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Development of Pedotransfer Functions in Soil Hydrology

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Chapter 13

ESTIMATING SOIL SHRINKAGE PARAMETERS

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I. IMPORTANCE OF SHRINK-SWELL PROPERTIES

There are several models of soil water flow that consider thesoil medium as an active site for chemical, physical and biological processes with a bimodal porous medium-, micro-and macro-pore systems (Jarvis, 1994; Tiktak, 2000; Van der Linden et al., 2001). Few of these models consider the soil medium as a structured medium with aggregates. However. the swelling-shrinkage behavior of these aggregates is almost never considered. Thus, literature on soil dynamics modeling describes soil hydraulic properties independently from the soil-water internal configuration. This leads to an empirical approach to represent and estimate soil-water dynamics and properties such as shrinkage, that induces cracks and fissures and play a major role in preferential flow, field capacity, wilting point, available water, air capacity, unsaturated hydraulic conductivity and water retention.

Most soil water models characterize soil medium by a constant bulk density and the dependencies of hydraulic conductivity *k* and soil matric potential *hon* volumetric water content *0.* To estimate these properties, soil scientists often tum to pedotransfer function (PTF) using basic soil texture and constituents data. Several of these PTFs are available in the literature, as shown in the present book review. However, the internal soil structure and its volume change as a function of water content is not taken intoconsideration. This study presents a conceptual and functional model of strnctured soil-water medium in which the internal volumes change (aggregates, water pools, micro- and macro-pore systems) is governed by the shrinkage parameters that are easily determined using continuously measured soil shrinkage curve (SC) (Braudeau et al., 2004). This chapter also describes how to estimate these SC parameters using available soil survey data.

2. SOIL-WATER MEDIUM FUNCTIONAL MODEL

2.1. Soil-water medium hierarchy and functionality

The soil-water medium of the soil horizon is termed here "pedostructure:' It consists of soil fabric with its variable amount of water. The pedostructure refers to

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the combina1ion of the soil fabric (morphological aspect) and its hydraulic functioning as revealed by the SC (specific volume vs. waler content). Braudeau et al. (2004) showed that the SC of the soil-water medium defines the specific volume of its basic component, the primary peds, V_{mi}. The p,imary peds have been first defined morphologically by Brewer (1964) as "the simplest peds occurring in a soil material: they cannot be divided into smaller peds, but they may be packed toge1her to fom, compound peds of higher level of organization. S-matrix of a soil material is the material within the simplest (primary) peds, or composing apedal soil materials, in which the pedological features occur; it consists of plasma, skeleton grains, and voids that do not occur in pedological features other than plasma separations." Figure I shows a schematic representation of the pedostructure taking into consideration the four hierarchical structural levels of soil: the horizon, the pedostructure, the primary peds and the primary particles.

