moist clay soil.

5.1 Seasonal water regime

Using weather data for 1979, a simulation run was made for the summer period July 1 – September 1 for a heavy clay soil in the Netherlands. The soil had 55% clay and was classified as a very fine, mixed mesic Typic Haplaquept. Vertical cracks were continuous and ponding of water inside cracks did not occur under natural conditions (Bouma and De Laat 1981). Independent measurements of bypass flow as a function of natural rainfall duration and intensity, were used to estimate fractions of natural rainfall that were likely to contribute towards bypass flow. These fractions turned out to be 20% for the period indicated (Bouma and De Laat 1981). Natural quantities of rainfall, that were used in the model for weekly periods, were therefore reduced by 20% to account for bypass flow. The assumption was made, in fact, that the fraction of rain that contributed towards bypass flow could be ignored. Upward unsaturated flow was characterized by the K_{macro} curve as shown in Figure 3.

Results are presented in Figure 4. Field measurements agreed well with simulations that considered both bypass flow and the effect of horizontal cracks, while the latter aspect had the largest impact. The significant effect of horizontal cracks on the upward flux of water is further illustrated in Figure 5 which shows the height (Z) above the water table to which a steady flux (q_c) of 2 mm day^{-1} can be maintained. The Z_{micro}-curve is based on the hydraulic conductivity curve of the peds and shows, for example, a Z value of 65 cm when the pressure head at 65 cm above the zero pressure level is –1000 cm. The corresponding Z value, when considering horizontal cracking, is only 35 cm. These results are important when considering possible upward movement of acid water by, unsaturated flow.

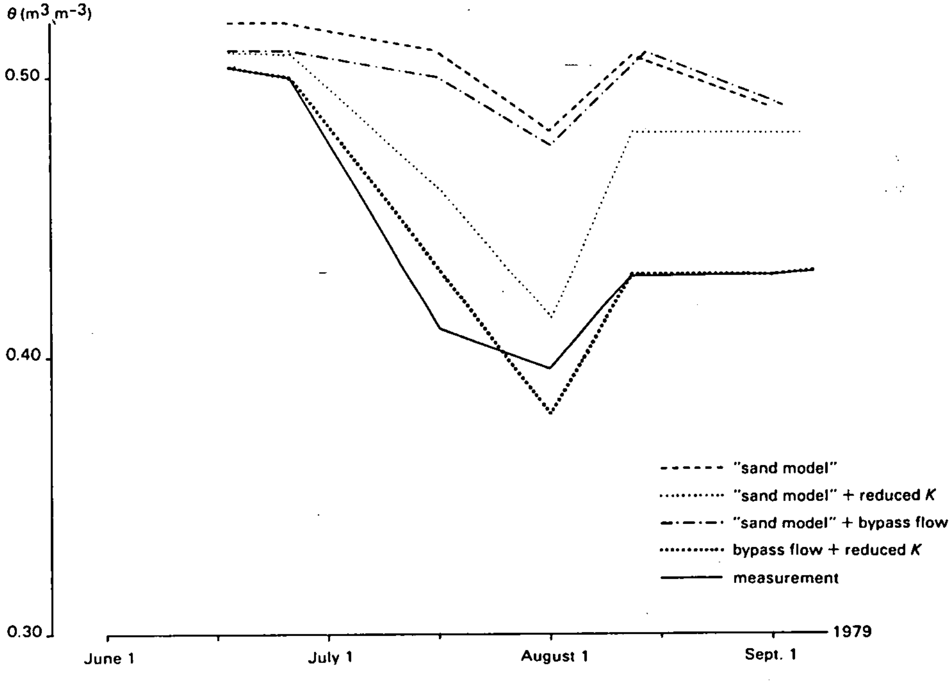


Figure 4 Measured and simulated moisture contents for a depth of 30 cm below surface in a Dutch heavy clay soil, showing the effects of bypass flow and horizontal cracking.

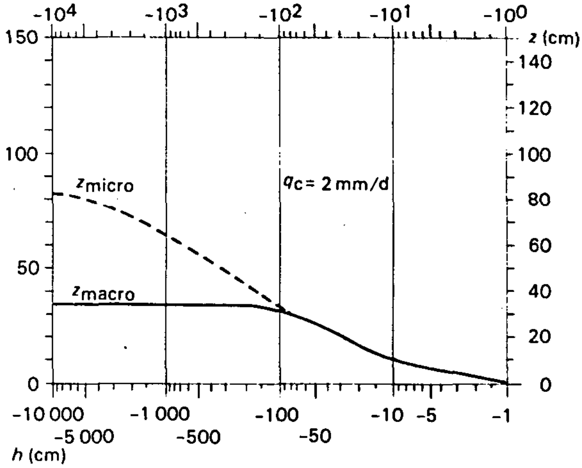


Figure 5 Curves that show the height (z) to which a steady upward flux of 2 mm d^{-1} can be sustained at defined negative pressure heads at the upper part of the flow system. The z_{micro} curve was derived from the k_{unsat} curve of the soil matrix. The z_{macro} curve reflects the effect of horizontal cracks (see Figure 3).

