

**Estimating Relative Hydraulic Conductivity from the Water Release
Characteristic of a Shrinking Clay Soil**

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ABSTRACT

To understand the hydraulic properties of soils, accurate prediction of unsaturated hydraulic conductivity is needed which is commonly derived from the soil water release characteristic. In fine-textured soils the modified Mualem-van Genuchten (MMVG) function has been used extensively to predict the change in relative conductivity with changes in matric potential, but this assumes that the soil is rigid with a constant porosity (CP) which is unrealistic for shrinking soils. We used a triaxial cell apparatus to accurately monitor soil volume changes during water release in a clay soil. From this we derived relative hydraulic conductivity functions based on either MMVG (CP), or based on geometrically-similar shrinkage (GSS) of all pore sizes by a constant factor as calculated from measured shrinking porosity (SP). The MMVG (CP) function predicted a decline in relative conductivity of up to three orders of magnitude from 0 to -400 kPa matric potential. This was similar to published data on the response of conductivity in the same soil to consolidation of larger pores. However, based on SP, the soil remained effectively tension-saturated (>0.97) down to a matric potential of -85 kPa due to normal shrinkage. The corresponding GSS (SP) function predicted only a modest decrease in relative conductivity from 1 to 0.85 over this range. In this case the larger pores, although reduced in size, are assumed to be still water-filled and conducting. The GSS function was probably the most realistic portrayal of hydraulic functioning in a tension-saturated shrinking clay soil.

Abbreviations: CP, constant porosity; GSS, geometrically-similar shrinkage function; MMVG, modified Mualem-van Genuchten function; MSE, mean square error; R^2_{adj} , proportion of the variance accounted for; SP, shrinking porosity.

The Mualem-van Genuchten approach (Mualem, 1976; van Genuchten, 1980) has been widely used to predict the change in relative hydraulic conductivity with matric potential, based on the soil water release characteristic (e.g. George et al., 2009; Gribb et al., 2009; Touma, 2009). The central assumption of this approach is that soil is a rigid material and porosity remains constant over the range of matric potentials. This is not realistic for many soils as there is often a loss of porosity upon drying due to shrinkage (Simms & Yanful, 2001; Garnier et al., 1997; Garnier et al., 1998; Ringrose-Voase et al., 2000; Kirby and Ringrose-Voase, 2000; Boivin et al., 2004; Gregory et al., 2010). In the extreme case, clay soils may exhibit normal shrinkage over a range of matric potentials where the loss of water upon drying is matched by the loss of pore volume by shrinkage such that the soil may remain tension-saturated (Haines, 1923; Bronswijk, 1991; Gregory et al., 2010). Over this range of matric potentials, the hydraulic conductivity of the soil may decline due to the reduction in porosity through shrinkage and not due to air entry as is implicit in the theoretical framework of the Mualem-van Genuchten function. However, Childs (1969) commented that the effects of shrinkage on hydraulic conductivity would be small compared to the effect of air-entry. Recent work has monitored changes in soil water content, evaporation and matric potential in soil profiles and combined this with measured changes in volume to predict or measure hydraulic fluxes and hence unsaturated hydraulic conductivity in a material coordinate approach (Hillel, 1980; Garnier et al., 1997; Ringrose-Voase et al., 2000; Kirby and Ringrose-Voase, 2000; Tang et al., 2009). Garnier et al. (1998) used a dual-energy synchrotron X-ray technique to simultaneously capture water content and bulk density changes in soil to predict hydraulic properties.

In this paper we wished to explore the effect of volume change on the prediction of relative hydraulic conductivity in an agricultural clay soil using a simple approach. We used a triaxial cell apparatus which accurately monitored changes in soil volume to measure the soil water release characteristic. From this we estimated the relative hydraulic conductivity in two different ways. One assumed unsaturated conductivity through a rigid constant pore volume (based on Mualem-van Genuchten) and the other assumed tension-saturated conductivity through a non-rigid shrinking pore volume (based on Childs, 1969).

MATERIALS AND METHODS

Soil Sampling and Preparation

The clay soil was collected from the upper 30 cm of an undrained, unfertilized grassland plot at North Wyke Research's Rowden Experiment in Devon, UK. Soil properties are given in Table 1. The soil was crumbled through a 4 mm aperture sieve and allowed to air-dry at room temperature. Immediately prior to the measurements, the soil was wetted to a gravimetric water content of 0.58 g g^{-1} , previously found to be suitable for preparing samples (Gregory et al., 2010), and stored in an air-tight container at $4 \text{ }^\circ\text{C}$ for 48 hours.

Soil Water Release Characteristic

A cylindrical soil sample (i.d: 50 mm, h: 25 mm) was made by compressing moist soil inside a brass mould by uniaxial compression to 200 kPa. The soil core was removed from the corer and placed inside a rubber membrane in a GDS STDTAS triaxial cell

(GDS Instruments Ltd, Hook, Hants, UK) fitted with an inner water-filled cell system (Fig. 1). The apparatus enabled the independent control of three pressures: radial (consolidation), pore air and pore water. Pore water pressure was delivered to the soil from a pressure-volume controller through a high air-entry porous disk pedestal on which the sample was seated. Both pore air and radial pressures were controlled by pressurised air, with the former delivered to the soil through a cap fitted to the upper surface of the sample. Soil volume changes to a precision of 1 mm³ were monitored by a differential pressure transducer connected to both the water surrounding the soil and the water in a reference cell (Ng et al., 2002).

