Scaling the saturated hydraulic conductivity of a vertic ustorthens soil under conventional and minimum tillage

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Abstract

With the aim of setting up a simplified method to measure hydraulic conductivity of structured soils at saturation, a method reported by Ahuja et al. (Soil Sci. Soc. Amer. J. 48 (1984) 699–702; Soil Sci. 148 (1989) 404–411), which also refers to the generalised equation of Kozeny–Carman and the scaling theory, is tested in this paper. Data were elaborated from hydraulic conductivity measurements $K_s$ on undisturbed soil cores taken from three plots of a sloping vertic soil which underwent various tillage practices for many years. In particular, following the proposed methodology, the spatial distribution effective soil porosity $\phi$ was first obtained. Once the distributions of hydraulic conductivity at saturation were obtained, it was possible to correlate the spatial variability of hydraulic conductivity with the variability of the unique factor $x$ scaled by effective soil porosity. Statistical elaboration indicated that the log-normal law is the one which best approximates the frequency distribution of scale factors $x_k$ and $x_f$. No significant differentiations were noted between the distributions of parameters relative to different soil tillage systems. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Hydraulic conductivity; Effective soil porosity; Scale factors; Soil tillage system

1. Introduction

In the last few decades, practices used for the mechanical manipulation of soil have undergone significant operative and technological changes. Most recent tillage operations have allowed a substantial increase in soil productivity and decrease in energy consumption. Tillage practices generally lead to an overall improvement in the hydrological characteristics of soil, thereby helping to create optimal crop vegetative conditions and markedly reducing soil erosion problems (Douglas et al., 1981; Hamblin and Tennant, 1981; Horton et al., 1989; Datiri and Lowery, 1991; Wu et al., 1992). One major consequence of tillage is that it modifies some soil physical and chemical properties, especially at the surface layer, such as total porosity, continuity and tortuosity of the pore system, pore-size distribution, surface roughness, degree of compaction, and hence bulk density, as well as nutrient distribution. Tillage methods in soils under long-term cultivation generally...
result in increasing total porosity of the ploughed layer, reducing consolidation and helping to set up bigger aggregates (Unger, 1984). However, long-term tillage operations could exert undesirable effects on soil properties (Bouma and Hole, 1971) and possible interactions between tillage and space–time variability in soil properties should also be taken into account (Cassel and Nelson, 1985; Van Es, 1993).

Given that the soil surface and uppermost horizon play an important role in determining the amount of incident water — whether rainfall or irrigation water — which becomes runoff, it is apparent that tillage may considerably affect the hydrology of an agricultural catchment (Freebairn et al., 1989; Mwendera and Feyen, 1993). An in-depth physical understanding of this effect can thus be extremely useful for obtaining reliable results when using comprehensive and dynamically integrated models developed to predict vegetation growth, infiltration, overland flow and sediment yield, and the ways in which such phenomena evolve in response to variations in climate or land use (Kirkby et al., 1992).

However, the implementation of such models requires new technologies and a new class of experiments, preferably to be conducted in the field, in order to evaluate soil hydraulic properties, the spatial distribution and variation of the porous system.

Many experimental studies have shown that soil hydraulic properties vary considerably even in the same mapping area (Nielsen et al., 1973; Comegna and Vitale, 1993), especially as regards hydraulic conductivity, which may have coefficients of variation in excess of 100%. The study of variability in field of hydraulic parameters may be simplified if we assume that soil microgeometry in two different sites may be similar. As shown by Miller and Miller (1955a,b), values of water potential and hydraulic conductivity measured in different areas may be referred to corresponding mean values by means of

\[ K(s) = \frac{K_{\text{ref}}}{\theta_{\text{ref}}} \]

where \( K(s) \) is the hydraulic conductivity at degree of saturation, \( s \), and \( K_{\text{ref}} \) and \( \theta_{\text{ref}} \) are effective soil porosity and water content, respectively. The validity of the above assumption was only confirmed by laboratory tests on sand filters (Klute and Wilkinson, 1958; Elrick et al., 1959) and, although there has been no actual response in soils, it was used by various authors (Warrick et al., 1977b; Simmons et al., 1979; Rao et al., 1983) by referring tensiometric and conductivity data to degree of saturation, \( s \), rather than to water content and water content \( \theta \), and evaluating the distribution of the similarity ratio not in reference to the microgeometry of the porous medium, but by ensuring that the hydraulic conductivity and retention curve, measured at different points, fitted in the best way. Thus we overcome the rigorous concept of geometric similarity introduced 40 years ago by Miller and Miller, and the similarity ratio is evaluated using regression techniques. Such techniques, generally indicated in the literature as functional normalisation techniques (Tillotson and Nielsen, 1984), aim to reduce the dispersion of experimental data, concentrating them on a mean reference curve which describes the relation to the study.

