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Hydraulic Functions of Soils Based Upon Characteristics of Porous System

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HYDRAULIC FUNCTIONS OF SOILS BASED UPON CHARACTERISTICS OF POROUS SYSTEM

LECTURE NOTES

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INTRODUCTION

The term soil hydraulic function contains soil water retention curve together with saturated and unsaturated hydraulic conductivity. Their knowledge is required for modeling of transport processes in soils. Pore size distribution and the configuration of the soil porous system are basic factors influencing soil hydraulic functions. E.g. the recently used model of unsaturated hydraulic conductivity $K(h)$

$$K(h) = K_S \frac{\text{(Portion of the porous system saturated by water as function of } h)}{\text{(The whole porous system saturated by water, } h = 0)}$$

K_S is saturated hydraulic conductivity and h is the pressure head (potential). The degree of saturation of the soil porous system by water is formulated as the soil water retention curve $h(\theta)$, where θ is the volumetric soil water content. The above described relationship is completed by the introduction of parameters related to tortuosity and to pores connection. Soil water retention curve has been described by the empirical equations, the most frequent ones are that of Brooks and Corey (1964) and equation of van Genuchten (1980). They have been broadly applied in numerous simulation models. The evidence on the unbalance of approaches is clear, since empirical equation enters into a physically based relationship. The lack of correspondence between the measured and modeled data is frequently defined and it is balanced by introduction of various attempts, as e.g. the concept of mobile and immobile water or by various types of fitting parameters. We expect the elimination of this imbalance by introduction of results of a detailed research on soil porous system resulting in a physical description of the soil water retention curve. We expect then a more exact description of transport processes in soils, especially of the preferential flow. The first step in the research is the introduction of the appropriate description of the pore size distribution.

Brutsaert (1966) studied four models of pore size distribution, among them the lognormal distribution in relation to soil water retention curve. We can conclude from his research that the lognormal distribution looks at least as an acceptable approximation. This assumption is supported by Walczak et al. (1982). A more detailed analysis was presented by Pachepsky et al. (1992) and Kosugi (1994), who formulated the lognormal pore size distribution function $g(r) = \mathrm{d}\theta/\mathrm{d}r$

$$g(r) = \frac{\theta_S - \theta_R}{\sigma r \sqrt{2\pi}} \exp\left\{-\frac{[\ln(r/r_m)]^2}{2\sigma^2}\right\} \tag{1}$$

where r is the pore radius, r_m is the geometric mean radius, σ is the standard deviation, θ_R is the residual soil water content when the liquid flow is essentially zero. The value of θ_R is usually not measured but it is found as a fitting parameter, and θ_S is the soil water content at saturation, i.e. at $h = 0$. Soil water retention curve is expressed as a cumulative function to Eq. (1) with $h = a/r$, where h is [cm], a is the coefficient dependent upon the geometry of pore section we use in the model. For a cylindrical pore of radius r [μm] and water at 20°C is a = 1490. The equation describing soil water retention curve is (Pachepsky, 1992, Kosugi, 1994)

$$S = \frac{1}{2} erfc\left[\frac{\ln(h/h_m)}{\sigma\ \sqrt{2}}\right] \tag{2}$$

with S the relative saturation, or parametric soil water content [dimensionless]

$$S = \frac{\theta - \theta_R}{\theta_S - \theta_R} \tag{3}$$

h_m is the pressure head related to r_m and $erfc$ is the complementary error function.

The equation of relative unsaturated conductivity $K_R = K/K_S$ was gradually improved (Childs and Collis George, 1950, Fatt and Dijkstra, 1951, Burdine, 1953, Mualem, 1976) up to the recent general form

$$K_R = S^{\alpha}\left[\frac{\int_0^r r^{\beta} g(r)dr}{\int_0^{\infty} r^{\beta} g(r)dr}\right]^{\gamma} \tag{4}$$

The interpretation of parameters α, β, γ was discussed in detail by Mualem (1992) and Mualem and Dagan (1978). With a certain simplification α represents the macroscopic description of tortuosity, when the pore is partially drained, then the flow path copies the irregular surface of the pore and the tortuosity increases. Parameter β is related to microscopic tortuosity, to pore radius, and it increases with the decrease of pore radius. Correlation between the pores, or connectivity is expressed by γ . More about Eq. (4) is in Lecture notes on Unsaturated Flow in Porous Media.