The soil was saturated by increasing the radial, pore water and pore air pressures in tandem to about 300 kPa over 48 hours. The radial pressure was set to be 5 kPa greater than the pore pressures to ensure saturation under a small effective stress and to maintain the integrity of the sample. A series of matric potentials were then set by increasing the radial and pore air pressures above the pore water pressure over a period of one hour and then maintaining these pressures over a period during which total volume and pore water volume were allowed to equilibrate, which typically took up to five days. A small 5 kPa net confining pressure (the difference between the radial and pore air pressures) was maintained. A series of matric potentials between -5 and -400 kPa were set in this manner before the sample was oven-dried at 105 °C for 48 hours at the end.

We fitted the van Genuchten (1980) function to our soil water release characteristic data firstly where we assumed that the initial soil volume did not change with matric potential (constant porosity, CP), and secondly where we did account for the actual measured changes in volume (shrinking porosity, SP):

$$\theta_h = \theta_r + \frac{\theta_s - \theta_r}{(1 + (\alpha h)^n)^{1-1/n}} \quad [1]$$

where θ_s , θ_r and θ_h are the saturated, residual and h matric potential volumetric water contents (cm³ cm⁻³) respectively, h is the matric potential (kPa), i.e. the absolute value) and α and n are fitted parameters. Note that in Eq. [1] we restricted θ_r to be non-negative and we applied the Mualem constraint ($m = 1 - 1/n$), which were both required to get the closed-form function for our subsequent hydraulic conductivity prediction (van Genuchten, 1980).

Relative Hydraulic Conductivity Assuming Constant Porosity

We followed the Mualem-van Genuchten approach to predict the relative hydraulic conductivity in a rigid (non-shrinking) soil, based on the fit of Eq. [1] to the soil water release characteristic data (Mualem, 1976; van Genuchten, 1980). Note that although we fitted Eq. [1] to the SP soil water release characteristic data (as well as CP), this merely acts as the input data and the subsequent hydraulic conductivity calculations thereafter are based on the assumption of rigidity of porosity implicit in this method. This is similar to the approach of Kirby and Ringrose-Voase (2000) where they fitted the Mualem-van Genuchten function to moisture ratio data (water volume as a fraction of the fixed volume of just the solid particles). As the n parameter was close to its lower limit of 1 (Table 2), as is common for fine-textured soils, predictions of relative hydraulic conductivity can become extremely sensitive to small changes in matric potentials close to saturation (Vogel et al., 2000). Hence we used the modified

Mualem-van Genuchten function (MMVG) of Vogel et al. (2000) for relative hydraulic conductivity:

$$\text{MMVG} = S_e^{\frac{1}{2}} \left[\frac{1-F(S_e)}{1-F(1)} \right]^2 \quad [2]$$

based on the following:

$$F(S_e) = \left(1 - S_e^* \left(1 - \frac{1}{n} \right)^{-1} \right)^{1 - \frac{1}{n}} \quad [3]$$

$$S_e^* = \frac{\theta_s - \theta_r}{\theta_m - \theta_r} S_e \quad [4]$$

$$S_e = \frac{\theta_h - \theta_r}{\theta_s - \theta_r} \quad [5]$$

$$\theta_m = \theta_r + (\theta_s - \theta_r) (1 + (\alpha h_s)^n)^{1-1/n} \quad [6]$$

where S_e and S_e^* are the effective and modified effective saturations respectively, θ_m is a fictitious extrapolated water content ($> \theta_s$, $\text{cm}^3 \text{cm}^{-3}$), and h_s is some near-saturation matric potential (kPa) with the same water retention function as that at saturation (Vogel et al., 2000). We chose h_s to be our first imposed matric potential (-5 kPa) based on our observation that this had a very similar water content to that at saturation.

Relative Hydraulic Conductivity Assuming Shrinking Porosity

As an alternative we considered the situation with our measured changes in soil porosity with matric potential (SP). Childs (1969, p194) demonstrated that if the pore sizes of one soil differ from those in a geometrically-similar soil by a factor of N , then the saturated hydraulic conductivities will differ by N^2 . We therefore expressed our total soil volume at each matric potential as a proportion of that at the initial saturation to derive the factor N and assumed that the pores express a geometrically-similar shrinkage (GSS) relative hydraulic conductivity function:

$$\text{GSS} = \left(\frac{V_h}{V_s} \right)^2 \quad [7]$$

where V_s is the total soil volume (cm^3) at saturation, and V_h is the total soil volume (cm^3) at h matric potential. As this is only strictly valid for saturated conditions, we applied this estimate to just those data that corresponded with a degree of saturation greater than 0.97 where the soil was essentially tension-saturated.