The \( z \) parameters identified using the above procedures often differ in each hydraulic property for which they were evaluated (Warrick et al., 1977b; Russo and Bresler, 1980; Ahuja et al., 1984b). Application of the similarity concept to the water budget of a small basin or irrigated area has recently produced encouraging results (Peck et al., 1977; Bresler et al., 1979; Sharma and Luxmoore, 1979; Warrick and Amoozegar-Fard, 1979). By means of a simulation model, the above authors examined the effects of spatial variability of soil hydraulic properties expressed in terms of the single stochastic variable \( z \), upon water budget components. The various components of the water budget, simulated by attributing log-normal frequency distributions to \( z \), agree closely with the values measured experimentally.

Furthermore, the relevant literature shows that applications of the similarity concept in the field are still too limited in number and restricted to soils of reasonable morphological similarity. Recently, the scaling theory of porous media was combined with simplified methodologies for hydraulic characterisation in structured soil based on the Kozeny–Carman equation, which relates hydraulic conductivity at saturation, \( K_s \), and effective soil porosity \( \phi \) (Ahuja et al., 1989, 1993; Franzmeier, 1991).
The aim of this study is to ascertain the validity of the above method for a clayey soil within an experimental area which is representative of hilly environments in southern Italy.

2. Materials and methods

Ninety tests were carried out on sloping plots subjected to different tillage systems and located in the experimental field of Guardia Perticara (Province of Potenza), whose pedological characteristics and location have been studied for about 20 years with regard to surface water erosion.

In the field, 16 rectangular plots (15 m × 40 m) were set along the slope lines. The average slope of each plot along the broader side was 14% while the transverse slope was virtually zero.

The plots underwent three tillage systems: ploughing at 40 cm (PL40); ploughing at 20 cm (PL20); non-tillage (NT). For many years the plots were under a continuous crop rotation of horse bean–wheat.

The soil examined is pedologically classifiable as vertic ustorthens, according to the USDA classification. It is therefore a vertic soil characterised by an A<sub>p</sub> horizon which, on average, extends to a depth of 30 cm, followed by a C<sub>c3</sub> horizon to a depth of about 100 cm.

At the three different depths (z=0–15, 20–40, and 40–60 cm) and at 10 sites in the three plots, undisturbed soil samples were collected by driving a steel cylinder 8 cm in diameter 12 cm high, perpendicularly into the soil while carefully excavating soil from around the samples. Then the core was removed. During sampling care was taken in order to reduce compaction of the soil and some inevitable disturbance. All cores were plugged at the top and bottom with rubber band and transported to the laboratory. There they were stored at 4°C constant temperature before making laboratory measurements.

The measurements carried out in the laboratory on ninety samples include: texture, bulk density ρ<sub>b</sub> and hydraulic conductivity K<sub>s</sub> at saturation, water content at saturation θ<sub>s</sub> and water content θ<sub>10</sub> at potential h = −10 kPa.

The percentages of sand, silt and clay (Table 1), according to the methods proposed by International Society of Soil Science (SISS), were calculated with the hydrometer method (Gee and Bauder, 1986). According to the SISS classification, the three soils have a clayey–sandy texture. Plot PL<sub>20</sub> has a slightly higher sand content than the other two, as well as the lowest clay content. The bulk density ρ<sub>b</sub> was obtained by oven-drying the soil samples at 105°C. Prior to the initiation of determining soil hydraulic parameters, the soil cores were gradually saturated from below, using de-aerated 0.01 M CaCl<sub>2</sub> solution, in the course of 60 h so as to guarantee the complete release of the air, and then brought to saturation. Saturated hydraulic conductivity, K<sub>s</sub>, was determined using a constant-head permeameter (Klute, 1986).

