Some theoretical and practical aspects of infiltration in clays with $D = \text{constant}$

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Abstract

In clay soils with highly developed swelling, as e.g. in Na-Vertisols, the water diffusivity approaches a constant value. The physical parameters of a model soil with $D = \text{const.}$ are discussed and compared to the observed values. When crusting of the surface due to the rain is considered, the approximate model with $D = \text{const.}$ on the surface of the clay soil is developed and the induced shift of the ponding time is examined.

1 Introduction

With increasing alkalinity of clays when the exchangeable sodium percentage ESP rises and the electrical conductivity EC is kept at low values, the relationship between the water diffusivity $D$ and the soil moisture $\Theta$ starts to be less non-linear /Kutílek, Semotán, 1975, Kutílek, 1983/. In order to demonstrate this phenomenon, the $D(\Theta)$ relationship is approximated by the exponential form

$$D = \gamma \exp (\beta \Theta)$$

/1/
where
\[ \gamma, \beta = \text{coefficients}, \]
\[ \Theta = \text{relative soil moisture}, \Theta = \frac{\Phi - \Theta_r}{\Theta_s - \Theta_r} \]
\[ \Theta_r = \text{residual soil moisture, here in equilibrium with relative vapor pressure } p/p_o = 0.95, \]
\[ \Theta_s = \text{saturated soil moisture}. \]

The value of \( \beta \) is related to ESP and to clay content in Table 1. The \( D(\Phi) \) data were evaluated from the absorption experiments on confined soil columns. Due to the confinement, the swelling was strongly reduced and restricted to the internal part of the column with slight swelling at the inflow end and with the induced compression of soil at the wetting front, or in the semi-wet portion of the column /Fig.1/.

Figure 1. The change of the bulk density of Na-Vertisol /ESP = 27.5%/ at the inflow end of the confined column
Owing to the fact that the free swelling was practically annulled, the results are reported in classical way with $\theta$ expressed as volumetric moisture and in Eulerian coordinates.

Table 1. Coefficient $\beta$ in Eq. /1/ for soils of various degree of alkalinity

<table>
<thead>
<tr>
<th>ESP,%</th>
<th>EC, mmho/cm</th>
<th>Clay,%</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.5</td>
<td>1.1</td>
<td>33</td>
<td>5.9</td>
</tr>
<tr>
<td>19.5</td>
<td>0.74</td>
<td>35</td>
<td>3.0</td>
</tr>
<tr>
<td>29.0</td>
<td>6.0</td>
<td>43</td>
<td>3.1</td>
</tr>
<tr>
<td>30.0</td>
<td>3.1</td>
<td>32</td>
<td>2.9</td>
</tr>
<tr>
<td>31.0</td>
<td>6.8</td>
<td>44</td>
<td>2.8</td>
</tr>
<tr>
<td>31.0</td>
<td>2.4</td>
<td>29</td>
<td>3.8</td>
</tr>
<tr>
<td>38.0</td>
<td>3.9</td>
<td>42</td>
<td>2.2</td>
</tr>
<tr>
<td>13.0</td>
<td>1.1</td>
<td>59</td>
<td>3.8</td>
</tr>
<tr>
<td>21.5</td>
<td>0.96</td>
<td>62</td>
<td>1.9</td>
</tr>
<tr>
<td>27.5</td>
<td>0.75</td>
<td>68</td>
<td>-1.4</td>
</tr>
<tr>
<td>39.0</td>
<td>0.75</td>
<td>63</td>
<td>-1.5</td>
</tr>
</tbody>
</table>

The coefficient $\beta$ decreases with the increase of ESP and when the sodification is combined with high clay content, $\beta$ reaches even negative values. We can therefore expect existence of a soil with $\beta=0$ and $D=const$. When the soil with $\beta$ negative was saturated with $Ca^{2+}$, the $D(\theta)$ changed substantially, $\beta$ reaching positive values /Kutílek, Semotán, 1975/. We can suppose that the main mechanism changing the $D(\theta)$ from exponential relationship to approx. $D=const.$ is the desaggregation and peptization of clay particles. Generally, $D=const.$ is a close approximation for the flow of water in confined alkali soils /Fig. 2/ and the discussion of the characteristics of the "linear" soil /Philip, 1969/ is appropriate and $D=const.$ can be exact for the real soil.