Statistical Analysis

All the statistical and model fitting analysis was performed with GenStat[®] 12th Edition (VSN International Ltd, Hemel Hempstead, UK). We used the FITNONLINEAR directive to derive the van Genuchten function for the soil water release characteristic, with matric potential expressed as the modulus. The key indices of goodness-of-fit

were the mean square error (MSE), and the proportion of the variance accounted for by the fit (R^2_{adj}), which is the difference between 1 and the ratio of the MSE and the mean of the total sum-of-squares (total variance). The R^2_{adj} value has the advantage over the conventional squared coefficient of correlation (R^2) in that it takes the number of parameters in the model into account.

RESULTS

Soil Water Release Characteristic

The soil water release characteristic of the clay soil with either an assumed CP (the initial porosity) or SP based on volume change measurements is shown in Fig. 2. The van Genuchten (1980) fits to the soil water release characteristic data (Table 2) are also shown. The SP water contents were greater at each matric potential as the denominator of the calculation (total soil volume) is lower.

In Fig. 3 the soil water release characteristic is expressed as degree of saturation. The degree of saturation at each matric potential was greater with SP rather than assuming CP and the difference increased as matric potential decreased. Saturation was greater than 0.97 for SP down to a matric potential of -85 kPa.

Relative Hydraulic Conductivity

The relative hydraulic conductivity functions are shown in Fig. 4. With the conventional MMVG function based on CP and SP, conductivity decreased by three and over two orders of magnitude respectively between saturation and -400 kPa. The alternative GSS estimate based on SP for just those potentials from saturation to -85 kPa, where the soil remained essentially tension-saturated (>0.97), predicted only a modest decrease from 1 to 0.85 over the same range.

DISCUSSION

The triaxial cell apparatus continuously monitored changes in soil volume and hence was very useful for measuring the soil water release characteristic accurately in a shrinking soil. If volume changes are not taken into account incorrect characterisations of such soils may be made (Fig. 2 and 3).

The assumption of the MMVG hydraulic conductivity function is that when matric potential decreases, water is released from progressively smaller pores which become air-filled. Hydraulic conductivity is therefore dependent on the cumulative volume of the smaller pores (Mualem, 1976; van Genuchten, 1980) and hence declines sharply with decreasing matric potential regardless of whether this is based on constant- or shrinking-porosity soil water release characteristic data (Fig. 4). However, the clay soil shrank upon drying and remained effectively tension-saturated down to a matric potential of -85 kPa, commonly associated with unsaturated conditions. The alternative GSS function, which simply assumed that all pores shrank by the same factor, predicted very little decrease with decreasing matric potential where the soil remained tension-saturated (Fig. 4). This is because the larger pores, although reduced in size, are assumed to be still present, water-filled and conducting. Indeed it is possible that smaller pores were affected by shrinkage more than larger pores (Bronswijk 1991; Cabidoche & Ozier-Lafontaine 1995; Boivin et al., 2004; Braudeau et al., 2005). As conductivity is dominated by the larger pores, this would further

support the view that conductivity in the tension-saturated phase was little-affected by shrinkage, as noted by Childs (1969). The GSS estimate is therefore likely to be a more realistic estimate of the relative hydraulic conductivity in a tension-saturated shrinking soil than the MMVG estimate.

Touma (2009) found that the MMVG approach underestimated measured unsaturated conductivity in a clay soil by up to two orders of magnitude. The field measurements in clay soils made by Ringrose-Voase et al. (2000) revealed a similar initial phase with little change in hydraulic conductivity as matric potential decreased to a threshold, followed by a rapid decrease with further drying. However, the threshold matric potential in their study was approximately -10 kPa, which was considerably greater than the -85 kPa potential that we found in our study. Garnier et al. (1997) found a decrease in conductivity of up to three orders of magnitude in a shrinking soil over a similar range of matric potentials as that reported here.

The differences between these studies and our study may be related to the different methodologies adopted. We recognise that our experiments were performed on repacked soil where the inherent field structure has been disturbed. Thus the nature of the inter-aggregate structure may not accurately reflect the nature of the structure in the field. It would be the larger inter-aggregate pores that most-likely would be the first to permit air entry to drive the characteristic decrease in hydraulic conductivity in the field studies of Ringrose-Voase et al. (2000). In addition, our focus remained on the hydraulic properties within our defined soil sample and any effects beyond this arbitrary boundary, such as lateral shrinkage between adjacent masses of soil and location within the profile, could not be captured. These contributing factors would all have been accounted for in the field measurements of Ringrose-Voase et al. (2000) and indeed shrinkage cracks would certainly have contributed to decreased hydraulic conductivities. We also carried out our experiment on the drying limb of the soil water release characteristic. Different behavior might have been observed during wetting due to hysteresis. Garnier et al. (1997) used an evaporation method to drive the release of water whereas we were able to directly impose a matric potential through subjecting the soil to differential pore air and pore water pressures.

