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DRAINAGE AND VERTICAL HYDRAULIC CONDUCTIVITY OF SOME DUTCH "KNIK" CLAY SOILS

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ABSTRACT

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The vertical *K*-sat of a clay layer, occurring between 30 and 60 cm below the soil surface, was measured in situ in early spring at thirteen sites, using large soil columns. Gypsum was used to form a barrier around the column and *K*-sat values were measured with an infiltrometer in columns that were first attached and then detached from the subsoil. This procedure allows an estimate of the occurrence of large continuous pores, such as vertical worm channels. Highest values were found in tile-drained grassland, followed by grassland with surface drainage only, and by tile-drained arable land. Relatively low *K*-sat for the silty subsoil, rather than the (high) vertical *K*-sat for the clay layer, is considered to be responsible for high groundwater tables in the wet season.

Undisturbed, large columns were taken to the laboratory and saturated for a period of three months to simulate prolonged swelling after a very wet season, and to measure chloride-breakthrough curves, for characterizing soil-pore continuity. The clay layer, sampled in the surface-drained grassland, showed no significant reduction of *K*-sat after prolonged swelling, but the one for arable land was reduced. Moreover, flow in the latter occurred through only a few relatively large, continuous pores, whereas a more heterogeneous pore system was found for the column from grassland. The already high *K*-sat of the clay layer in surface-drained grassland increased as a result of tile drainage. Compaction of the clay layer in tile-drained arable land reduced *K*-sat well below the level found in surface-drained grassland.

1. INTRODUCTION

Non-calcareous clay soils in the northern part of the Netherlands are generally used as grassland for high-intensity dairy operations. The clay occurs as a layer of approximately 30 cm thickness, starting 30 cm below the soil surface.

Traditionally, surface drainage by shallow parallel ditches is applied in these soils to lower the watertable in spring, which is often close to the soil surface. To facilitate runoff to these ditches, the land surface in between has been slightly rounded in the past. Modern agriculture requires the use of heavy machinery and both the inadequate drainage and the uneven land surface give serious problems in terms of lagging production and poor workability. An alternative solution could be to tile-drain and level the land, but this has been attempted only locally as yet.

Whether or not tile drainage can be recommended for these soils depends on both economic and hydrological factors. Confining our attention to the latter aspect, two practical questions are most prominent: (i) Is the vertical K-sat of the clay layer sufficiently high in wet periods to allow adequate movement of water to the underlying soil and to the drains? If not, and this was generally expected, drains will have only a minor effect in lowering the watertable, which would then be a perched watertable on top of the slowly permeable clay layer, with a second watertable in the subsoil in which the drains are situated. Many natural soils with slowly permeable horizons overlying more permeable sediments with deep watertables have such properties (Schlichting, 1973; Vepraskas et al., 1974). Traditionally, these clay layers were supposed to have a very low K-sat in the wet season (Edelman, 1950; Mückenhausen et al., 1962). Very low values were indeed measured with the auger-hole method but the results may reflect inadequacies of the test (section 2.2). (ii) Does the vertical K-sat of the clay layer increase after an extended period of time in tile-drained soil? Such long-term effects, if present, would make tile drainage attractive, even if less favourable results occurred in the first few years. Field and laboratory experiments were based on these practical questions. Measurements were made in surface-drained grassland and in tile-drained grass- and arable land. The drainage system in the grassland was only three years old, the one in arable land had functioned for a period of twenty years. Arable land is uncommon in the area, but was included in the study to assess the effect of land use.

2. SOILS AND METHODS

2.1 *Soil conditions*

Non-calcareous, sticky, clay soils, occurring in northwestern Germany and in the north of the Netherlands, have traditionally been seperated from other clay soils because of their lower permeability and denser structure. These soils are called Knickböden (Mückenhausen et al., 1962, p. 135) or knip- or knikbodems (Edelman, 1950, pp. 125, 135, 136). Some current classifications of these soils are: Poldervaagggrond (De Bakker and Schelling, 1966) and Typic Fluvaquent (Soil Survey Staff, 1975).