Only for simplified applications, bearing in mind that the soil in question behaves like semi-rigid soil and water stable due to the mineral composition of the clayey material, in this paper the definition of effective porosity of Brutsaert (1967) and Corey (1977) was used with field capacity assumed as soil water content at −10 kPa pressure head, being fully aware that field capacity is not a precisely defined soil parameter. Water content at saturation θ<sub>s</sub> and subsequently water content θ<sub>10</sub> were then measured, by means of kaolin–sand box apparatus consisting of two sets of ceramic tanks each of which could contain up to 12 soil cores. For the drainage soil cores to measure potential in the range from 0 to −10 kPa, use whose made of a reference Mariotte wessel to set values of suction head. The equilibrium water content corresponding to the monitored potential was measured gravimetrically.
cally. Gravimetric water contents were converted to volumetric water contents by multiplying with measured oven-dry bulk density values.

Having obtained the values of conductivity and water contents, we evaluated the possibility of linking conductivity to effective soil porosity, following the methodology proposed by Ahuja et al. (1984a). To estimate the distribution of hydraulic conductivity at saturation, Ahuja proposes using the spatial distribution of effective soil porosity \( f \) (i.e. the difference between the total porosity \( P \) and the water content \( y \)). He also proposes correlating \( K_s \) and \( f \) by means of the law of power proposed by Kozeny–Carman

\[
K_s = B\phi^n
\]  

in which \( B \) and \( n \) are constants evaluated by simple linear regression.

Moreover, Eq. (1) may be combined with scaling theory to deduce the frequency distribution of scale factors \( z_s \) starting from the distribution of scale factors \( z_i \).

As shown by the above authors, supposing the surface tension and the coefficient of kinematic water viscosity are constant, the following formula holds for two geometrically similar porous media: \( W_i = z_{W,i}W \) which links a generic hydraulic property \( W_i \) measured at site \( i \), to the value \( W \), at the reference site. The factor \( z_{W,i} \) is the ratio between the lengths characterising the internal geometry of the medium at site \( i \) and that of the reference medium, while the exponent \( p \) assumes a value of 1 when the hydraulic property considered is the water potential \( h \), and a value of two when reference is made to hydraulic conductivity \( K \) (Simmons et al., 1979).

In particular, with reference to hydraulic conductivity \( K_{S,i} \) we obtain

\[
K_{S,i} = \bar{K}_S z_i^2
\]  

where \( K_s \) may be obtained by the equation

\[
\bar{K}_S = \left( \frac{\sum_{i=1}^{N} \sqrt{K_{S,i}}}{N} \right)^2
\]  

and \( z_i \) may be calculated as follows:

\[
z_i = \frac{N \sqrt{K_{S,i}}}{\sum_{i=1}^{N} \sqrt{K_{S,i}}}
\]  

once the condition of normalisation has been assumed \( \sum_{i=1}^{N} z_i/N = 1 \). Finally, combining Eq. (1) with (4), we obtain

\[
z_i = \frac{N \sqrt{\phi_i^p}}{\sum_{i=1}^{N} \sqrt{\phi_i^p}}
\]  

where \( \phi_i = \phi \) at site \( i \).

Eq. (5) enables scale factors to be calculated for each site without knowing the constant \( B \). Thus a few \( K_s \) measurements, preferably taken at the level of modal soil profile, allow us to arrive at an estimate for average hydraulic conductivity at saturation \( K_s \).

### 3. Results and discussion

In order to characterise the spatial variability of the water content, the data were elaborated statistically, with the frequency distribution being reported in Table 2, where for each tillage system: mean, standard deviation and coefficient of variation of water contents \( \theta_s \) and \( \theta_{10} \) are presented. The data reported in the table show low standard deviations and hence low coefficients of variation, which is highest (10%) in the plot PL20, while lower values are recorded for the other plots.