Matthews et al. (2010) measured the saturated hydraulic conductivity of the same clay soil at different porosities created by isotropic consolidation using triaxial apparatus. They derived a linear relationship ($R^2_{\text{adj}}=0.97$) between porosity and the logarithm of saturated hydraulic conductivity (Matthews et al., 2010). As the range of porosities in that and the present study was similar, despite the different mechanisms controlling porosity change, we can further assess our alternative hydraulic conductivity functions. The measured saturated porosity of our soil (0.597) corresponded to an estimated saturated hydraulic conductivity of $2.29 \times 10^{-5} \text{ cm s}^{-1}$ by the fit of Matthews et al. (2010). This standard initial estimate can be used to convert the relative MMVG and GSS functions to absolute hydraulic conductivities. We just chose the MMVG relative hydraulic conductivity function based on the conventional CP soil water release characteristic data for the purposes of this exercise. The estimated absolute hydraulic conductivities corresponding to the 0 to -85 kPa matric potential range are plotted against either CP (MMVG) or SP (GSS) in Fig. 5, together with the fit to the Matthews et al. (2010) data.

The observed similarity in the magnitude of the decrease in hydraulic conductivity between the MMVG (path AB) and the Matthews et al. (2010) data for consolidated soil (path AD) is interesting. The MMVG estimate assumes that as the soil dries, larger pores become air-filled and no longer contribute to the flow of water, which continues in the smaller pores. Consolidation as a process primarily affects larger

pores (Richard et al., 2001; Dexter et al., 2008; Li & Zhang, 2009; Gregory et al., 2010) and thus the reduction of larger pores means that water flow is restricted to the smaller pores which are affected less by consolidation. In short, consolidation and air-entry are similar in their effect on hydraulic conductivity as they both preferentially reduce the contribution of the larger pores. Incidentally, when the MMVG estimates of absolute hydraulic conductivity were plotted not against CP but against the corresponding SP, we found that this was described very well by the Matthews et al. (2010) fitted line ($R^2_{\text{adj}}=0.930$; $\text{MSE}=0.016$), although it is important to note that the fitted line was specific to this particular soil. In contrast, the GSS estimate predicted only a modest decrease in conductivity (path AC in Fig. 5) in a tension-saturated shrinking soil and this is likely to be the most realistic estimate.

In summary, shrinking soils remain tension-saturated at matric potentials typically associated with unsaturated conditions (Fig. 3) and this probably had only a minor impact on hydraulic conductivity (Fig. 4). Air only entered the soil at matric potentials lower than -85 kPa in the present study and only at potentials lower than this would a considerable decrease in conductivity be predicted.

CONCLUSIONS

The modified Mualem-van Genuchten function, which assumed a rigid porosity and air entry into progressively smaller pores as soil dried, predicted a considerable decrease in unsaturated hydraulic conductivity in a clay soil from 0 to -85 kPa. This approach may be similar to the effect of consolidation on conductivity where the larger pores are preferentially affected. However, the clay soil shrank and remained tension-saturated at matric potentials as low as -85 kPa with little air entry. A more-realistic estimate based on geometrically-similar shrinkage of all pores by a common shrinkage factor predicted that conductivity was little-affected by shrinkage in the tension-saturated range as the pores, though reduced in size, are assumed to be still present, water-filled and conducting.

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Table 1. Selected properties of the clay soil.

Property	Units	Clay soil
Location		North Wyke Research, Devon, UK
Field		Rowden
Grid reference	GB National Grid	SX652994
	Latitude	50°46'42" N
	Longitude	03°54'54" W
Soil classification	Soil Survey of England & Wales group†	Stagnogley soil
	Soil Survey of England & Wales series‡	Hallsworth
	UN FAO World Reference Base†	Gleyic Luvisol
	USDA Soil Taxonomy†	Typic Haplaquept
Landuse		Grass, unfertilised, grazed
Sand (2000-63 µm)	g g ⁻¹ dry soil	0.147
Silt (63-2 µm)	g g ⁻¹ dry soil	0.396
Clay (<2 µm)	g g ⁻¹ dry soil	0.457
Texture	Soil Survey of England & Wales class†	Clay
Particle density	g cm ⁻³	2.439
Organic matter	g g ⁻¹ dry soil	0.138

† Avery (1980)

‡ Clayden and Hollis (1984)

Table 2. The van Genuchten (1980) function parameters (with $m = 1 - 1/n$ and $h = |\text{kPa}|$, Eq. [1]) of the soil water release characteristic of the clay soil based on either an assumed constant porosity (CP) or a measured shrinking porosity (SP) (Fig. 2). Parameters θ_s and θ_r are the saturated and residual volumetric water contents ($\text{cm}^3 \text{cm}^{-3}$) respectively, and α and n are fitted parameters. The MSE value gives the mean square error and the R^2_{adj} value gives the proportion of the variance accounted for by the fit.