The studied soil profiles are not entirely composed of the non-calcareous clay. The clay layers vary in thickness between a few to 60 cm and start at 20 to 120 cm below the soil surface. However, the most common thickness is between 25 and 45 cm and the layers generally start between 40 and 80 cm below soil surface. The lower 5—10 cm consists of a dark band with a slightly higher organic matter content which is formed by a zone of vegetation during sedimentation. The topsoil has an organic matter content between 5 and 10%

and its texture varies between silt loam and silty clay loam (Soil Survey Staff, 1975). The subsoil is quite variable in texture, due to the marine sedimentary regime. The upper 10—15 cm is non-calcareous but rests on calcareous marine sediments, which were completely reduced at depths varying from 120 to 150 cm below the surface. A detailed soil survey of the area was used to select the most representative test sites with clay layers of 25—40 cm thickness (including the dark band) starting at depths between 25 and 50 cm below the soil surface. Topsoils had strongly developed subangular blocky structures. Ped sizes increased with depth, forming large compound prisms in the clay layer with vertical ped faces and worm channels extending into the generally more silty subsoil which had only weakly developed peds. Grassroots always penetrated the clay layer, extending into the subsoil. Some representative textures of soil used in this study are presented in Table I.

2.2 *The vertical K-sat of the clay layer*

Many methods, both for field and laboratory use, are available for measurement of *K*-sat (Luthin, 1957; Bouwer, 1962). Non-critical application of any of these methods in well structured clays may yield non-representative results for the vertical K-sat, due to: (i) Basic features of some in-situ tests, that give a *K*-sat value as a resultant of ***both*** vertical and horizontal *K*. This is true for the double tube and the auger-hole method. (ii) Inadequate sample sizes if soil cores are used for laboratory measurements (Anderson and Bouma, 1973). (iii) Puddling and compaction during sampling or test preparations, which is likely when working in wet clay. This problem is particularly relevant because only a few larger pores, such as cracks or worm and root channels, contribute to saturated flow in these soils (Bouma and Anderson, 1973). Puddling results in closing of such larger pores, and measured *K* values will be unrepresentative. The assumption that *K*-sat of the clay layer in the soil type under discussion is low, was a result of measurements with the auger hole method. (iv) The season-

TABLE I

Representative textures and organic matter contents of soils used in this study. Subsoils varied considerably in texture and the three types reported represent the range observed

Soil layer	Texture			Organic matter
	clay	silt	sand	(%)
Topsoil	32	50	18	5.0
Clay layer	50	45	5	0.1
Subsoil 1 (column 10)	21	50	29	0.1
Subsoil 2 (column 6)	10	25	65	0.7
Subsoil 3 (column 2)	41	47	13	0.1

al changes of soil structure and pore patterns due to pronounced swelling and shrinkage of these soils. These processes may be active for months before equilibria are reached. *K*-sat values after a wet season are significantly different from those obtained after a dry period, even if the soil is prewetted for several days.

Considering the above four limitations, an in-situ test (see Fig.1) was used, as described by Baker and Bouma (1976). A vertical column of soil, with a diameter of 30 cm and a height equal to that of the clay layer, was carefully carved out in situ in a pit, and the topsoil was removed to the level of the clay layer. A 10-cm high infiltrometer was put on top of the soil column and its sides were sealed with gypsum which was poured as a slurry into a 5-cm wide collar around the soil column. Before applying the gypsum the vertical walls of the column were gently rubbed by hand with a thick clay slurry to prevent lateral movement of the gypsum into the column. Water was applied to the infiltrometer and infiltration rates were determined with a burette and mariotte device, maintaining a low hydraulic head on top of the soil column (Bouma et al., 1971, 1974; Bouma and Denning, 1972). The test was continued until a steady infiltration rate was obtained for at least several hours.