Soil with $D=constant$
2.1 Derivation of soil characteristics

Two searched soil characteristics $H(\theta)$ and $k(\theta)$ should comply with the condition

$$D = K \ k(\theta) \ \frac{dH(\theta)}{d\theta} = \text{const.} \ /2/$$

where

- $K =$ saturated hydraulic conductivity,
- $k(\theta) =$ relative unsaturated hydraulic conductivity,
- $H =$ pressure head,
- $H(\theta) =$ moisture retention curve.

Condition /2/ can be rewritten in

$$\frac{d\theta(H)}{dH} = \text{const.} \ k(H) \ /3/$$

The relationship $k(H)$ should be monotoneous and the same is for $d\theta(H)/dH$ in order to keep $k(H)$ real. This leads to the restriction in the use of the analytical forms of $\Theta(H)$. The expression of Brooks and Corey /1964/ meets the condition and will be used in this discussion in the form

$$\Theta = \left(\frac{H_y}{H}\right)^2 \ /4/$$

where

$H_y, \lambda =$ parameters with physical meaning discussed in detail by Brooks and Corey.

Further on, we follow two types of interpretation of soil physical characteristics. Interpretation I declares $\Theta(H)$ as the single basic and sufficient characteristic, from which $k(\theta)$ can be deduced. Interpretation II uses two independent experiments for the determination of $H(\theta)$ and $k(\theta)$. Theoretical relationship of both characteristics is used for the development of approximate expressions.
The \( k(\Theta) \) relationship deduced from \( \Theta(H) \) according to physical models of porous media leads after introduction of Eq. /4/ to the general relation

\[
k(\Theta) = \Theta^{a/\lambda + b}
\]

where

\( a = 2, b = 3 \) in Burdin's /1953/ method,
\( a = 2, b = 2 \) in Childs and Collis-George's /1950/ method,
\( a = 2, b = 2.5 \) in Mualem's /1976/ method.

Substitution of Equations /4/ and /5/ in Eq. /2/ gives

\[
D(\Theta) = -\frac{H_v}{\lambda} \frac{K}{\Theta_s - \Theta_f} \Theta^{(a-1)/\lambda + (b-1)}
\]

The condition \( D = \text{const.} \) will be satisfied if

/1/ either \( \lambda = -(a-1)/(b-1) \)
/2/ or \( a = b = 1 \).

The first condition is in accordance with the Interpretation I, and e.g. for the Burdin's method we get \( H = H_v \Theta^2 \) and \( k = \Theta^{-1} \). However, both characteristics are not physically real. We get similar physically not real results for other methods of \( k(\Theta) \) evaluation from \( H(\Theta) \).

In the second condition, \( a, b \) are very different from the theoretical values of models developed for soils with strong non-linear \( D(\Theta) \) relationship. It means that the soil with \( D = \text{const.} \) differs from other soils not by parameter \( \lambda \) with a specific \( H(\Theta) \) relationship, but that the difference is in a special method of prediction of \( k(\Theta) \). This development is in accordance with the Interpretation II. Since this condition is physically acceptable, we get the following characteristics of a soil with \( D = \text{const.} \).

\[
H = H_v \Theta^{-1/2} \quad k = \Theta^{1/2 + 1} \quad D = -\frac{H_v}{\lambda} \frac{K}{\Theta_s - \Theta_f}
\]

If \( \lambda = 1 \), the conductivity function is quadratic and such a
soil is identical with the soil described by Burger's equation /Clothier et al., 1981/. It means that the Burger's equation describes a specific case within the family of soils with D=const.

2.2 Numerical and analytical solutions of a model soil

The above derived characteristics in Equations /7/, /8/, /9/ of a soil with D=const. were used for the analytical and numerical solution of the horizontal infiltration /absorption/. In the analytical solution of the diffusivity equation only Eq. /9/ was applied while in the numerical solution of the capacity equation both Eq. /7/ and /8/ were used. The results obtained by two different procedures serve as a proof of correctness of the derived characteristics and the comparison of results indicate the range of error due to the numerical procedure, too.