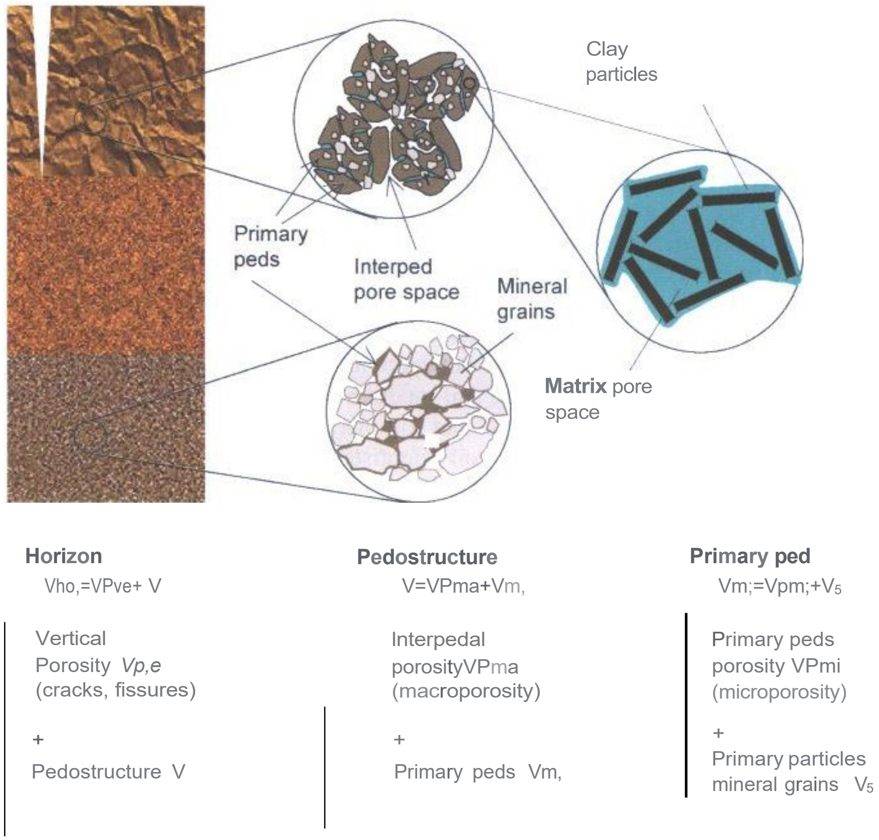

Figure I. Schematic representation of the pedostructure, taking into consideration the structural levels of the soil horizon: the horizon, the pedostruture, the primary peds and the primary particles.

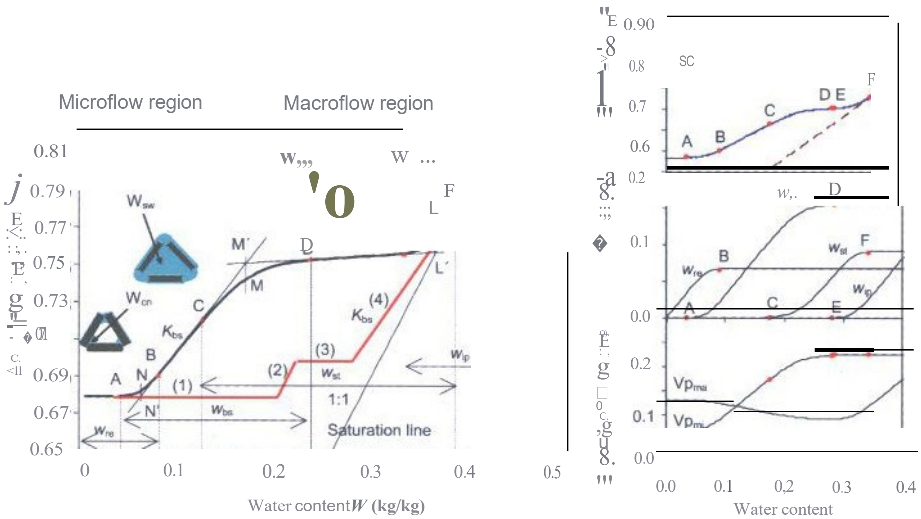

Figure 2. Various configurations of air and water partitioning into the two pore systems, inter- and intra-primary peds, related to the shrinkage phases of a standard SC. Wen represents the condensed water lodged in interstitial pore site, and W,w represents the swelling water lodged in interstitial pore site that can be interped macro-pores (ma) or matrix micro-pores (mi). The various pools of water. w,c, wb" w.i. w;p, are represented with their water content curves. The linear and curvilinear shrinkage phases are delimited by the transition points (A-F). Points N', M'. and L' are the intersection points of the tangents at those linear phases of the SC.

2.2. Characterization of the pedostructure using shrinkage curve

It was assumed that as soil dries, water leaves the soil from pore of gradually decreasing sizes. Starting from saturation (point F in Figure 2), the interpedal porosity (macro-pore volume, VPma) empties up to point C while the primary peds porosity (micro-pore volume, Vpm;) begins to shrink at point D. losing its water (Wm,) without air entry from point D up to point 8.

For each pore system (inter-pedal and intra-primary peds), water removal is divided into two stages: a first stage during which water leaves the pore system without air intake, with the peds (macro-system) or clay particles (micro-system) approaching each other (shrinkage phases F-E and D-A, respectively). During the second stage water leaves the pore system while being replaced by air, and the peds or clay particles touch (shrinkage phases F-C or 8-0, respectively). The ranges for covering the two phases are the curvilinear sections of the SC (phases F-E, C-D, and 8-A). Thus, for each pore system, there are two water pools, "swelling" and '·non-swelling." Removal of water from the swelling pool induces volume change (shrinkage), while removal of water from the non-swelling pool does not induce any significant volume change. The swelling and non-swelling water pools of the macro-pore system are w_{ip} and w_{st}, respectively, and those of the micro-pore system are w_{bs} and w_{re}. The subscripts *ip, st, bs,* and *re,* refer to as interpedal, structural, basic, and residual shrinkage phases, respectively.