Kosugi (1999) introduced $g(r)$ from Eq. (1) into Eq. (4) to get the equation of the relative unsaturated hydraulic conductivity K_R (h). We obtain after rearrangement of his equations (Kutílek, 2004)

$$K_R = S^{\alpha}\left\{\frac{1}{2} erfc\left[(\ln\frac{h}{h_m})\frac{1}{\sigma\sqrt{2}} + \frac{\beta\sigma}{\sqrt{2}}\right]\right\}^{\gamma} \tag{5}$$

Applicability of equations have been experimentally checked by their authors and e.g. in publications of Leij et al.(2002), Vervoort and Cattle (2003) for mono-modal soils where the derivative curve to soil water retention curve has one peak only. The derivative curve can be identified with the pore size distribution curve, see Eq. (1).

However, we find frequently (Durner, 1992) two or even three peaks on the derivative curve to the soil water retention curve and then we speak on bi-modal or tri-modal soils. Othmer et al. (1991) demonstrated the bi-modality of Gleyic Hapludalf loamy soil. They applied the van Genuchten (1980) and Mualem (1976) description of soil hydraulic functions to the bi-modal model and they obtained a substantial improvement of unsaturated conductivity function $K(h)$, when the measured data were considered as a standard. The prediction of water content in the field soil was improved for time interval of four months by the use of bi-modal model, too, when the data were compared to results obtained with mono-modal simulation model. Gerke and van Genuchten (1993) introduced the concept of dual porosity and later on they used dual conductivity model, which was broadly exploited in numerical simulation studies (_im_nek et al., 2003). However, the pore size distribution was described on the basis of the equation of van Genuchten in existing simulation programs.

Our aim is to apply the theory on hydraulic functions of lognormal pore size distribution to bi-modal soils.

THEORY

Classification of soil pores

We assume that two peaks on the pore size distribution function appear due to the existence of two porous systems within the domain of capillary pores. Further on, we use the classification of soil pores based on the laws of hydrostatics and hydrodynamics (Kutílek and Nielsen, 1994) with the terminology of micropores slightly modified in accordance with proposal of Tuller and Or (2002):

1. Submicroscopic pores where the clusters of water molecules do not allow the existence of continuous water flow paths due to the small size of pores.
2. Micropores, or capillary pores where the shape of air-water interface is determined by the configuration of pores and by the forces on the interface (capillary forces). The unsaturated flow of water is described by Darcy-Buckingham and Richards equations. The category of micropores is further subdivided into two subcategories in bi-modal soils:

2.1. Matrix (intra-aggregate, intra-pedal, textural) pores within soil aggregates or soil blocks. The arrangement of the soil skeleton, coating of aggregates, cutans and nodules typical for each soil taxon have main influence upon the soil water hydrostatics and hydrodynamics in the matrix domain. Saturated hydraulic conductivity is strongly reduced when compared to conductivity of the whole soil (Horn, 1994).

2.2. Structural (inter-aggregate, inter-pedal) pores between the aggregates, or eventually between the soil blocks. Their morphology and interconnection depends upon the shape, size and stability of aggregates and blocks, or, generally upon the soil genesis and the type of soil use.

3. Macropores (non-capillary) pores of such a size that capillary menisci across the pores are not formed. A more detailed classification of macropores is related to their origin, shape, stability and persistence in time.

Lognormal Model of Hydraulic Functions in Bi-Modal Soils

We are dealing with subcategories of matrix and structural pores in this study. The boundary between the domains of matrix and structural pores is denoted h_A . It is the air entry value of the matrix domain, too. It is determined as the minimum value between two peaks on the derivative curve to the retention curve, illustrative example is in Fig. 1. If there exist two or three minima, we consider the minimum minimorum (i.e. the lowest minimum between the peaks) as h_A, see Fig. 2. Equation (2) of soil water retention curve and Eq. (3) of relative saturation of soil by water have then the forms (Kutílek, 2004)

$$S_i = \frac{1}{2} erfc\left[\frac{\ln(h_i / h_{mi})}{\sigma_i \sqrt{2}}\right] \tag{6}$$

$$S_i = \frac{\theta_i - \theta_{Ri}}{\theta_{Si} - \theta_{Ri}} \tag{7}$$

where $i = 1$ is for matrix pores and $i = 2$ for structural pores. With the principle of superposition, applied already by Othmer et al. (1991) and by Zeiliguer (1992) we define

$$\theta = \theta_1 + \theta_2 \tag{8}$$

Since coarse micropores of $r > r(h_A)$ would cause instability of aggregates, we assume that the matrix porous system does not contain coarse micropores above h_A. Then

$$\theta_{S1} = \theta(h_A) \text{ and } \theta_{S2} = \theta_{S\text{-}EXPER} - \theta_{S1}. \tag{9}$$