5.2 Irrigation or ponding

A model, composed of three submodels as explained in Section 3, was used to predict infiltration of water during sprinkling irrigation in a dry, cracked clay soil (Hoogmoed and Bouma 1980). Measured hydraulic conductivity (Figure 3, the regular curve) and moisture retention data were used. The model correctly predicted reduced wetting of surface soil due to bypass flow. Lateral infiltration of free water from the walls of the cracks into the dry matrix was very low, due to the presence of cutans and very rapid downward movement of free water along air filled planar voids.

Planar voids were not filled with water here as water moved downwards as narrow bands on the vertical walls of air filled planar voids. On the contrary, continuous ponding of water at the soil surface results in filling of the planar voids. Their number per unit surface area, and their width and depth determine the available volume for storage. Infiltration occurs into the upper soil surface, and laterally from the filled planar voids. A field study was made in which these various flow processes were combined (Bouma and Wösten 1984). The volume of air filled planar voids, available for storage of water, could be reliably estimated by making counts of gypsum filled voids in horizontal cross section. Lateral infiltration into the peds was simulated by using a measured D-θ function in a simulation model (subsystem 3, as defined in Section 3), which also needed the total length of planar voids within a given horizontal cross sectional area (D-θ stands for the Diffusivity as a function of the moisture content). Measured and calculated data agreed well in terms of the depth of penetration along the planar voids and the total volume of laterally absorbed water which is a function of the total length of the planar voids in horizontal cross section. This length can only be obtained by morphometric techniques (Figure 6). Thus, the process of lateral infiltration from planar voids can be described in quantitative terms, when a D(θ) relation is known.

6 Discussion

Formation of acid sulphate clays and transport of acid water is, of course, governed by patterns of water and air movement in the soil. Water and air movement in clay soils is highly influenced by planar voids and other macropores. The morphometric techniques, described in this paper, allow realistic predictions of patterns of water movement using existing simulation models. Emphasis is placed on the characterization of planar voids in terms of length per unit cross sectional area, (through which lateral infiltration has to occur) and vertical and horizontal continuity (which governs up-and downward fluxes).

Methods described are independent and quantitative. Matrix properties are expressed in terms of a singly hydraulic conductivity, diffusivity and moisture retention function. This is allowed when effects of swelling and shrinkage are expressed in terms of volume fractions of water of the soil matrix only, excluding the volume of the planar

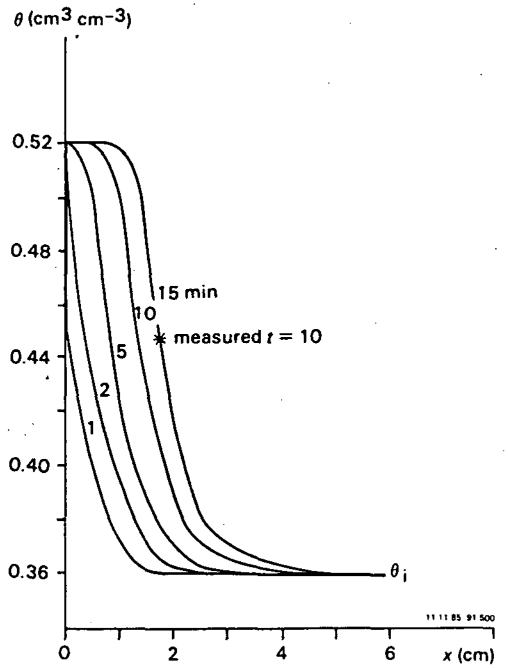


Figure 6 Calculated moisture distributions as a function of time and distance from surface of infiltration in a dry clay soil per unit surface area. The numbers 1, 2 etc. indicate the duration of infiltration (min).

voids. Planar void continuity is much more important than void width.

The method presented implies exclusive use of soil morphometric data, which could not have been obtained by physical methods. These data include: (1) The length of horizontal planar voids in horizontal cross section; (2) The vertical area of planar voids that is available for lateral infiltration, and (3) the area of air filled horizontal cracks in the subsoil.

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