In the numerical method, the implicit scheme of final differences was used for the solution of the capacity equation

$$\frac{d\Theta}{dH} \frac{\partial H}{\partial t} = \frac{\partial}{\partial x} \left[ k(H) \frac{\partial H}{\partial x} \right]$$

/10/

In the analytical solution of

$$\frac{\partial \Theta}{\partial t} = D \frac{\partial^2 \Theta}{\partial x^2}$$

/11/

with

$$\Theta = \Theta_i \quad x > 0 \quad t = 0$$

/12/

$$\Theta = \Theta_s \quad x = 0 \quad t > 0$$

/13/

we obtain according to Crank /1956/

$$\Theta = \Theta_i + (\Theta_s - \Theta_i) \text{erfc} \left( \frac{x}{2\sqrt{Dt}} \right)$$

/14/
Further on, sorptivity $S$ was calculated according to Philip /1969/

$$S = 2\left(\theta_S - \theta_i\right)\sqrt{\frac{D}{\pi}} /15/$$

The model soil was characterized by $D = 0.04167 \text{ cm}^2 \text{min}^{-1}$, $H_V = -1 \text{ cm}$, $\lambda = 1$, $\theta_S = 0.45$, $\theta_i = 0.05$, $\theta = 0.10$, $K = 0.0167 \text{ cm min}^{-1}$, $k = \theta^2$. Following results obtained by the two methods were compared:

/1/ The moisture profile $\theta(x)$ at the sequence of time intervals were compared and selected data at $t = 61 \text{ min}$ and $t = 900 \text{ min}$ are in Table 2.

Table 2. Moisture obtained by analytical, $\theta_A$ and numerical, $\theta_N$ procedure for soil with $D = \text{const.}$

<table>
<thead>
<tr>
<th>$x$, cm</th>
<th>$t$ 61 min $\theta_A$</th>
<th>$\theta_N$</th>
<th>$t$ 900 min $\theta_A$</th>
<th>$\theta_N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.33009</td>
<td>0.33799</td>
<td>0.41783</td>
<td>0.41816</td>
</tr>
<tr>
<td>3</td>
<td>0.16416</td>
<td>0.17980</td>
<td>0.35516</td>
<td>0.35618</td>
</tr>
<tr>
<td>6</td>
<td>0.10273</td>
<td>0.10598</td>
<td>0.27095</td>
<td>0.27280</td>
</tr>
<tr>
<td>9</td>
<td>0.10002</td>
<td>0.10016</td>
<td>0.20454</td>
<td>0.20678</td>
</tr>
<tr>
<td>18</td>
<td>-</td>
<td>-</td>
<td>0.11318</td>
<td>0.11417</td>
</tr>
<tr>
<td>27</td>
<td>-</td>
<td>-</td>
<td>0.10064</td>
<td>0.10075</td>
</tr>
</tbody>
</table>

Better agreement between the exact and numerical solutions was found for greater time as it can be expected.

/2/ Cumulative infiltration $I$ was determined in both cases by numerical integration of the moisture profiles using the Simpson's rule and the results are compared in Table 3 with exact $I$ obtained from $S$ which was computed according to Equation /15/. The error due to the numerical integration is negligible when compared to the error induced by the procedure of final differences, but, generally, good agreement exists between the numerical and analytical procedures and the agreement increases again with time.
Table 3. Cumulative infiltration $I$, cm.

<table>
<thead>
<tr>
<th>$t$, min</th>
<th>$\int \Theta_N , dx$</th>
<th>$\int \Theta_A , dx$</th>
<th>$S = 0.080615$ exact $I = S , t^{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>61</td>
<td>0.69214</td>
<td>0.62949</td>
<td>0.62963</td>
</tr>
<tr>
<td>900</td>
<td>2.45085</td>
<td>2.41843</td>
<td>2.41846</td>
</tr>
</tbody>
</table>

/3/ When the time dependency of the cumulative infiltration $I(t)$ and of the infiltration rate $v(t)$ as obtained by final differences was evaluated, the values of $S$ and $\alpha$ in the equation $I = S \, t^{\alpha}$ were not in agreement with the general theory $\alpha = 0.5$ nor with the exact data obtained analytically. Both $S$ and $\alpha$ were time dependent, gradually approaching the theoretical data after great time, as we can again expect from the nature of the numerical method. The comparison of the results gained by two different procedures of solutions shows that the final differences offer data only slightly different from the exact solutions and the reason for it is in the approximative nature of the numerical procedure. The correctness of the derivation of the soil characteristics in Eq. /7/, /8/ and /9/ can be taken as confirmed.