Uninhibited infiltration, due to the freshly exposed soil surface, in the column, resulted in saturated conditions as indicated by tensiometry. As the next step, the soil columns were detached from the subsoil and the infiltration measurements were repeated (Fig.1). During the latter experiments there was atmospheric pressure at the bottom of the column where outflow occurs. This allows a simple transformation of the measured flux into a *K*-sat value. Hydraulic conditions in attached columns may be more complicated because of generally unknown moisture potentials at the bottom of the columns. However, tensiometer values indicated moisture potentials to be very close to atmospheric pressure in the lower parts of the attached columns, thus also allowing a simple *K*-sat calculation. The purpose of the dual measurement was to obtain

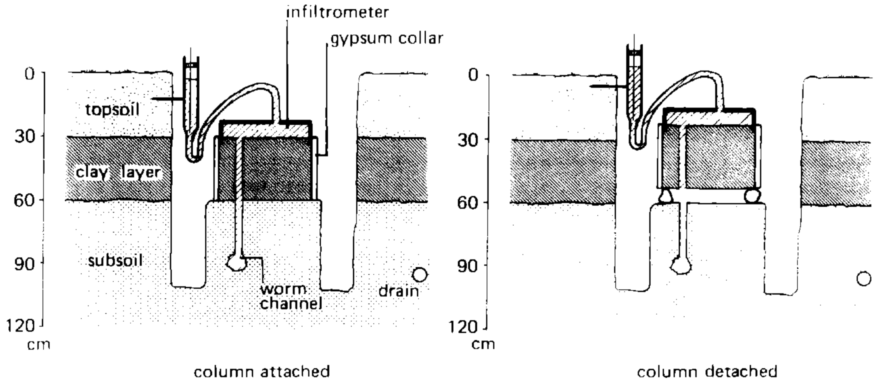

Fig.1. Schematic diagram, showing the principle of the measurements on the attached and detached soil columns.

an idea about the presence of continuous large vertical pores, such as worm holes, within the column (see section 3).

The testing procedure applied here avoids many of the problems discussed because: (i) The measurement applied strictly to vertical flow. (ii) The sample has the height of the layer to be tested and only horizontal dimensions could possibly be inadequate. However, the diameter of 30 cm is considered adequate. (iii) Puddling is avoided as the soil column is carefully cut out in situ and flow occurs through untouched soil which is enclosed by a tightly fitting gypsum collar. (iv) Measurements were made in early spring when water tables are high and the clay has been swelling for several months.

However, testing in spring as such may not always be adequate to obtain results that are representative for conditions after a very wet winter. For example, in this study measurements were made in the relatively dry period February through May 1976 (Fig.2a). Additional experiments were therefore designed to simulate the situation after a long wet period. For this purpose duplicate soil columns from surface-drained grassland and tile-drained arable-land were