For $0 > h \geq h_A$ is

$$\theta_1 = \theta_{S1}\,,\ S_1 = 1 \tag{10}$$

and θ_2 is obtained by optimization, $S_2 < 1$. (11)

For $h < h_A$ is θ_1 obtained by optimization, $S_1 < 1$. (12)

$\theta_{S\text{-}EXPER}$ denotes the saturated water content determined experimentally.

Unsaturated hydraulic conductivity is modified to bi-modal soil in a similar way and

$$K_{R_i} = S_i^{\alpha_i}\left\{\frac{1}{2}\operatorname{erfc}\left[\left(\ln\frac{h_i}{h_{mi}}\right)\frac{1}{\sigma_i\sqrt{2}} + \frac{\beta_i\sigma_i}{\sqrt{2}}\right]\right\}^{\gamma_i} \tag{13}$$

The subscripts in parameters $\alpha_i, \beta_i, \gamma_i$ reflect the assumption that values of parameters could differ for the two domains. With $K_i = K_{Ri}K_{Si}$ and using the principle of superposition we obtain

$$K = K_1 + K_2. \tag{14}$$

The value of K_{S2} is obtained by optimization and $K_{S1} = K_{S\text{-}EXPER} - K_{S2}$. The procedure allows us to define separately conductivities of the two domains and to separate from the measured K that portion K_2 which can be considered as preferential conductivity, see Fig. 4 as an illustrative example.

This procedure differs from the approach of Kosugi and Inoue (1999) who have first constituted two (or generally n) subsystems but finally in evaluating relative unsaturated conductivity they have treated the soil as one system. The consequence was that they did not differ between parameters of subsystems and α, β, γ were common to the whole optimization procedure. The conductivities of matrix domain and of structural domain were not obtained as separate ones.

Optimization was performed in following steps: The experimentally determined data of the soil water retention curve $\theta(h)$ are first transformed into $S(h)$ according to Eq. (3). Then, a cubic spline function is fitted resulting in a smooth curve $S(\ln h)$ passing through the experimental data. It is assumed that θ_R is the water content at h = -15000 cm. When θ_R was considered as equal to the estimate of hygroscopic coefficient, the parameters were only slightly changed. θ_R was therefore kept equal to the measured water content at h = -15000 cm. The curve was calculated from smooth curve $S(\ln h)$. Let us note that the curve is identical to the pore size distribution if h is recalculated to equivalent pore radius r. When the model of cylindrical pores is used, then for contact angle equal zero and for tabled viscosity at 20°C is $r = 1490/h$, where r is in μm and h in cm. This very simple type of recalculation is taken as a first approximation. If we knew the dependence of pore shape upon pore size and upon horizons we could proceed to a higher approximation of r.

The value h_A separating the two principal pore domains was obtained as the minimum between two major peaks on the derivative curve. Next the parameters $h_{m1}, h_{m2}, \sigma_1, \sigma_2$ (Eq. 6) were determined for conditions (8) to (12). The non-linear curve fitting was carried out by conjugate gradient method applied to find the minimum of a function $f(x)$ of n variables (Powell, 1977,1978). The procedure provides a fast rate of convergence. 180 equidistant sample points were read from the smoothed $S(h)$ curve and used in fitting. The optimized parameters $h_{m1}, h_{m2}, \sigma_1, \sigma_2$ enter into Eq. (13) for each of the domains. The optimization was similar to the procedure applied to the soil water retention curve. A smooth curve was plotted through the experimental points by cubic spline. Th whole range of conductivity was subdivided into 130 sample points which were used for fitting the parameters. Saturated conductivity K_{S2} was determined together with parameters α_1, β_1, α_2, β_2 from Eq. (13) by Powell´s (1977, 1978) conjugate gradient method for condition (14). We assumed $\gamma = 1$ according to the study of Kosugi (1999), who found that the value of γ is in majority of instances close to 1 for log-normal distribution.