2.3. Application to the real soil

Na-Vertisol with ESP = 27.5%, EC = 0.75 mho cm$^{-1}$ is used in this study. Its $D(\Theta)$ was obtained by horizontal infiltration and is plotted in Figure 2. The Crank's /1956/ expression for calculation of mean $\overline{D}$

$$\overline{D} = \frac{5}{3(\Theta_S - \Theta_i)^{5/3}} \int^\Theta_S \left( \Theta - \Theta_i \right)^{2/3} D(\Theta) \, d\Theta / 16$$

offers $\overline{D} = 2.944 \times 10^{-4}$ cm$^2$ min$^{-1}$ when $\Theta_S = 0.49$ and $\Theta_i = 0.12$. 

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Figure 2. The relationship between water diffusivity \( D \) and the volumetric moisture in Na-Vertisol /ESP 27.5%/.

\( \frac{D}{D} \) indicates the weighted-mean diffusivity

Sorptivity is according to Eq. /15/ \( S=7.164 \times 10^{-3}\,\text{cm min}^{-1/2} \). The values of the consumption of water during the experiment give \( S=8.504 \times 10^{-3}\,\text{cm min}^{-1/2} \). However, the systematic error due to the evaporation through the walls of the tubing etc. cannot be excluded since the experiment ran slowly and lasted for 30 days. Therefore the term consumption instead of cumulative infiltration is used. From the experimentally determined moisture profile after \( t=43320\ \text{min} \) we get by integration \( I=1.44\ \text{cm} \) and \( S=6.919 \times 10^{-3}\,\text{cm min}^{-1/2} \), while the exact value obtained by Philip's procedure /1955/ gives \( S=7.318 \times 10^{-3}\,\text{cm min}^{-1/2} \). When the approximative expressions for sorptivity were tested and plotted as \( S(\theta_i) \), we have
found that the Philip's/1969/ solution, Eq./15/based on $D$ was the closest one to the exact values. The equation of Parlange /1971/ offered $S$ lower by approx. 15%, the expression of Parlange /1975/ gave the results higher approx. by 15%, and the theory of Philip and Knight /1974/ resulted in data higher approx. by 30%, when the exact values of $S$ obtained by Philip's /1955/ procedure were taken as the basis for comparison. Here again, we can see the difference from the relations derived for soils with $D(\phi)$ strongly non-linear /Elrick, Robin, 1981/. We can conclude that $\bar{D}$ computed from Eq. /16/ offers reliable results.

Greater differences between the experimental and computed $\theta$ data occur when the moisture profiles $\theta(x)$ are compared /Table 4/.

Table 4. Comparison of the experimental and computed $\theta(x)$ for $t=43320$ min, $\theta_0=0.12$, $\theta_s=0.49$

<table>
<thead>
<tr>
<th>x, cm</th>
<th>$\theta_{\text{exper.}}$</th>
<th>$\theta_{\text{comp.}}$ for $D=\text{const.}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>0.420</td>
<td>0.446</td>
</tr>
<tr>
<td>3.0</td>
<td>0.278</td>
<td>0.324</td>
</tr>
<tr>
<td>6.2</td>
<td>0.199</td>
<td>0.201</td>
</tr>
<tr>
<td>11</td>
<td>0.145</td>
<td>0.131</td>
</tr>
</tbody>
</table>

In spite of lower accuracy in computing the moisture profiles, we can see that the general shape of the computed moisture profile is identical with the experimental one. We are allowed to conclude that the approximation of $D=\text{const.}$ is appropriate. When the physical nature of the alteration of the physical properties is considered, we can assume that the approximation with $D=\text{const.}$ is suitable in all instances when the desaggregation and peptization of clay particles occur in heavy soils.
3. Crusting of soils due to the rain infiltration