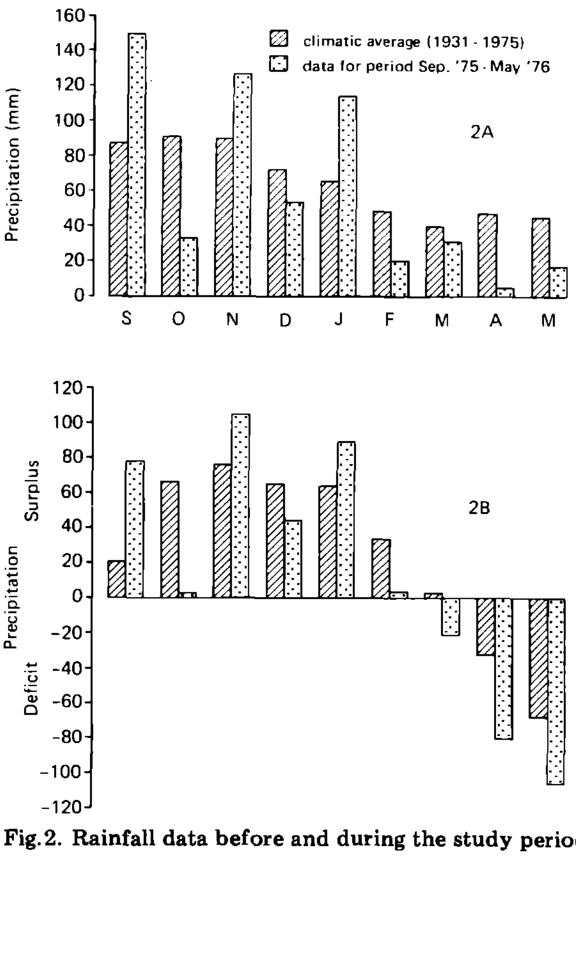

Fig.2. Rainfall data before and during the study period.

carved out as described above. The vertical walls were covered with grease and cheesecloth and a gypsum collar was poured as before. After drying of the gypsum the columns were transported to the laboratory and saturated for a period of three months. Saturated hydraulic conductivity measurements were made periodically to follow the change of *K* upon continued swelling. Swelling itself was determined with the Saran method and was (similar to Grossmann et al., 1968) expressed in terms of a Linear Extensibility (*LE*sat), defined as $(Vm/Vd)^{1/3}-1$, where *V*m = volume of saturated clod and *V*d = volume of stove-dry clod. Bulk densities for saturated soil were calculated. Grease was used to avoid flow between the walls of the column and the gypsum collar, which occurred after about six weeks in columns prepared with gypsum only. This problem was not encountered during the one-day in-situ field measurements of *K*-sat, as evidenced by dye studies. *K*-sat values for the subsoil were determined with the auger hole method; a routine practice used for determining optimal drain distance (Luthin, 1957).

2.3 *Flow through structured clay soil*

Understanding flow patterns through well structured clay is quite helpful for interpreting differences among measured *K*-sat values. Saturated flow under low gradients through isotropic, homogeneous porous media such as sands, is generally associated with low hydrodynamic dispersion (Brenner, 1962; Rose

TABLE II

Vertical *K*-sat values for the clay layer, measured in situ at thirteen locations, in attached and detached soil columns. Also presented are *K*-sat values for the subsoil (auger-hole method) and the number of tubular pores observed in the top surface of the soil column

Column	Land use	Drainage conditions	Number of tubular pores		*K*-sat (cm/day) clay layer		*K*-sat subsoil
			2—5 mm	>5 mm	attached	detached	(cm/day)
1	grassland	tile drained	11	1	65	430	6
2	grassland	tile drained	17	1	144	>500	5
3	grassland	tile drained	14	2	500	>500	300
4	grassland	surface drained	14	3	26	67	41
5	grassland	surface drained	13	4	53	98	49
6	grassland	surface drained	31	7	53	116	14
7	grassland	surface drained	13	—	57	140	4
8	grassland	surface drained	18	3	57	192	< 4
9	grassland	surface drained	9	4	92	92	25
10	grassland	surface drained	28	1	47	151	17
11	arable land	tile drained	4	1	12	—	38
12	arable land	tile drained	5	—	13	20	8
13	arable land	tile drained	3	—	18	14	45

and Passioura, 1971; Anderson and Bouma, 1977 a, b). Flow patterns through structured clays are quite different. Rapid movement occurs along a few larger pores, such as cracks or worm and root channels, whereas, simultaneously, very slow movement occurs through the fine porous natural soil aggregates ("peds") (Anderson and Bouma, 1973, 1977 a, b). A breakthrough curve can be used to characterize these types of flow. This curve was determined using a 300 ppm $CaCl_2$ solution. The chloride concentration in the effluent from the column was measured with a chloride electrode. The displaced volume of liquid at the moment that the first chloride is found in the column effluent, is an approximate measure for the volume of the largest pores participating in the flow. The rate of increase of the chloride concentration in the effluent is a function of the pore size distribution and of large-pore continuity, and can be used as an indicator for these structural features (Anderson and Bouma, 1977 a, b). The final concentration in the effluent is identical to that of the influent when either all water in the soil has been displaced by the chloride solution or when the flow through the fine soil pores is so slow that displacement of untraced water does not result in a measurable dilution of column effluents (section 3.2).