Porosity	van Genuchten (1980) parameters:				Indicators of goodness-of-fit	
	θ_s	θ_r	α	n	MSE	R^2_{adj}
CP	0.598	0	0.015	1.246	1.64×10^{-5}	0.997
SP	0.596	0	0.008	1.240	1.67×10^{-5}	0.993

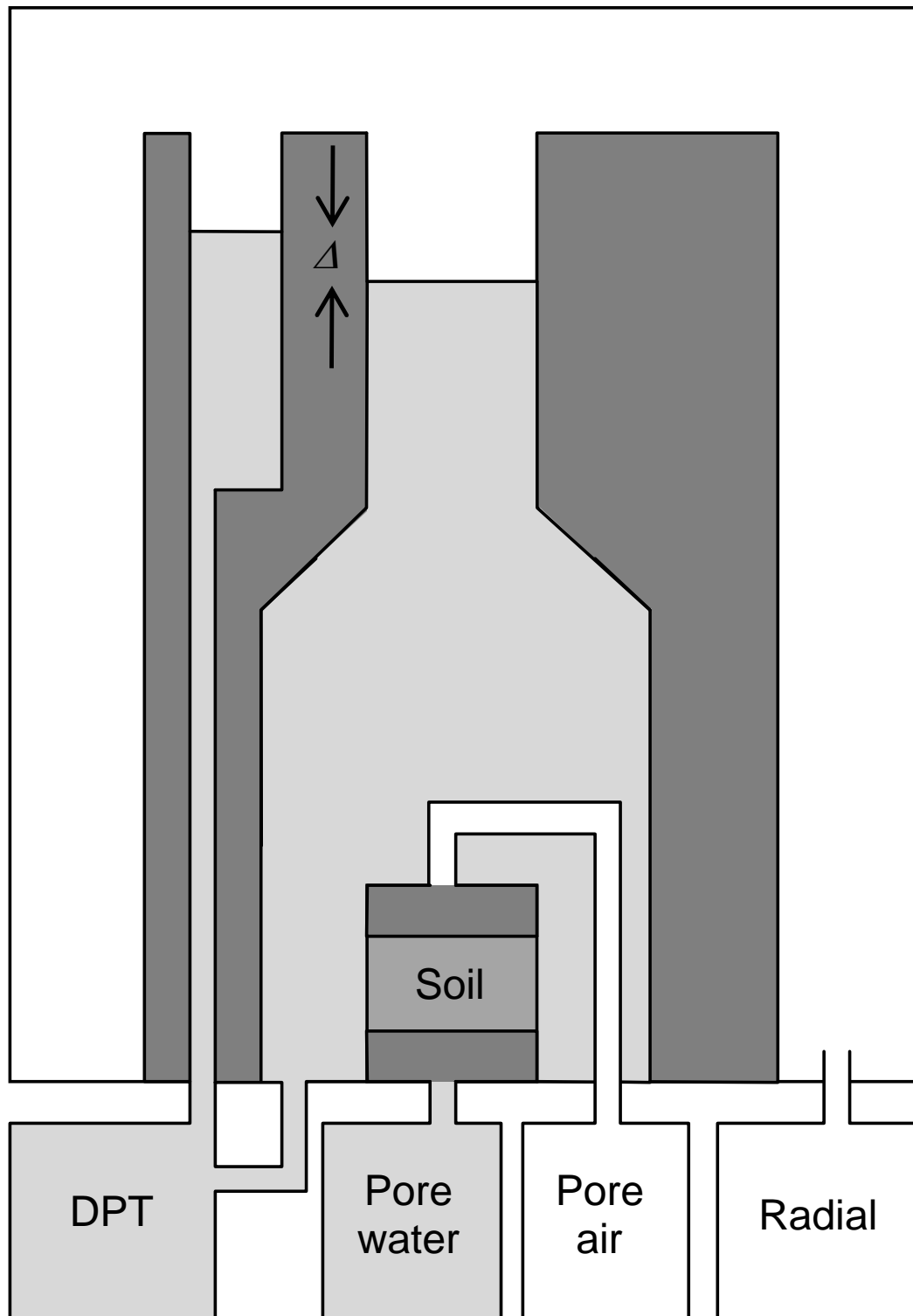


Fig. 1. Schematic of the triaxial cell apparatus used in the experimentation (Ng et al., 2002). The soil is subjected to a matric potential controlled by the difference between pore air and pore water pressure, delivered to the upper and lower surfaces respectively, whilst under a confining radial (consolidation) pressure. Volume change is accurately calculated by a calibrated differential pressure transducer (DPT) which monitors the difference between the water level surrounding the soil in an inner cell assembly and that in an isolated reference cell (Δ).