The main mechanism of crust formation due to the rain is the desaggregation of the surface, the washing in of fine particles and compaction of the immediate surface by raindrop impact /McIntyre, 1958/. Morin et al. /1976/ suppose that the sealing efficiency of the crust is increased by the action of a very high hydraulic gradient across the crust, and they conclude from their experiments that the crust thickness ranges from $10^{-2}$ to $10^{-1}$ cm. The first number is in agreement with finding of McIntyre. Further on, the authors state that the conductivity of the crust on loess and on sandy loam is lower by 3 or 4 orders of magnitude, i.e. for loess, the crust conductivity should be in ranges $7 \times 10^{-5}$ to $7 \times 10^{-6}$ cm min$^{-1}$. These data lead to the assumption that the crust can be defined as a soil desaggregated to such an extent that the crust hydrodynamic characteristics are close to the characteristics of desaggregated Na-Vertisol. Accepting this premise, we can discuss the influence of the crust upon practical behavior of the soil during rainstorm infiltration using the theoretical development on soils with $D_{-} \text{const.}$ The most instructive is the influence of the soil crust upon the shift of the ponding time.

Let us assume in accordance with the results of McIntyre and Morin et al. that the crust hydraulic conductivity $K_c$ decreases exponentially with the cumulative rain. If the rain intensity is taken constant, $v_r$, the crust conductivity $K_c$ can be expressed by

$$K_c = K_o \exp (-c_1 v_r t)$$  /17/

where

$K_o =$ conductivity of the undisturbed soil at $t = 0$ at $z = 0$.

The final value of the conductivity of the crust at the ponding time $t_p$ is $K_{cf}$. Analogically to Eq. /17/, the decrease of the water diffusivity in the crust is expressed by
\[ D_c = D_0 \exp (-c_2 v_r t) \] /18/

where

\[ D_0 \] is computed acc to Eq. /16/ as the mean-weight diffusivity of the undisturbed soil at \( t=0 \) at \( z=0 \).

Since \( K_{cf}/K_0 \approx 10^{-3} \) to \( 10^{-4} \) and \( H_{v}/\lambda \) is expected in accordance with Na-Vertisol to be \( 10^{-1} \) while in microaggregated clays it is \( 10^0 \), we suppose that \( D_{cf}/D_0 \approx 10^{-2} \) to \( 10^{-3} \) and \( c_1 > c_2 \).

Provided that the Philip's /1969/ algebraic equation \( v = St^{-1/2} + A \) is applicable with \( v = \) infiltration rate, the ponding time \( t_p \) is calculated from /Kutílek, 1980/

\[
t_p = \frac{s^2}{A^2} \frac{(2b-1)}{4b(b-1)^2} \]

/19/

where

\[ b = \frac{v_r}{A} \]

When mean diffusivity and conductivity of the crust are used in time interval \( <0, t_p> \), we get with Eq. /15/ and taking \( A = (1/3)K \)

\[
t_p \approx \frac{(\theta_s - \theta_s')^2 D^* (6v_r - K^*)}{v_r (3v_r - K^*)^2} \]

/20/

where

\[ D^* \approx \frac{D_0}{t_p c_2 v_r} \]

\[ K^* \approx \frac{K_0}{t_p c_1 v_r} \]

If the crust formation process was not considered as developing in time and the final values of \( D_{cf} \) and \( K_{cf} \) were incorrectly considered, the \( t_p \) could be shortened up to approx. by one order of magnitude. The moisture profile below the crust is computed from the integrated equation of continuity inserting for \( v_r \) the reduced flux below the surface film. The water storage in the crust is neglected.
Acknowledgements

For the analytical data on ESP and EC and for the selection of samples, I am indebted to E.L. Strmecki, FAO. For the numerical analysis by final differences, the program of J. Mls from our Laboratory was used. I acknowledge with gratitude the cooperation of T. Vogel on Chapter 2.

References


Discussion

P.A.C. Raats:
Is the curve in Figure 1 based on only the pairs of data points shown? Is the Figure intended to show how the measured expansion in the interval 0 - 0.5 cm might be compensated for by compression in the interval 0.5 - 2 cm?

Author:
The data in the domain of compression were measured, but they are...
scattered, just indicating the compression phenomenon. The line is drawn on the basis of equality of areas.