Braudeau et al. (2004) showed that the volume change equation could be written as a linear combination of the water pool equations:

$$dV = K_{re}dw_{re} + K_{bs}dw_{bs} + K_{st}dw_{st} + K_{ip}dw_{ip} \quad (1)$$

that gives, after integration:

$$V = V_o + K_{re}w_{re} + K_{bs}w_{bs} + K_{st}w_{st} + K_{ip}w_{ip} \quad (2)$$

where K(s) are the slopes of the linear shrinkage phases, w(s) are the corresponding water pool, and V_0 is the specific volume at dry state (Figure 2).

The authors showed also that the SC, continuously measured under laboratory conditions as in Braudeau et al. (1999) (30°C, unconfined sample, atmospheric pressure), can be assumed to represent a suite of equilibrium states between the water pools and the two pore systems, micro- and macro-pores. The water pools expressions as defined by the SC are:

$$w_{ip} = \frac{1}{k_L} \log[1 + \exp(k_L(W - W_L))]$$

$$w_{st} = -\frac{1}{k_M}\log[1 + \exp(-k_M(W - W_M))] - \frac{1}{k_L} \log[1 + \exp(k_L(W - W_L))]$$

$$w_{bs} = \frac{1}{k_N} \log[1 + \exp(k_N(W - W_N))] + \frac{1}{k_M} \log[1 + \exp(-k_M(W - W_M))]$$

$$w_{re} = -\frac{1}{k_N} \log[1 + \exp(-k_N(W - W_N))] + W_N$$

The parameters K_{re}, K_{bs}, K_{st}, K_{ip}, k_N, k_M, k_L, W_N, W_M, W_L, V_0 used in these equations are parameters of the SC. They can be obtained graphically from the measured SC knowing points N', M', and L', the intersection points of the straight lines tangent to the linear sections of the SC and N, **M**, and L, the corresponding points of the SC (Braudeau et al., 2004). Parameters k_N, k_M, k_L are determined using equations listed in Table I.

Using the SC and water pool properties of Figure 2, the following relationships are defined:

$W_{mi} = w_{bs} + w_{re}$ the water content in primary peds

$$W_{ma} = w_{ip} + w_{st}$$

$$\mathrm{Vp}_{mi} = \min(\mathrm{Vp}_{mi}) + w_{bs}/\rho_w$$

$$\mathrm{Vp}_{ma} = V - \mathrm{Vp}_{mi} - V_s$$

Table I
Relationships between pedoslructure SC parameters (Braudeau et al., 2004) and the XP model transition points (Braudeau et al., 1999)

Shrinkage phases concerned	Relations between parameters of the PS model and with parameters of XP model
Basic and residual (N)	kN = (Kb, - Krc)/(VN, - VN) ln(2)
	= 4.8 ln(2)/(WN - WA)
	= 3.46 ln(2)/(W8- WN)
Basic and structural (M)	KM= (Kb, - K51)/(VM' - VM) ln(2)
	= 4.8 ln(2)/(WM - Wo)
	= 3.46 ln(2)/(Wc - WM)
Interpedal and structural (L)	KL = (Kip - K51)/(V1.;- Vd ln(2)
	= 4.8 ln(2)/(WL - WE)
	= 3.46 ln(2)/(Wr - WL)

PS, pedostructurc; **XP,** exponential model of the SC.

$$\min(\mathrm{Vp_{mi}}) = \max(w_{\mathrm{re}}/\rho_{\mathrm{w}}) = W_{\mathrm{N}}/\rho_{\mathrm{w}}$$

$$\max(\mathrm{Vp_{mi}}) = (\max(w_{\mathrm{re}}) + \max(w_{\mathrm{bs}}))/\rho_{\mathrm{w}} = W_{\mathrm{M}}/\rho_{\mathrm{w}}$$

$$\max(\mathrm{Vp_{ma}}) = \mathrm{Vp_{maSat}} = (W_{\mathrm{L}} - W_{\mathrm{M}})/\rho_{\mathrm{w}}$$