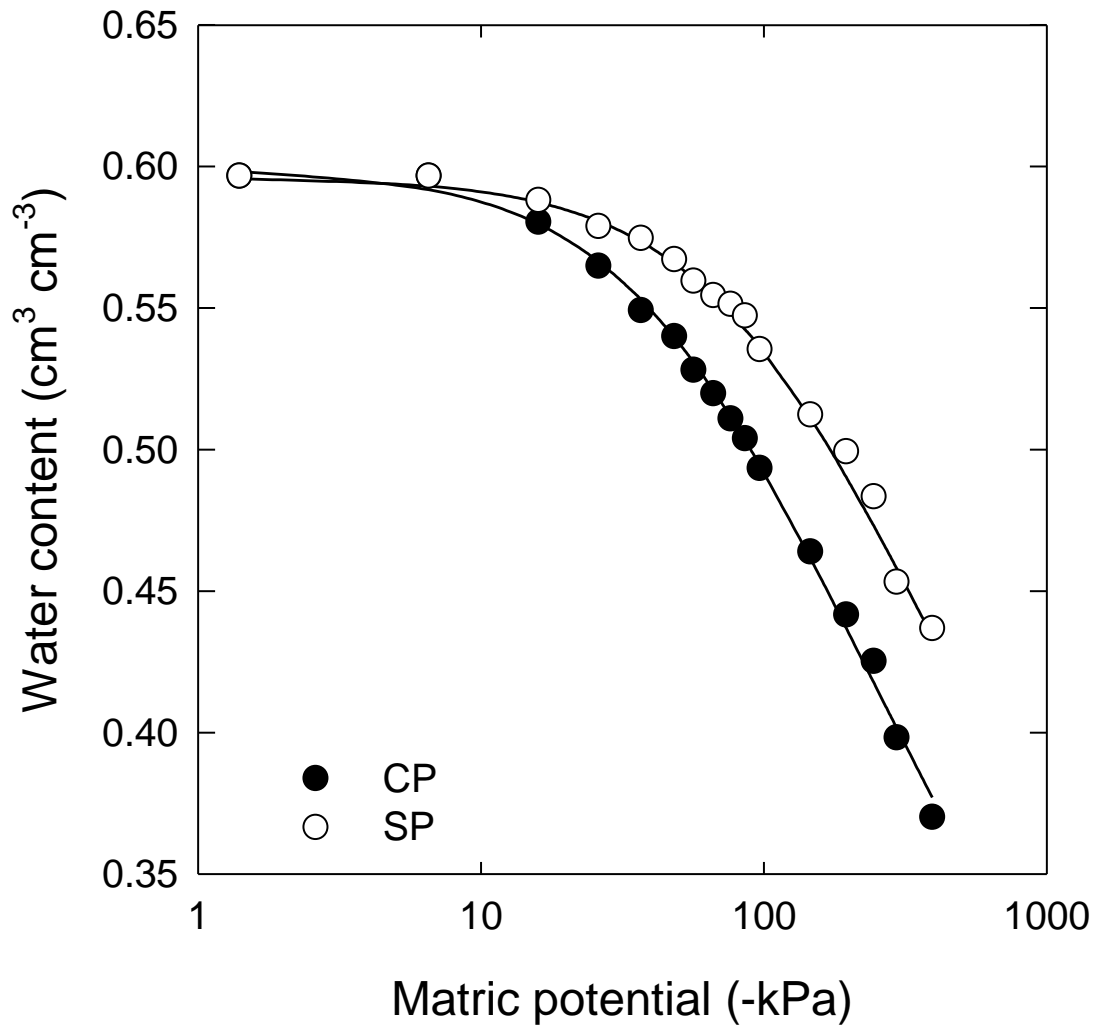


Fig. 2. The soil water release characteristic of the clay soil with either an assumed constant porosity (CP, black circles) or a measured shrinking porosity (SP, white circles). The van Genuchten (1980) fits (Table 2, Eq. [1]) are also shown (lines).