P.A.C. Raats:
The linkage of the Brooks/Corey representation of the physical properties to the Burgers' equation is interesting. From a theoretical point of view, Burgers' equation deserves attention since 1) it contains a physically realistic, minimally nonlinear, gravitational term, and 2) thanks to the Cole/Hopf transformation, analytical solutions can be obtained for a wide variety of conditions. My question is: for the same soil and the same initial and boundary conditions, would retaining gravity have a significant influence upon the results of your calculations?

Author:
The influence of gravity is supposed to be less significant than in strongly nonlinear soil. However, the computation has not yet been done.
Hydraulic conductivity and structure of three Australian irrigated clays

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Swelling clay soils are widespread in the eastern Australian hinterland, occupying about 10^9 ha of alluvial plains, gently sloping fans, and undulating to gently rolling uplands. The three sites to which reference is made are on irrigated areas of alluvial plains. In the management of irrigated swelling soil, hydraulic conductivity in the swollen ('saturated') state is significant for profile drainage, salt leaching, and the re-establishment of aerobic root zone conditions following irrigation or heavy rainfall. The aim was to examine the relationship between hydraulic conductivity, structure and macro-porosity.

At Kerang irrigated cereal cropping (not rice) and pasture production, which began some 80 years ago, soon led to shallow watertables and salinization of the soil. By judicious management and drainage, partial reclamation has been achieved and allows some crop and pasture production. At the site sampled (a Chromustert) the upper 0.2-0.3 m was dark coloured subangular blocky (10-30 mm) clay, with many grass roots, some with rusty staining. This graded into a brown, friable, angular and subangular blocky (10 mm breaking to 3 mm) zone, with many fine (<1 mm) and some larger (3 mm) cylindrical voids, often with dark soil infills. These voids continued beyond 0.8 m. Below 0.5 m some slickensided surfaces were apparent, many aggregates were sub-rounded or tubular in form and some soft and nodular carbonate occurred.

At Benerembah the area has been irrigated for some 25 years, mainly for rice, other cereals and pasture, and the watertable is at 10-15 m and rising. At the sample site (a shallow surfaced Natrustalf, with vertic
characteristics when cultivated, cf. Chromustert), the brown, weakly structured surface layer passed sharply to a dense, massive red-brown clay with few widely spaced vertical planar voids and with few roots and few visible voids. Below about 0.3m there were occasional oblique planar surfaces with slickensides, increasing in frequency with depth, and also a few small carbonate nodules.

At Narrabri irrigation began about 20 years ago for cotton production and since then some soil structural degradation has occurred as a result of tillage and other cropping operations. Watertables do not occur. The sample site (a Pellustert) had 0.15m of very dark grey, crumbly, self-mulching clay, overlying columnar (115 x 70mm) clay, breaking to subangular blocky. Strong parallelepipedal structure with many slickened surfaces occurred below 0.25m. Only occasional fine cylindrical voids were visible. Scattered small carbonate nodules occurred throughout the profile.

Standard analytical data (Table 1) were obtained for profiles sampled at the three sites. 'Saturated' hydraulic conductivity (K) was measured by two techniques (Table 2). Dye solutions (first methylene blue, then Rhodamine WT) were allowed to soak into the undisturbed blocks which, subsequently, were horizontally sectioned at 0.05m intervals and examined by incident light microscopy.

Table 1. Analytical data for Kerang (Kg), Benerembah (B), and Narrabri (N)

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Clay content (%)</th>
<th>pH</th>
<th>EC1(dS/m)</th>
<th>ESP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kg</td>
<td>B</td>
<td>N</td>
<td>Kg</td>
<td>B</td>
</tr>
<tr>
<td>0-0.1</td>
<td>51</td>
<td>38</td>
<td>62</td>
<td>7.0</td>
</tr>
<tr>
<td>0.1-0.2</td>
<td>-</td>
<td>59</td>
<td>-</td>
<td>7.4</td>
</tr>
<tr>
<td>0.2-0.4</td>
<td>71</td>
<td>60</td>
<td>63</td>
<td>7.6</td>
</tr>
<tr>
<td>0.5-0.7</td>
<td>65</td>
<td>47</td>
<td>-</td>
<td>7.9</td>
</tr>
</tbody>
</table>

1 pH and electrical conductivity of 1:5 soil:water suspension
2 Exchangeable sodium percentage

The dye investigations showed that the flow in all 3 soils occurred mainly in cylindrical voids which often contained roots and/or faecal pellets. Dyed voids were far more frequent in the Kerang soil than the
When dyed roots intersected planes, the dye sometimes spread out in dendritic patterns over part of the planar surfaces but, in general, these surfaces appeared not to provide continuous pathways for flow.