MATERIALS

The theory was tested on data sets on soil water retention curves and on unsaturated hydraulic conductivity functions obtained from the UNSODA data base (Leij et al., 1996, and Nemes et al., 1999) and on the data sets published by Othmer et al. (1991). All soils and their horizons were typical by their bi-modality. Soil characteristics relevant to the studied problem are in Table 1. Soil water retention curves of both sources, the UNSODA data base and of Othmer were determined on undisturbed soil samples in the laboratory. Unsaturated conductivity data were determined in laboratory for the used UNSODA data base and in the field by instantaneous method by Othmer.

RESULTS AND DISCUSSION

Soil Water Retention Curves

Parameters of soil water retention curves, Eq. (6) were determined for conditions (8) to (12). They are in Table 2. The computed retention curves are very close to the experimentally determined data. The matrix domain is separated from the structural domain by a minimum on the derivative curve h_A , see Figs. 1 and 2. The value h_A is in very broad ranges extending from 8 cm in B horizon of sandy Dystrochrept up to 626 cm in B horizon of silt loam Hapludalf. The equivalent pore radii are from186 μm to 2.4 μm. If sand is excluded, the ranges are 30 to 626 cm, i.e. 50 to 2.4 μm. The value of separation of structural (interaggregate) pores from the matrix (textural) pores is therefore not a fixed value of pressure head, or pore radius. It is in broad ranges, dependent upon the soil taxon, soil horizon, texture and probably upon soil use, too. The classification systems of soil pores by Brewer (1964), Luxmoore (1981), Greenland (1981), Ahuja (1984) and others are based upon fixed boundaries between pore size categories as e.g. macropores, mesopores, micropores, or between transmission and storage pores. Their objectivity is questionable when we consider our results.

There was a small difference between h_A found directly on the derivative curve and h_A optimized together with h_{mi} and σ_i. We preferred then the use of directly determined data from the derivative curves. We have detected an inferior minimum on the derivative curve in 30% of studied soils, example is in Fig. 2. Inferior minimum corresponds in our studied soils to h = 2 to18 cm in the domain of structural pores. Its nature cannot be determined without a detailed micromorphologic research. Let us note that Pagliai et al. (1989) and Pagliai and Vignozzi (2002) detected this type of secondary minimum at radius equivalent to h = 3 to 5 cm (r = 300 μm to 500 μm) by direct micromorphologic studies of some soils and their use. We have included those secondary minima into structural domain without attempting for inclusion of hypothetical subclasses in this study.

The values of σ_i and h_{mi} in Table 2 offer information on pore size distribution in matrix and structural domains. The shape of the pore size distribution is related to σ close to 1 in majority of instances and there is a tendency to obtain the curve slightly more flat in matrix domain of B horizon. An opposite tendency is in the structural domain of B horizon. The equivalent mean pore radius is variably changing with depth in matrix domain. It decreases in structural domain of B horizon of Hapludalfs when compared to A horizon..

Using the tabled parameters, we plotted the retention curves of the matrix and of the structural domains, example is in Fig. 3. If the pressure head is replaced by the equivalent radius r , we obtain the cumulative function of pore size distribution of individual domains.

In Table 3 we use the equality $\theta_{Si} = P_i$, where P_i is the porosity of the i-th domain. Structural porosity decreases with the depth from A hor. to B hor. when it is compared to matrix porosity. Gleyic process contributes to this decrease. Contribution of structural porosity to the total porosity is in ranges from 0.357 to 0.161, and it is decreasing with the depth, too.

When the restrictive conditions (9) and (10) are not applied, we obtain in 50% a slight improvement of computed retention curves, i.e. they are closer to experimental data, but in remaining 50% the error of the computed retention curves increases. The improvement of the retention curve in those 50% of instances does not result in improvement of computed conductivities, quite opposite, se the next chapter. In addition to it, we do not assume that the matrix could contain coarse capillary pores of dimensions of hundreds μm. As we have already mentioned, the coarse pores would cause instability of aggregates and their disintegration into smaller aggregate units.

Saturated Hydraulic Conductivity

Saturated hydraulic conductivity of the structural domain K_{S2} was optimized together with parameters of unsaturated conductivity function. Saturated hydraulic conductivity of the matrix domain $K_{S1} = K_{S\text{-}EXPER} - K_{S2}$. The data are in Table 4. The values of matrix saturated conductivity are from one and half order of magnitude up to three orders of magnitude lower than saturated conductivity of structural domain, see Table 3. Saturated conductivity of sand is the only one exception. Our results are in agreement with direct measurements of Horn (1994) who obtained saturated conductivities inside of aggregates by several orders of magnitude lower than saturated conductivities of the whole soil.