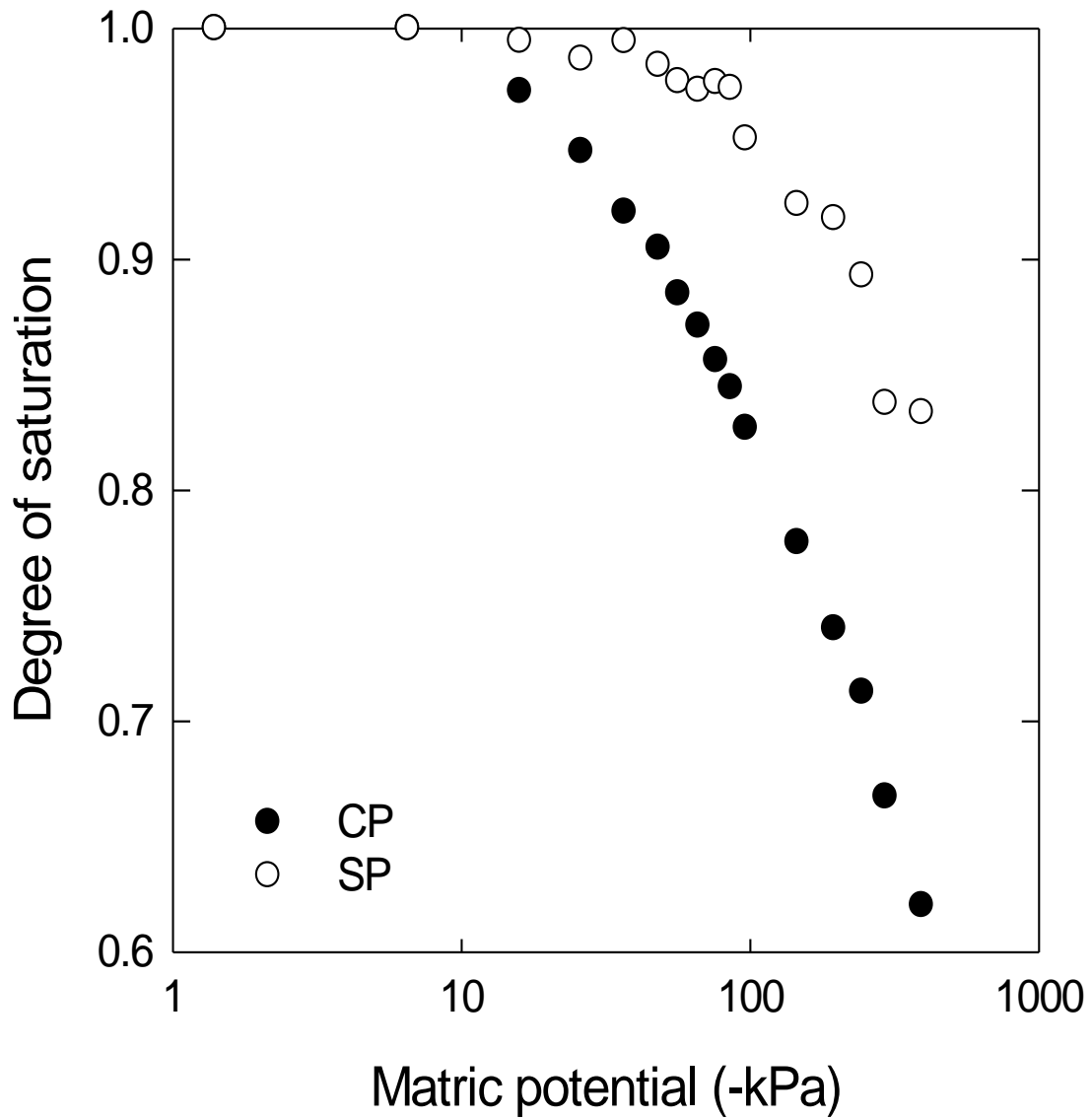


Fig. 3. The soil water release characteristic of the clay soil, expressed as degree of saturation, with either an assumed constant porosity (CP, black circles) or a measured shrinking porosity (SP, white circles).

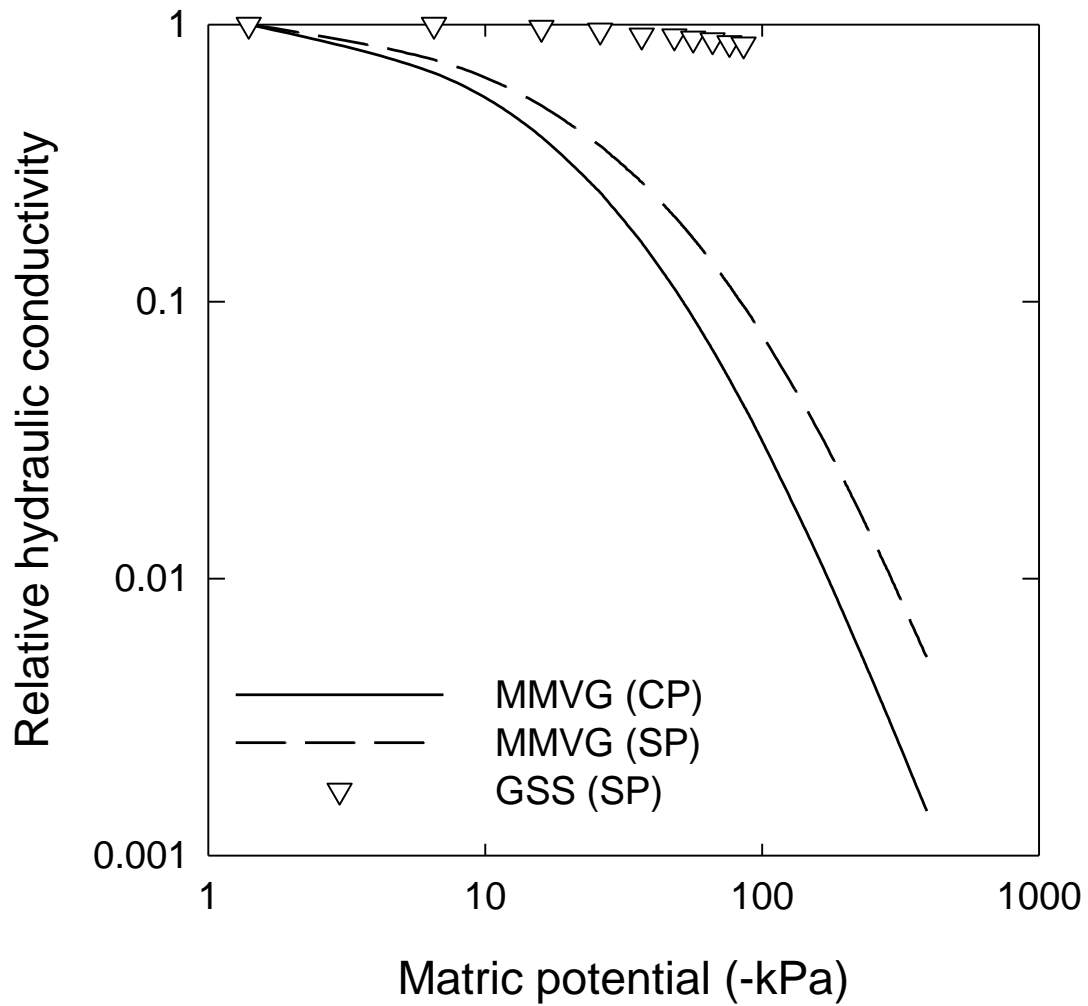


Fig. 4. Estimates of the relative hydraulic conductivity of the clay soil by the modified Mualem-van Genuchten function (MMVG, Eq. [2]) based on an assumed constant porosity (CP, solid line), or a measured shrinking porosity (SP, broken line), and the geometrically-similar shrinkage function (GSS, white triangles, Eq. [7]) based on SP. For the GSS estimate, only those data where the soil remained essentially tension-saturated (>0.97) are plotted.