Mean saturated hydraulic conductivity and effective soil porosity for the three plots are summarised in Table 2.

| Table 2 | Mean (\( \bar{\theta} \)) (cm\(^3\)/cm\(^3\)), standard deviation (S.D.) (cm\(^3\)/cm\(^3\)), coefficient of variation (CV) of water contents \( \theta_s \) and \( \theta_{10} \), relative to different tillage systems \( \theta_s \) and \( \theta_{10} \) are averaged over the profile |
|---------|----------|----------|----------|----------|----------|----------|----------|
| NT      | \( \theta_s \) | \( \theta_{10} \) | \( \theta_s \) | \( \theta_{10} \) | \( \theta_s \) | \( \theta_{10} \) | \( \theta_s \) | \( \theta_{10} \) |
| PL40    | 0.430    | 0.353    | 0.439    | 0.344    | 0.425    | 0.319    | 0.431    | 0.337    |
| PL20    | 0.027    | 0.020    | 0.035    | 0.032    | 0.043    | 0.025    | 0.037    | 0.030    |
| All data| 6        | 6        | 8        | 9        | 10       | 8        | 8        | 9        |
Table 3. The data were statistically elaborated taking account of the fact that parameters $K_s$ and $\phi$ have a distribution frequency which is well approximated by a log-normal law. The table supplies: the mean, variance and coefficient of variation, with $m$ and $s$ representing, respectively, the mean and standard deviation of the natural logarithm of $K_s$ and $\phi$. For the three plots, similar mean parameter values are recorded, unlike the coefficients of variation which, as expected, are rather high, in agreement also with the literature (Warrick and Nielsen, 1980).

<table>
<thead>
<tr>
<th></th>
<th>NT (19 tests)</th>
<th>PL40 (28 tests)</th>
<th>PL20 (28 tests)</th>
<th>All data (75 tests)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_s$</td>
<td>0.361</td>
<td>0.269</td>
<td>0.419</td>
<td>0.335</td>
</tr>
<tr>
<td>$\phi$</td>
<td>0.104</td>
<td>0.132</td>
<td>0.148</td>
<td>0.131</td>
</tr>
<tr>
<td>Variance</td>
<td>1.822</td>
<td>0.274</td>
<td>1.569</td>
<td>0.795</td>
</tr>
<tr>
<td>CV%</td>
<td>374</td>
<td>194</td>
<td>299</td>
<td>266</td>
</tr>
</tbody>
</table>

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Table 4. The data were statistically elaborated taking account of the fact that parameters $K_s$ and $\theta$ have a distribution frequency which is well approximated by a log-normal law. The table supplies: the mean, variance and coefficient of variation, with $m$ and $\sigma$ representing, respectively, the mean and standard deviation of the natural logarithm of $K_s$ and $\theta$. For the three plots, similar mean parameter values are recorded, unlike the coefficients of variation which, as expected, are rather high, in agreement also with the literature (Warrick and Nielsen, 1980).

<table>
<thead>
<tr>
<th></th>
<th>NT</th>
<th>PL40</th>
<th>PL20</th>
<th>All data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z_K$</td>
<td>1.094</td>
<td>1.033</td>
<td>1.093</td>
<td>1.049</td>
</tr>
<tr>
<td>$z_\phi$</td>
<td>1.035</td>
<td>1.011</td>
<td>1.036</td>
<td>1.017</td>
</tr>
<tr>
<td>Variance</td>
<td>1.158</td>
<td>0.511</td>
<td>0.926</td>
<td>0.754</td>
</tr>
<tr>
<td>CV%</td>
<td>98</td>
<td>69</td>
<td>88</td>
<td>83</td>
</tr>
</tbody>
</table>

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best approximates the frequency distribution both of $x_k$ and $x_{af}$.

Table 4 reports estimates of the mean, variance and coefficients of variation of factors $x$ based on the log-normal distribution. Examination of the table shows that the estimates of parameter means are substantially similar whether individual plots or all data are considered. Moreover, on elaborating the data of hydraulic conductivity at saturation the coefficients of variation obtained are higher than those from elaborations of effective soil porosity. Such behaviour is probably due to both the fact that hydraulic conductivity is much more sensitive to variations in soil saturation and because the methods used for measuring conductivity are not yet very reliable with regard to structured soils.