Unsaturated Hydraulic Conductivity

Unsaturated hydraulic conductivity function $K_i(h)$ of both domains depends upon parameters α, β, γ and upon parameters of the soil water retention curve h_m , σ, see Eq. (13). We assumed in the first approach that the parameter $\gamma = 1$. Optimization procedure was performed for condition (14) and the data are in Table 4. The parameters α_1, β_1 of the matrix domain differ substantially from α_2, β_2 of the structural domain, in matrix domain is $\alpha_1 < 0$ and $\beta_1 > 0$ in majority of instances, while in structural domain is $\alpha_2 > 0$ in majority of instances and β was roughly in 50 % positive and in 50% negative. The opposite sign is for pairs α_1, α_2 or for β_1, β_2 in 65% of instances. All discussed differences in values of parameters are proof that the shape, connectivity and tortuosity of pores are different in the two domains and that their hydraulics has to be treated separately, as it was proposed in earlier publications (Othmer et al., 1991, Gerke and van Genuchten, 1993). Verwoort and Cattle (2002) studied relationships between the quantified parameters of micromorphology of pores and the parameters α, β of Eq. (5) for monomodal clay soil. Their statement on increasing β with decreasing r is valid for our domains, too, since β is lower in structural domain than in matrix domain. There is an agreement on the mutual relation of α, β. When α is decreasing with the depth in a certain taxon, then β is increasing and vice versa.

When all three parameters α, β, γ were optimized in the second approach, the value of parameters α, β were changed but the accuracy of fitted $K(h)$ was increased only in some instances (about 50% of studied soils), in others the accuracy was decreased, judging according to the values of RMSE and maximum relative error. The general characteristic behavior of parameters α, β was not changed. The value of γ was negative in 15% for matrix domain and in 15% approaching zero value, see Table 5..

The frequent occurrence of negative values of parameters brings doubts on their direct physical interpretation. It is physically absurd to speak on negative tortuosity. It is therefore probable that the parameters are related to tortuosity and pore connectivity through a functional relationship which enables a negative value of the parameter. Or, the parameters are just fitting parameters without physical intepretation.

The restrictive conditions (7) and (8) leading to separation of the two domains cause a singularity at $h = h_A$ in the $S(\theta)$ and $K(h)$ relationships. When the restrictive conditions (7) and (8) are not applied in the retention curve, then the optimized $S(\theta)$ and $K(h)$ are monotonous smooth function, but the sum of errors is increased, compared to $K(h)$ function computed for retention curves with conditions (7) and (8). In addition to it, the existence of very coarse capillary pores in aggregates is not possible. This was the reason for keeping the restrictive conditions (7) and (8) valid, i.e. to keep both domains separated.

If we use uniformly $\alpha = 0.5$, $\beta = 1$, $\gamma = 2$ (Mualem, 1976) with two domains of retention curves, we obtain errors of more than one, or two orders of magnitude in certain parts of the $K(h)$ function.

CONCLUSIONS

1. The modified theory on hydraulic functions in a bi-modal lognormal pore size distribution system is well applicable. Eq. (6) of soil water retention curve with conditions (8) to (12) offers data either identical or with negligible error when the experimental data are taken as reference. Water retention curves of matrix and of structural pores can be plotted separately and the separate porous systems can be identified.
2. The structural porosity is substantially lower than the matrix porosity. However, the separation of both domains occurs at non-constant pressure head h_A with its value in broad ranges from 30 to 626 cm, corresponding to equivalent pore radius from 50 μm to 2.4 μm, if sand is excluded. The classification systems of soil pores based upon fixed boundaries between pore size categories are not objective.
3. Matrix saturated conductivities are by one and half order of magnitude up to three orders of magnitude lower than saturated conductivities of the structural domain.
4. The parameters characterizing the unsaturated conductivity function α_1, β_1 and α_1, β_1, γ_1 of the matrix domain differ substantially from α_2, β_2 or α_2, β_2, γ_2 of the structural domain. The porous systems are assumed to be different in the two domains.
5. A simple physical interpretation of all three parameters α, β, γ does not exist and the eventual functional form has to be searched on basis of soil micromorphology relating parameters to tortuosity, pore connectivity and other characteristics of the porous system.

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Table 1. Characteristics of soils.