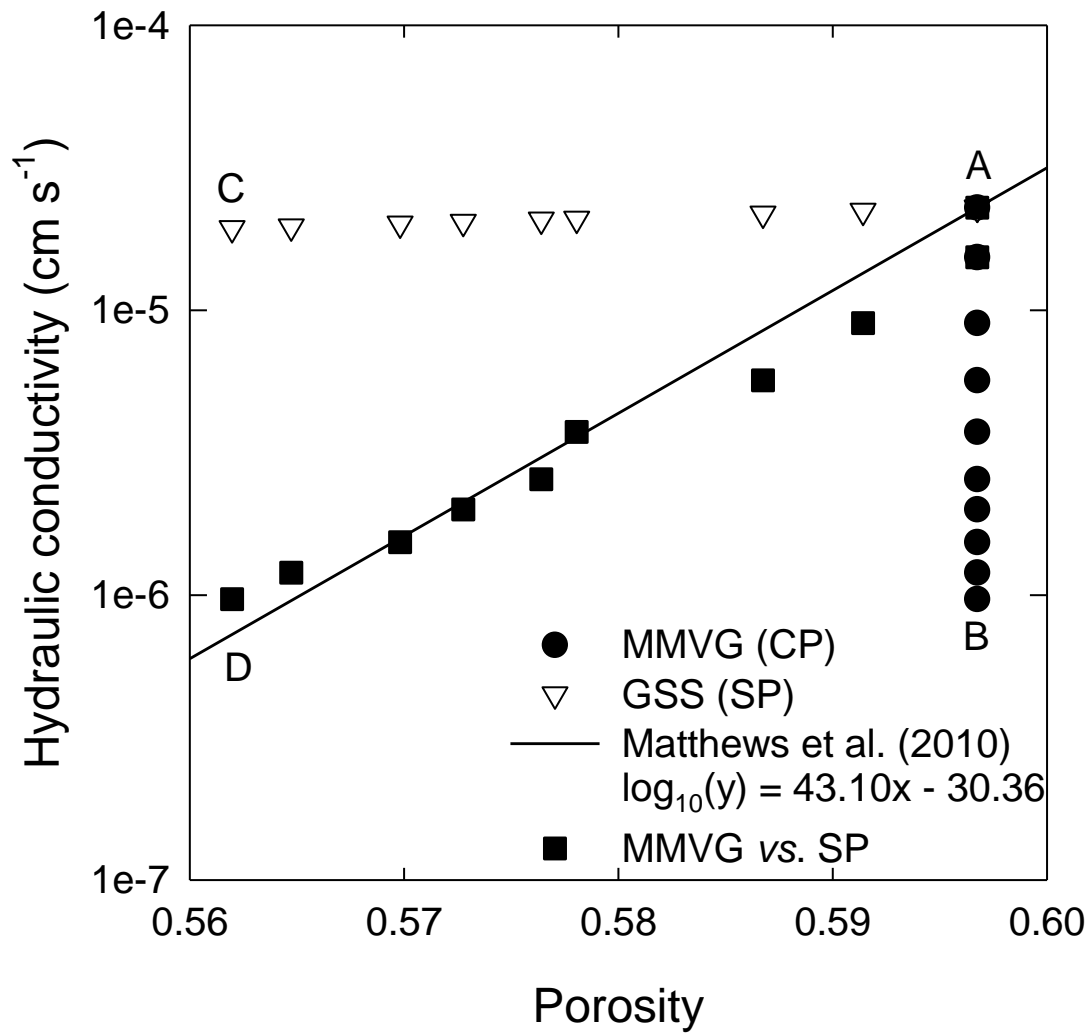


Fig. 5. Estimates of the absolute hydraulic conductivity of the clay soil by the modified Mualem-van Genuchten function (MMVG, black circles, path AB, Eq. [2]) based on an assumed constant porosity (CP), or the geometrically-similar shrinkage function (GSS, white triangles, path AC, Eq. [7]) based on measured shrinking porosity (SP), for matric potentials from 0 to -85 kPa. The fit reported by Matthews et al. (2010) in the same clay soil where the porosity was reduced by isotropic consolidation is plotted (line, path AD) and this was used to predict the saturated hydraulic conductivity at the initial porosity (0.597) as $2.29 \times 10^{-5} \text{ cm s}^{-1}$. The MMVG estimates are also plotted against the corresponding measured SP (black squares, path AD).