Figure 2 shows an example of the continuously measured SCs where the corresponding change in the water pools (Wrc, wb,, w,i, and »-"ip) and the two specific pore volumes (VPmi and Vpma) are represented according to the above equations. Points A-Fare the transition points of the shrinkage phases also shown on the corresponding curves of the waler pools. These points mark the effective beginning or end of water removal from each pool. The water content at these points (WA, W8, ... Wr) are characteristics of the soil and are determined from the continuously measured SC using a standard method developed by Braudeau et al. (2004) according to the equations listed in Table I.

Figure 2 also shows a schematics of the swelling process when dry aggregated soil sample is immersed in water. Four events occur immediately before the primary peds swelling: (I) the entry of water into the soil medium through the interpedal voids; (2) the spacing of aggregates; (3) the water entry into the dry micro-pores of the primary peds, filling the residual micro-pore dry space in few seconds; and (4) swelling of the primary peds which takes up to 2 h (Braudeau, I995). The length and slope of each phase are calculated according to the hydro-structural characteristics defined by the SC in the shrinkage cycle, assuming that they are the same for the swelling as for the shrinkage process, i.e.,: Kb,= dV/dWmi; max(VpmJ and min(VPmi)-

3. SEEKING PEDOTRANSFER FUNCTIONS FOR THE SC USING THE PEDOSTRUCTURE CHARACTERIZATION

The above section presents a conceptual pedostructure model that determine both the internal structural volume change as a function of water content and the corresponding SC.

This section demonstrates the use of available soil characteristics such as texture, COLE, water retention curve. field capacity and wilting point, to estimate the SC parameters according to their significance in thepedostructure model. and thus to construct an optimal approximation to the SC. Comparison of some SC parameters with existing P'TFs will be presented.

The 11 parameters that characterize the SC described in the section above may not all be needed for modeling the *in situ* SC. therefore, we will examine the minimum set parameters to approximate the SC *in situ,* which will require additional hypothesis.

3. l. The required parameters for crossing scales from laboratory to the field

Table 2 summarizes the descriptive variables (specific volumes, water contents) of the soil horizon and of the soil medium (pcdostruclure, primary peds, and primary particles). The volume change relationship which was assumed above to calculate the variation of pedostructure volume according to the water pools can be used as a '·scaling law" of the soil-water medium, relating specific structural volumes at different organizational levels. Starting from the micro-porosity of the primary peds, one can write:

$$\mathrm{d}V_{\mathrm{mi}} = k_{\mathrm{re}}\mathrm{d}w_{\mathrm{re}} + (1/\rho_{\mathrm{w}})\mathrm{d}w_{\mathrm{bs}}$$

where $k,c = K,e/Kb,\cdot$ Then for the pedostructurc level,

$$\mathrm{d}V = K_{\mathrm{bs}}\rho_{\mathrm{w}}\mathrm{d}V_{\mathrm{mi}} + K_{\mathrm{st}}\mathrm{d}w_{\mathrm{st}} + (1/\rho_{\mathrm{w}})\mathrm{d}w_{\mathrm{ip}}$$

To pass from the pedostructure to the horizon specific volume, Vhor· three weak assumptions can be made: the slopes K,t and Kre are negligible, $w;p = 0$ due to overburden presssure, and the shrinkage of the pedostructure *in situ* is isotropic.

This latter assumption relates to the vertical porosity, YPvc, (which one can observe as cracks or fissures) of which the vertical direction is due to gravity and the opening to air due to the pedostructure shrinkage (Figure 3). Since the pedostructure volume change starts from point D, the opening of the vertical porosity which crosses the soil horizon appears only for $W < W_0$. while for $W > W_0$ the two specific volumes Vhor and V coincide: Vhor = V, and V_0 = Vhoro can he taken as reference.