Soil code	Soil taxon	Depth cm	Soil horizon	Soil texture	Soil structure
UNSODA (Leij et al., 1996, Nemes et al., 1999)					
2750	Bruennli series	0-30	(E)B	Loam	n.d.
2751		30-60	Bv	Sandy loam	n.d.
2752		60-100	(Sd)BC	Loam	n.d.
4660	Typic Dystrochrepts	15-25	Ah	Sand	single grain
4661		30-40	Bv	Sand	single grain
4670	Typic Hapludalf	20-30	A1	Silt	coherent
4671		40-50	Ag1	silt loam	coherent to fine
4672		70-85	Bt	silt loam	Fine to moderate
Othmer et al. (1991)					
S 15	Gleyic Hapludalf	15	Ap	Loam	medium subangular
S 60		60	Btv	Loamy silt	medium subangular and blocky

n.d. not determined

Table 2. Parameters of soil water retention curves, Eq. (6) in matrix (indexed by 1) and structural (indexed by 2) domains, separated by pressure head h_A .

Soil	z, cm	h_A, cm	Matrix domain			Structural domain		
			θ_{S1}	h_{m1}, cm	σ_1	θ_{S2}	h_{m2}, cm	σ_2
UNSODA								
2750	0-30	403	0.390	2864	1.05	0.217	29	1.36
2751	30-68	344	0.393	4044	1.09	0.122	19	1.88
2752	60-100	384	0.376	3011	1.09	0.099	18	1.71
4660	15-25	15	0.318	64	1.78	0.145	3	0.85
4661	30-40	8	0.326	33	1.06	0.102	3	0.73
4670	20-30	296	0.336	1249	0.81	0.126	47	1.50
4671	40-50	185	0.337	1366	0.92	0.075	59	0.71
4672	75-85	626	0.307	3229	1.15	0.087	140	1.22
Othmer †								
S 15	15	55	0.318	1086	1.48	0.148	6.8	1.20
S 60	60	30	0.35	788	1.63	0.069	10.0	0.94

† Parameters according to Kutílek (2004)

Table 3. The ratio of saturated water contents θ_i and of saturated hydraulic conductivities K_{Si} in matrix domain (indexed by i = 1) and in structural domain (indexed by i = 2) of soils. The ratio of structural porosity θ_{S2} to total porosity P.

Soil	Depth, cm	Horizon	θ_{S1}/θ_{S2}	θ_{S2}/P	K_{S1}/K_{S2}
UNSODA					
2750	0-30	(E)B	1.80	0.357	0.0026
2751	30-60	Bv	3.22	0.237	0.0058
2752	60-100	(Sd)E	3.80	0.208	0.0010
4660	15-25	Ah	2.19	0.314	0.049
4661	30-40	Bv	3.20	0.238	0.237
4670	20-30	A1	2.67	0.273	0.0021
4671	40-50	Ag1	4.49	0.182	0.031
4672	75-85	Bt	3.53	0.221	0.0035
Othmer					
S15	15	Ap	2.22	0.318	0.0105
S60	60	Btv	5.20	0.052	0.0067

Table 4. Parameters of relative unsaturated hydraulic conductivity, Eq. (13) with $\gamma = 1$ for matrix (indexed by 1) and structural (indexed by 2) domains.

Soil	z, cm	Measured K_S cm/day	Fitted					
			Matrix			Structural		
			K_{S1}, cm/day	α_1	β_1	K_{S2}, cm/day	α_2	β_2
UNSODA								
2750	0-30	190.08	0.185	-1.94	3.33	189.59	0.024	1.79
2751	30-60	25.92	0.015	-0.53	1.402	25.90	3.44	-0.47
2752	60-100	14.95	0.015	-0.60	1.52	14.87	4.13	-0.56
4660	15-25	625.5	30.87	0.96	0.92	593.88	0.92	-1.83
4661	30-40	1140	218.2	-1.22	2.81	920.2	0.022	0.094
4670	20-30	88.99	0.189	-1.04	2.64	88.80	2.19	-0.64
4671	40-50	12.27	0.368	-0.99	2.50	11.90	0.024	0.98
4672	75-80	2.42	0.009	-0.50	1.26	2.58	2.59	-0.78
Othmer †								
S15	15	11.50	0.12	1.0	2.3	11.38	0.45	0.70
S60	60	15.0	0.10	-0.3	1.4	14.9	-1.0	1.8

† Parameters according to Kutílek (2004)

Table 5. Parameters α, β, γ of relative unsaturated hydraulic conductivity, Eq. (13) in matrix (indexed by 1) and structural (indexed by 2) domains.