The $x_k-x_{af}$ distributions for all the data, reported in the fractile diagram of Fig. 2, show good agreement except for the extremes of the distribution where, for the reasons given above, larger systematic errors are expected in test observations relative to $K_s$ and $\phi$.

Finally, the investigation was extended to a comparison by layer of all the parameters considered. The data reported in Table 5 show a moderate variability in water contents $\theta_s$ and $\theta_{10}$. By contrast, in Table 6 greater spatial variability in the conductivity $K_s$ and effective porosity $\phi$ is observed, which may be well represented by log-normal distributions.

Analysis of Table 7 shows that the estimates of the main statistical moments of scale factors $x_k$ and $x_{af}$ are quite similar. Moreover, Fig. 3 which reports in a log-
Table 5
Mean ($\bar{x}$) (cm$^3$/cm$^3$), standard deviation (S.D.) (cm$^3$/cm$^3$), coefficient of variation (CV) of water contents $\theta_s$ and $\theta_{10}$, relative to different layers. $\theta_s$ and $\theta_{10}$ are averaged over the profile

<table>
<thead>
<tr>
<th></th>
<th>$z$=0–15 cm</th>
<th>$z$=20–40 cm</th>
<th>$z$=40–60 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{x}$</td>
<td>0.443</td>
<td>0.456</td>
<td>0.403</td>
</tr>
<tr>
<td>S.D.</td>
<td>0.031</td>
<td>0.019</td>
<td>0.033</td>
</tr>
<tr>
<td>CV%</td>
<td>7</td>
<td>4</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 6
Mean, variance and coefficient of variation (CV) (for representing log-normally distributed data) of hydraulic conductivity at saturation $K_s$ (cm/min) and actual porosity $\phi$ relative to the different layers, $K_s$ and $\phi$ are averaged over the profile

<table>
<thead>
<tr>
<th></th>
<th>$z$=0–15 cm</th>
<th>$z$=20–40 cm</th>
<th>$z$=40–60 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_s$</td>
<td>0.368</td>
<td>0.389</td>
<td>0.241</td>
</tr>
<tr>
<td>$\phi$</td>
<td>0.129</td>
<td>0.179</td>
<td>0.103</td>
</tr>
<tr>
<td>Mean*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variance*</td>
<td>1.232</td>
<td>0.286</td>
<td>0.457</td>
</tr>
<tr>
<td>CV%**</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ a \exp(m + \sigma^2/2). \]
\[ b \exp(2m + \sigma^2)[\exp(\sigma^2) - 1]. \]
\[ c \sqrt{\exp(\sigma^2) - 1}. \]
normal probabilistic diagram the factors $\alpha_{K}$ relative to the different layers, shows that the log-normal law best approximates $\alpha_{\phi}$ distributions.

Finally, Fig. 4 evidences that the theory of similar media is validated in that the parameters $\alpha_{K}$, relative to the layers $z=0-15$ and $z=40-60$ cm, are arranged around a 45° sloping curve and going through the origin and are well correlated, with a correlation coefficient equal to 0.97.

### 4. Conclusions

In the light of the above results, we may conclude that, once an analytical expression has been assigned to the relation which links conductivity $K_s$ to effective soil porosity $\phi$, the use of the similar media theory allows the variability in the hydraulic parameters of the soil in question to be linked to the variability in parameter $\alpha$.

Long-term tillage effects on hydraulic properties of soil considered here appear to be related more to the particle-size distribution than to the specific treatments. Even though the pore geometry and soil structure at surface undergo important modifications due to the various tillage methods employed, these changes are nonetheless unstable with time due to alterations resulting from meteorologic and environmental factors, including wetting and drying cycles in the soil profile. Therefore as a general rule, a progressive annulment of tillage effects on soil structure and hydraulic properties can be observed and this behaviour is far more evident in the case of vertisols that significantly shows a tendency to regenerate their structure as time elapses.

With a view to supplementing the present research with field tests, infiltration tests will be carried out on the same plots by means of more appropriate equipment, such as tension infiltrometers which allow better assessment of the effects of the porous system on soil hydraulic properties in a field of water content values close to saturation (Perroux and White, 1988; Shouse and Mohanty, 1998).

### References


Ahuja, L.R., Naney, J.W., Green, R.E., Nielsen, D.R., 1984a.