Table 2
Summary of parameters and variables for the soil-water medium at the pedeostructure and horizon scales, respectively. All variables are referred lo mass of primary particles

Volume of concern	Specific volume	Specific pore volume	Water content	Condensed water pool	Swelling water pool
Horizon	Vhor	Vphor	Whor		
Vertical porosity	*Vp,c*		Wvc		
Pedostructure	*V*	Vp	*W*		
Interpedal porosity	Ypma		Wma	*w,,*	W;p
Primary peds	Vm;	Vp,,,;	*W,,,;*		
Primary peds porosity	Vp,,,;		Wrni	Wrc	*Wt,,*
Primary soil particles	vs				

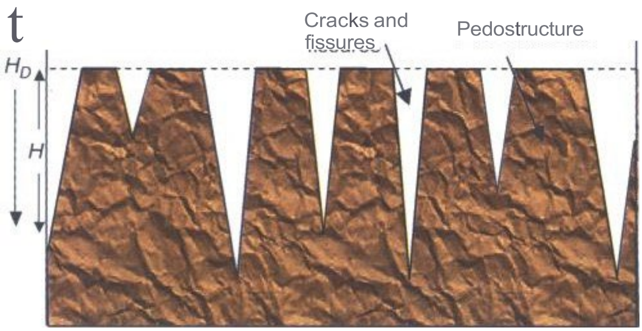

Figure 3. Schematic configuration of the soil horizon and a pedostructure showing the open cracks and fissures that opens to air as soil dries. Hand *Ho* are the soil horizon depth al the desired moisture level and point D, respectively.

That leads to the following equations:

dVhor/Vhnr = *d.H/H* = (I/3)dV/V

where *H* is the thickness of the soil horizon.

Integrating the above equation starting from point D. one obtains:

$$V_{hor}/V_{horD} = (H/H_D) = (\Delta V/V_D + 1)^{1/3} \approx (V - V_D)/3V_D + 1 = (V + 2V_D)/3V_D$$

Vhor = (V + 2Vo)/3 and YPve = Vhor - *V* = (2/3)(Vo - V)

Consequently, all of the variables listed in Table 2, from the particle level to the soil profile, are uniquely related to Wat equilibrium state of the soil-water medium.

According to the assumptions posed above about *in situ* soil horizon shrinkage (Wo is the beginning of opening of the cracks, isotropic shrinkage for *W* < *Wo* and vertical shrinkage for *W* > Wo), only the part of the curve corresponding to the water contents < *Wo* has to be estimated and the number of independent parameters is reduced to six. Those are (while assuming *K,1* = 0 and *K,e* = 0): *VN'* =VA= *Vo;* VM, = Vo = VL,; *Ws*, *We*, Wo,Kbs·

3.2. Significance of the SC parameters and its corresponding approximation

Table 3 presents the pedostructure shrinkage characteristics and its corresponding agronomic laboratory tests. The relationships between the phase transition points: A, B, ... , F, and the pedostructure SC parameters were shown in Table I. Each shrinkage phase, delimited by these points corresponds to a particular configuration of the hydrated pedostructure which induces some particular physical soil agronomical property at the macroscopic scale. These properties are evaluated using standard laboratory tests such as the porous pressure plate apparatus to determine the available water capacity.

The permanent wilting point is defined as the soil moisture below which a plant can no longer extract water and wilts in an irreversible way. At that moisture level, water is held by

Table 3
Definition and mean of determination of some common soil physical properties according to the pedostructure model

Shrinkage characteristics and parameters	Definitions and significance with reference lo the pedostructure		Correspondent agronomic laboratory tests
Pai1icular soil water states			
WA	Shrinkage limit of primary peds	11\,s vanishing	Shrinkage limit
W8	Air entry point in primary peds	Effective decreasing of *w,e*	1500 kPa pressure plate test (approximate)
We	No more water in inter-ped pore space	*w,,* vanishing	Limit tensiometer reading (approximate)
Wu	Beginning shrinkage of primary peds	Effective decreasing of *wi,,*	330 kPa pressure plate test (approximate)
WE	Shrinkage limit between peds	ll';p vanishing	Higher limit of plasticity (approximate)
Pedohydral parameters linked to structural properties			
W).f	Intersect of structural and basic linear shrinkage phases		Maximum value of Ypm;
WN'	Intersect of residual and basic linear shrinkage phases		Minimum value of Yp111;
Wt.·	Intersect of structural shrinkage phase and the load line		Total pore volume *Vp* at moist state (phase E-D)
vf'l = vL' = *vi)*			
vN' = v0 = vA	Standard case, *K*re and *Ksi* negligible:	V_0 = Kt,,(WM - W,.) - *VA*	Specific volume of horizon and pedostructure at field capacity
Indicators of the soil swelling potential			
CGμ= *WM - Wr-:/Pw*	Total shrinkage of primary peds, from wet to dry state		Swelling potential of soil
CG = *V*M' - *Vr--:'*	Total shrinkage of pedostructure. from wet to drv state		Specific swelling potential of soil