Soil UNSODA	z, cm	α_1	β_1	γ_1	α_2	β_2	γ_2
4660	15-25	2.05	9.90	0.02	0.88	-3.60	64.3
4661	30-40	5.45	-1.24	-6.89	0.47	-5.56	4659
4670	20-30	-2.78	2.07	2.22	1.67	-2.40	249
4671	40-50	-1.09	3.44	0.86	0.28	16.63	0.03
4672	75-85	5.41	-1.40	-18.15	2.53	4.83	0.013

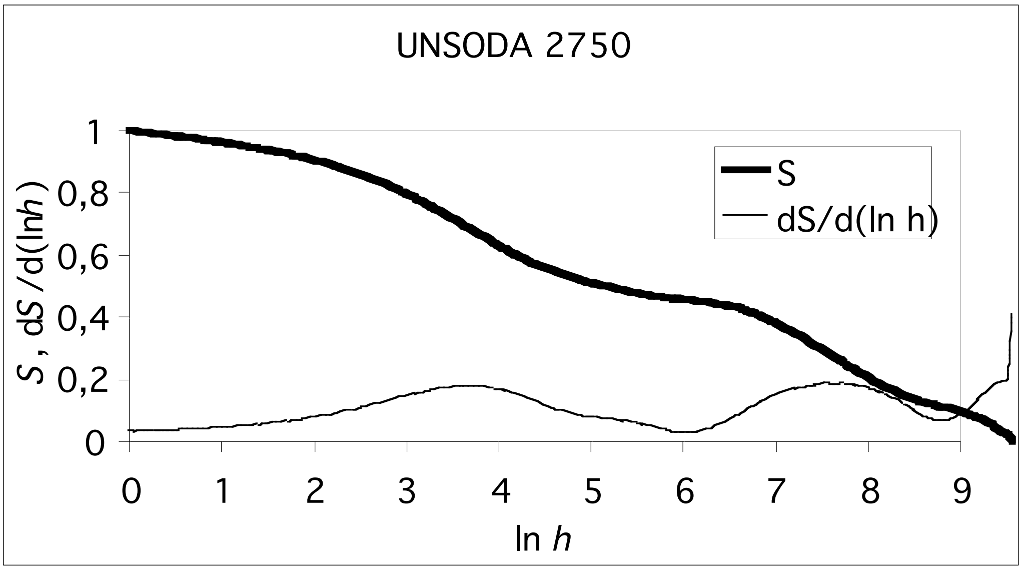

Fig. 1. Soil water retention curve *S(h)* and its derivative d*S*/d(ln *h*) for UNSODA 2750, *S* is the relative saturation of soil by water, *h* is the negative pressure head, cm. Separation of matrix from structural domain is at h_A = 403 cm.

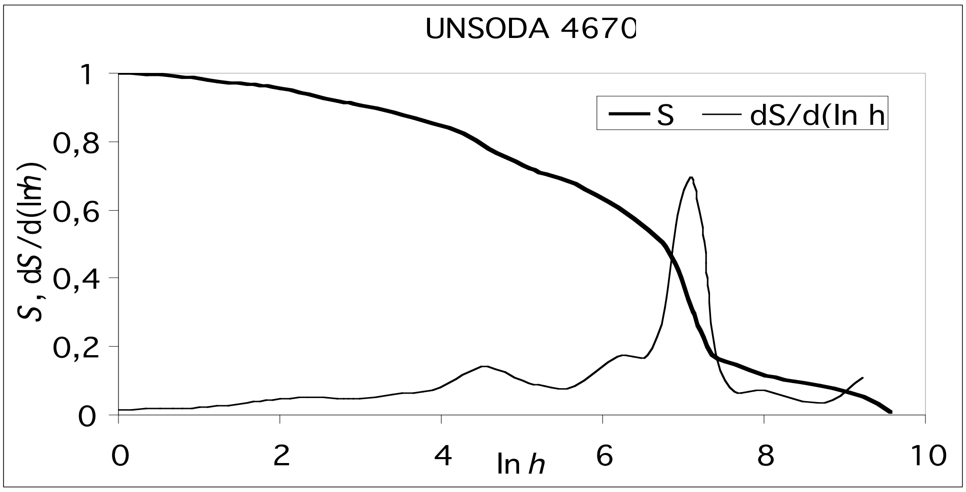

Fig. 2. Soil water retention curve *S(h)* and its derivative d*S*/d(ln *h*) for UNSODA 4670