Table 2. 'Saturated' hydraulic conductivity (mm/day) by two methods

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Undisturbed blocks</th>
<th>Well permeameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kg</td>
<td>B</td>
</tr>
<tr>
<td>0.2-0.45</td>
<td>70</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>370</td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td>420</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5-0.75</td>
<td>23</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>210</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>280</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
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1Method of Bouma & Dekker (1981) except that the excavated block was first coated with rapid setting cement before encasing it in gypsum.
2A constant head method due to W.D. Reynolds & D.E. Elrick (priv.comm.).
3Irrigation waters used for Kg, B and N of EC 150, 40, and 200μS/cm and SAR 2.7, <1 and 1.4 respectively.
4'Drainage' waters used for Kg, B and N of EC 50000, 950 and 1150μS/cm and SAR 51, 5 and <1 respectively.

For the undisturbed blocks and the well permeameters (Table 2), the Kerang soil, with many cylindrical voids, had the highest K values, despite high clay content and ESP (Table 1). The Narrabri soil showed greater variation in K values, at least some of which was probably associated with previous, widely spaced ripping. Zero values for the well permeameter method at 0.5-0.75m may have been caused by smearing of the walls of the permeameter holes. Though the Narrabri soil had very frequent planar voids and low ESP, its K values were generally low. Cylindrical voids were rare. The low K values for the Benerembah soil also were associated with rare cylindrical voids and, in addition, few planar voids and high ESP.
The identification of cylindrical rather than planar voids as the significant pathways for saturated waterflow in the Kerang soil, provides an explanation for the rapid development of watertables and consequent salinity following the advent of irrigation. Conversely the presence of the cylindrical voids should allow rapid drainage and desalination. Destruction of their continuity by tillage or other means should be avoided, otherwise very low profile permeability is likely to develop as a result of the high sodicity levels. Thus tillage should be restricted both in depth and frequency, and should be accompanied by an appropriate ameliorant, e.g. gypsum, to maintain the permeability of the tilled layer.

The Benerembah soil, on the other hand, presents a more difficult management problem. Porosity created by deep ripping or deep ploughing in an attempt to improve water entry into, and drainage from the profile is unlikely to persist for long because of high subsoil ESP values. Massive doses of gypsum would be required to lower the profile sodicity levels appreciably.

The Narrabri soil with low ESP values, might be expected to benefit from deep tillage because the porosity created is likely to be persistent and provide the needed rootzone drainage for re-establishing aerobic conditions after irrigation and rain. In this soil, unlike the others, mole drainage could perhaps be a proposition.

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References

A fertilization study on a clayey soil in southern Bavaria showed no definite effects of K- and P-fertilizer levels on crop yields during a four-year period since its start in 1974 (Vogl, 1982). This finding initiated in 1978 a study for evaluating the soil water regime and its effect on crop yields. Monitoring soil water tensions during the growing seasons 1978-1980 showed unexpectedly rapid changes in soil water tension (Vogl, 1982), the reason of which was at first glance not detectable.

The soil of the study site in the so-called Tertiary Hill Country in southern Bavaria is an Aquic Chromudert derived from Tertiary calcareous (up to 57% carbonates) clay (37-62% clay, 22-41% silt, 4-22% sand) overlain by a thin loess layer (28% clay, 39% silt, 33% sand). Smectites dominate in the Tertiary clay. During 1978-1980 the crops on the site were winter wheat, winter barley followed by rape as intercrop, and corn, respectively.