3. RESULTS AND DISCUSSION

3.1 *Results and interpretation of K-measurements*

Results of the in-situ measurements of the vertical *K*-sat of the clay layer are summarized in Table II. Values for the *detached* columns are all very high, but highest for tile-drained grassland. Differences with surface-drained grassland and tile-drained arable land are statistically significant at the 90% level, according to the Wilcoxon two sample test, which was applied because *K*-sat distributions are generally not normal (Van Eeden and Rümke, 1958; Baker and Bouma, 1976). The very high *K*-sat values are probably due to the occurrences of worm and root channels forming easy conduits for the water. The number of cylindrical pores larger than 2 mm diameter appearing at the freshly cleaned upper soil surface of the column was counted. Results, reported in Table II, show high numbers for all grassland soils, and relatively low numbers for the arable land. These differences are well reflected in differences among *K*-sat values found in both detached and attached columns. During field investigations earthworms were frequently observed in grassland subsoils, below the clay layer. During measurements in attached columns, the worm channels merely fill with water which can only drain through adjoining smaller voids. However, when the columns are detached the channels are continuous throughout the sample (see Fig.1) and conduct very high volumes of water (Bouma and Anderson, 1973). This phenomenon was strongest for the tile-drained grassland, followed by the surface-drained grassland and the arable land where no significant differences between the two types of measurement were found (Table II). Analysis of chloride breakthrough curves offers a more sensitive procedure for judging pore continuity (section 2.3; 3.2).

K-sat values for the subsoil, obtained from the auger-hole method, are relatively low (Table II). A direct comparison with the values for the clay layer is complicated by the different methods used. Values from the subsoil may have been affected by puddling effects. They reflect not only the vertical but also horizontal conductivities. Of particular interest are data for column 3. The underlying subsoil had a very high K-sat of 300 cm/day. This value can be considered representative for those of grassland soils after a period of tile drainage exceeding three years. Column 3 itself had also a very high K-sat. This single observation suggests that the significant increase of K-sat of the clay layer following three years of drainage, may at least be expected to increase further as time progresses. The relatively low K-sat of the subsoil therefore determines the level of the groundwater in these soils. This can be demonstrated by considering groundwater tables measured from February through May. Some representative examples are presented in Fig.3. Tile-drained grassland with a subsoil K-sat of 5 cm/day (curve A in Fig.3) has higher groundwater tables for a longer period of time, as compared with tile-drained grassland with a subsoil K-sat of 300 cm/day (curve B in Fig.3). (The two observation wells are equidistant from the drains). The corresponding overlying clay layer (sampled in columns 2 and 3 respectively) has very high K-sat values in both, which could not be responsible for the observed differences in watertables. The highest watertables were measured in surface-drained grassland. The selected test location had a subsoil K-sat of 4 cm/day, but also a clay layer (column 7 in Table II) with a very high K-sat.