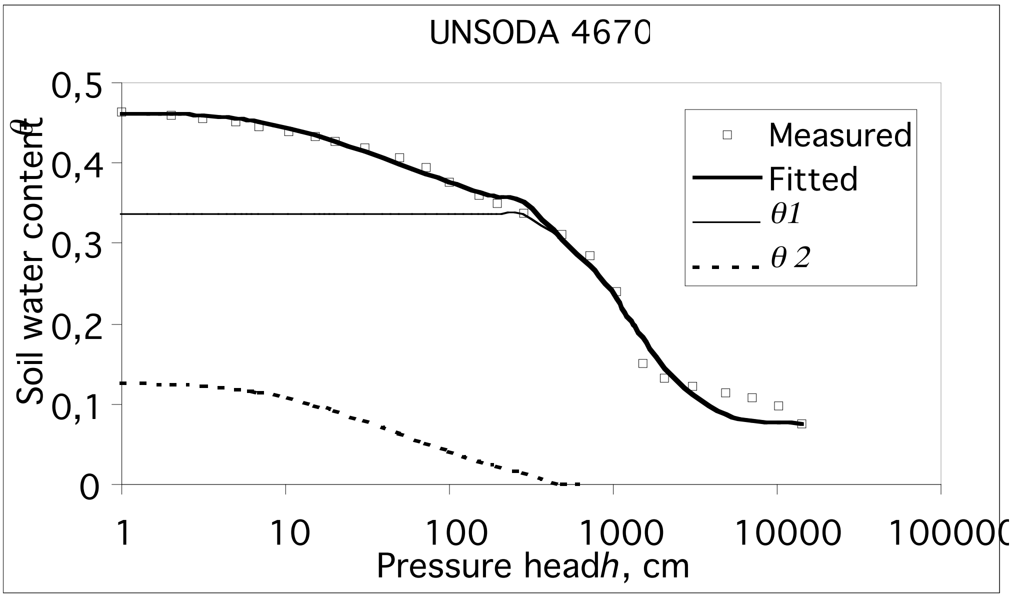

Fig. 3. Separation of soil water retention curves for matrix domain (index 1) and structural domain (index 2) for UNSODA 4670.

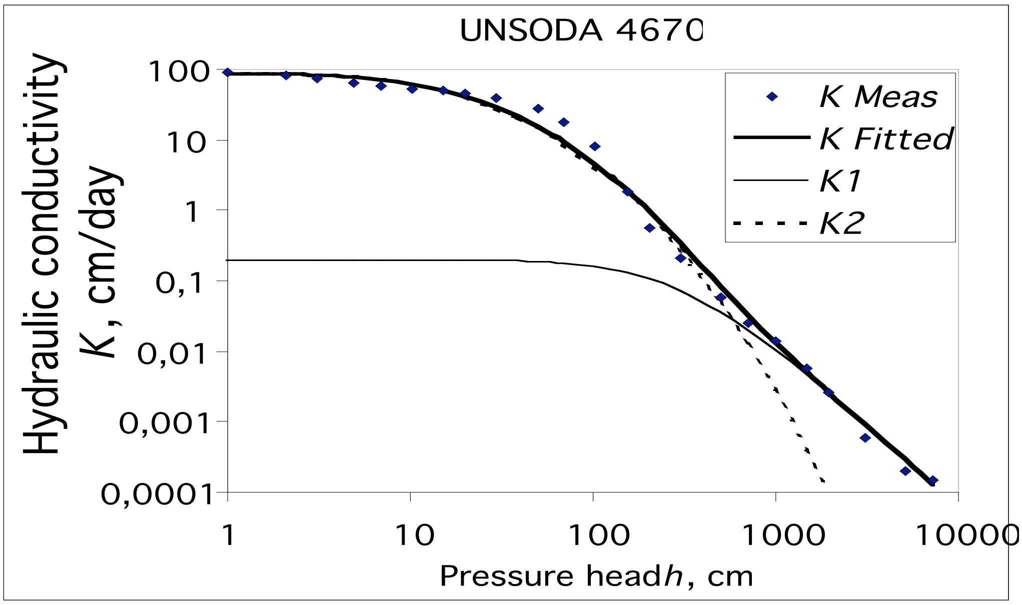

Fig. 4. Results of fitting procedure compared to measured data and separation of unsaturated hydraulic conductivities for matrix (index 1) and structural domains.

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