Mercury tensiometers were installed at 8 different depths between 25 cm and 160 cm (in 3 replicates down to 65 cm and 2 replicates at the other depths). Self-made tensiometers constructed from PVC-pipes (26 mm outer diameter) fitted tightly in auger holes (25 mm diameter), thus obviating precipitation running off into the soil along the tensiometer shaft. They were arranged such that any interaction between two neighbouring depths was eliminated. Soil water characteristics and saturated hydraulic conductivities were determined on undisturbed soil core samples in the laboratory, and unsaturated hydraulic conductivities were calculated using the equation from Campbell (1974). Tensions were read
and precipitations recorded daily during the growing seasons. The resulting soil water tension/time curves for each depth were smoothed by fitting a third order polynomial using the procedure of Savitzky and Golay (1964).

The smoothed soil water tension/time curves for depths >85 cm showed a typical feature in the seasons 1978 and 1979. Soil water tensions slowly increased by about 200 cmWC within 3-6 weeks and rapidly decreased by the same amount within 7-10 days. This saw-tooth like feature was more pronounced in 1978 than in 1979 and was only faintly developed in 1980 (Figure 1). For depths <85 cm the saw-tooth like feature could only be observed in 1978 before harvesting, and it vanished more and more with decreasing distance to the soil surface. After harvesting, soil water tensions in ≤85 cm remained between 0 and 50 cmWC, if no intercrop had developed. In 1980, due to much precipitation during the first growing stages of corn (which is well developed late in the season), soil water tensions were near or below 0 cmWC in all depths until corn was well developed. Periods with high precipitation coincided in 1978 and 1979, with a large decrease of soil water tension at all depths (Figure 1).

Initially, poor tightening between soil and tensiometer shafts was considered to be responsible for the saw-tooth like behaviour of the tension/time curves. Two reasons, however, were contradictory to this. Firstly, a tensiometer installation check showed no possibility for water to flow deep into the soil along the tensiometer shaft. Secondly — and this is very important — if there would be a poor tightening then the tensions should change more rapidly and drastically in the upper horizons than in the deeper horizons, particularly after harvest when no transpiration occurs. Water flow through macropores having a high continuity, which may develop as cracks in this clayey soil during a dry period, seems to be a more plausible cause for the saw-tooth like feature of the tension/time curves. This is confirmed by the soil water characteristics and unsaturated hydraulic conductivities of the horizons, field observations on cracking, and water tensions in the upper horizons.

The low unsaturated hydraulic conductivities of the upper horizons even at low soil water tensions cause most of the water of a higher precipitation following a dry period to flow downward, along the walls
of the cracks developed during the dry period, and not into the aggregates of the upper horizons. The very large changes of soil water

![Soil Water Tension Time Curves](image)

Figure 1: soil water tension/time curves for the 85, 115, 135, and 155cm depths in the seasons of 1978 and 1979, and corresponding precipitation
tension (e.g. $260\text{cmWC}$ in the range between 100 and $400\text{cmWC}$) due to a small change in water content ($2\%\text{v. H}_2\text{O}$) of the horizons >85 cm depth, also cause a rapid decrease in the soil water tension in the subsoil horizons. This phenomenon was also observed by Germann and Beven (1981) and Kutilek (1980; personal communication) and explained in the same way. The relatively dry soil aggregates do not swell quickly enough on water supply to hinder surface water to flow down. Thus, after a longer rainfall period, water-logged soil conditions may occur in some parts of the subsoil, even though the soil horizons above and below of this part are relatively dry. Drainage of the water takes place only to a small degree, because the unsaturated hydraulic conductivities of the horizons >150 cm are low even near saturation. No cracks develop below this depth.

After harvest when evapotranspiration is strongly reduced, soil water tensions within rooting depth decreased to about $30-50\text{cmWC}$ for the rest of the year. Although the aggregates of the upper horizons swelled to some extent due to wetting up of the soil, the cracks are more or less intact in the surface soil as well as in the subsoil. The low unsaturated conductivities of the surface soil even at low water tensions, and the high continuities of the cracks cause heavy precipitation to cause the saw-tooth like feature of the water tension/time curves in the subsoil horizons.

After a wet spring and planting a crop that is well developed late in the season (e.g. corn), no cracks will develop and, thus, as in 1980, no saw-tooth like feature of the water tension/time curve will be observed.

References


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