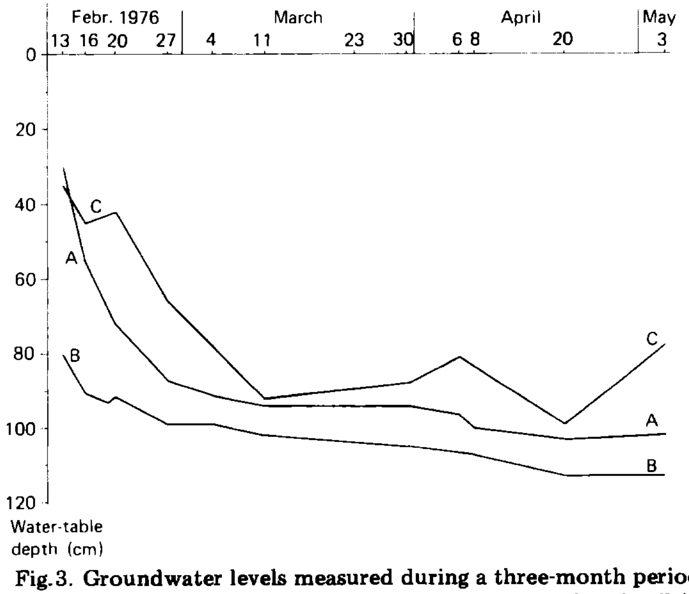

Fig.3. Groundwater levels measured during a three-month period at three locations. Curve A for tile-drained grassland with a moderately permeable subsoil (corresponding with column 2 in Table II); curve B for tile-drained grassland with a highly permeable subsoil (column 3 in Table II) and curve C for surface-drained grassland with a moderately permeable subsoil (column 7, Table II).

3.2 *Flow after prolonged saturation*

K-sat values of duplicate soil columns of the clay layer in surface-drained grassland and tile-drained arable land were periodically measured in the laboratory during three months. Columns sampled in arable land behaved significantly differently from those sampled in grassland. The former showed an irregular decrease in *K* upon continued swelling whereas the latter remained high. *LE*sat-values for saturated soil averaged 0.133 for grassland and 0.121 for arable land. These values, which are not significantly different, are relatively high (Grossmann et al., 1968) and illustrate the considerable swelling properties of these soils.

K-sat values for the clay layer in the arable land stabilized at a rate of approximately 2 cm/day, indicating a significant drop from the average 15 cm/day, measured in situ when moisture potentials in the clay layer were approximately −30 cm in early spring (Fig.2). The clay layer can thus still conduct water, even after prolonged swelling. However, this conclusion can be drawn more conclusively for the clay layer under grassland. Earthworms were found in effluents from the grassland columns during the measurements, suggesting a varying configuration of the porous system. For example, one of the columns suddenly showed a *K*-sat of more than 20 m/day when, apparently, one fresh large worm channel formed a continuous large pore throughout the column. Rates could be reduced after plugging the hole, but remained at or above the levels measured in situ. Differences in bulk density of the clay layer in samples from grassland and arable land are an indication for differences in structure. Bulk densities, derived from large Saran coated clods, were 1.06 and 1.18 g/cm^3 respectively at saturation, indicating the occurrence of compaction in the arable land. However, these bulk values are inadequate to explain differences among measured *K*-sat values, since the latter are a function of the pore size distribution of the porous medium and, particularly, of the continuity of the larger pores. Equivalent pore size distributions cannot be derived from moisture retention data (the pF curve) in swelling soils, because the capillary pore model does not apply (Denning et al., 1974). Pore size distributions can be observed in thin sections (Ismail, 1975), but a two-dimensional image, as such, is inadequate to predict the crucial three-dimensional pore continuity. However, breakthrough curves, measured at the end of the prolonged swelling period and presented in Fig.4, can be used to estimate pore continuity as naturally occurring in the 30-cm thick clay layer. Very rapid breakthrough was achieved in both soils. The first chloride in column effluents was measured after the passage of only 1 cc of liquid in the columns from the arable land, representing instant breakthrough, and about 6 cc in the grassland columns. This represents a fraction of only 2×10^{-4} and 10^{-3} (= t in Fig.4) of the entire water-filled pore space because the columns contained 5044 cc (arable land) and 5614 cc (grassland) of liquid at saturation, respectively.

Apparently some relatively large pores conduct water very rapidly, thereby by-passing water which also moves downward through finer pores inside the peds, but more slowly. Expressed as a percentage of total pore volume, these larger pores occupy an estimated 0.12 vol %. Such low percentages are characteristic for the volume of a few planar or tubular voids in soil (Bouma and Anderson, 1973). The observed rapid breakthrough represents very high hydrodynamic dispersion. Lack of dispersion would require outflow of at least 5000 cc of water before appearance of chloride (Brenner, 1962). The remainder of both breakthrough curves illustrates the quite different pore patterns in the two soils. Column effluents (with chloride concentration C_e) reached the concentration of the applied chloride solution C_i after passage of only 150 cc of liquid from the columns of arable land, as compared with 4000 cc for those of grassland. Generally, the point where $(C_e—C_o/C_i—C_o) = 1$ is not reached before *complete* displacement of all the original water from the soil (corresponding with $t \geqslant 1$). But very small dilutions cannot be measured, and are hydraulically insignificant because they result from very slow water movement through very fine soil pores. Lack of complete displacement at $(C_e—C_i/C_i—C_o) = 1$, which occurs very clearly in the columns from arable land (t = 0.03 !), indicates that flow occurs through only a few relatively large continuous pores in a very fine-porous compacted soil. Movement through continuous pores of smaller size is initially effective in diluting the solution which enters and leaves the column through the large pores, but very slow flow rates through the fine pores are, apparently, not effective in achieving further dilution to be measured with standard techniques used in this study. A large volume of original water is therefore left in the column at $(C_e—C_o/C_i—C_o) = 1$. This volume was 99.5% of the original water, as estimated by a graphical integration technique for the breakthrough curve. The curve indicates that flow apparently follows only a few relatively large, continuous pores. Such flow can be easily eliminated either by *closing* of the larger pores during compaction or by *filling with air* due to small negative moisture potentials. Both mechanisms are likely to occur, and this may explain the very wet conditions on the arable land observed in the spring of 1974, after a very wet winter.

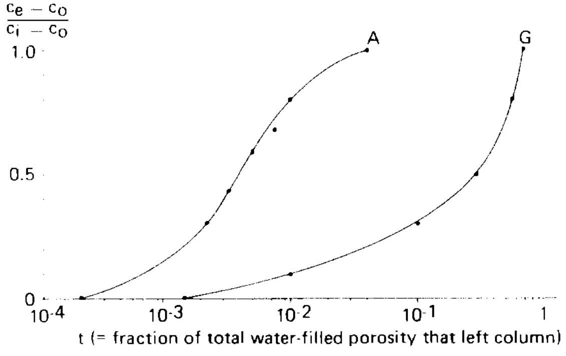

Fig. 4. **Breakthrough curves for saturated flow in soil columns from grassland (G) and arable land (A). C_e = chloride concentration in column effluent, C_i = chloride concentration of applied solution, C_o = initial chloride concentration in the column.**

The grassland columns behaved significantly differently. The $(C_e - C_o/C_i - C_o) = 1$ point was reached at t = 0.7, indicating that here too (smaller) pockets with the original water remain. These were estimated to constitute 21% of the original volume. A more heterogeneous pore structure with continuous pores of varying sizes is thus indicated by the shape of the breakthrough curve for the grassland.

4. CONCLUSIONS

(1) The vertical *K*-sat for the clay layer in surface-drained grassland is high, also after prolonged swelling, and cannot be the primary cause of seasonally high watertables near the soil surface. These appear to result from the inadequate capacity of the more slowly permeable subsoil to conduct water. This crucial capacity can be significantly improved by tile drainage.

(2) After three years, tile drainage of grassland resulted in a significant increase of the already high *K*-sat of the clay layer.

(3) Tile-drained arable land showed compaction of the clay layer, a strong reduction of the number of worm channels and a lower *K*-sat, particularly after prolonged swelling. This low *K*-sat results in seasonally shallow water tables. Moreover, as indicated by chloride breakthrough data, saturated flow occurred through only a few relatively large pores whereas flow in the clay layer under grassland occurred through a more heterogeneous pore system with continuous pores of varying sizes.

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