the soil matrix at a very low potential which was found to correspond experimentally to near 1500 kPa of air pressure in the Richard's pressure membrane apparatus (Miller and Mazurak, 1955). Up to point B($W > W_8$). the plasma of the primary peds ensures the flow of water in the soil and thus the renewal of the water extracted in contact with the membrane (or porous plate). Beyond point B, air entry breaks the capillary continuity of clay plasma and traps the water which no longer reaches the porous plate. This point is thus connected to the so-called permanent wilting point, or pF 4.2, currently given in soil databases.

Field capacity can be associated with the hydro-structural state at point D. At this point the gravitational drainage of the water from the inter-aggregate macro-porosity slows down because of the micro-macro-pore water exchange which takes place starting at this point.

In the same way than for the pressure membrane tests above, one can replace the various indicators of soil swelling such as the coefficient of linear extensibility (COLE) proposed by Grossman et al. (1968) with the pedostructure characterization.It consisted of measuring the lD variation of an undisturbed soil sample between wet (or retention capacity) and dry state:

$$\mathrm{COLE} = (L_{\mathrm{moist}} - L_{\mathrm{dry}})/L_{\mathrm{dry}}$$

These indicators of soil swelling differ in the soil sample preparation and the initial water content. The COLEstd is measured on undisturbed soil cores while the $\mathrm{COLE}_{,00}$ uses water saturated soil paste rods. More recently, McKenzie et al. ([994) proposed the LSmod test (modified Linear Shrinkage test) coming from a modification of the standard one $\mathrm{LS}_{,1}$d that was habitually used in Australia (Standards Association of Australia, 1977). Table 4 gives their definition, the mode of preparation and the theoretical formulation of these indicators in terms of the SC parameters.

The indicator which corresponds best to the data provided by retractometry is the LSmod because the soil sample preparation is the same (gently disaggregated and <2 mm sieved soil):

$$\mathrm{LS}_{\mathrm{mod}} = (1/3)(V_{\mathrm{M}'} - V_{\mathrm{N}'})/V_{\mathrm{M}'}$$

The swelling capacity of the primary peds can be defined as:

$$\mathrm{CG}^{\mu}(\max \mathrm{Vp}_{\mathrm{mi}} - \min \mathrm{Vp}_{\mathrm{mi}}) = (W_{\mathrm{M}} - W_{\mathrm{N}})/\rho_{\mathrm{w}}$$

The measurement of the COLErod or the $\mathrm{LS}_{\mathrm{std}}$ on a sample would provide two essential soil properties for agronomic modelling (if the initial specific volume of the soil sample is known), namely the micro-swelling capacity and dry specific micro-pore volume:

$$\mathrm{CG}^{\mu} = 3\mathrm{LS}_{\mathrm{std}}V_{\mathrm{M3}} \text{ and } \min \mathrm{Vp}_{\mathrm{mi}} = W_{\mathrm{N}} = V_{\mathrm{M3}} - \mathrm{CG}^{\mu} - V_{\mathrm{s}}$$

where V_{M_3} is the initial specific volume of the sample in the $\mathrm{LS}_{,1}$d test (Table 4).

The COLE,id and LSmoc1 would provide the values of the swelling capacity of the aggregated soil which can be defined as:

$$\mathrm{CG} = V_{\mathrm{M}'} - V_{\mathrm{N}'} = K_{\mathrm{bs}}(W_{\mathrm{M}} - W_{\mathrm{N}}) = K_{\mathrm{bs}}\rho_{\mathrm{w}}\mathrm{CG}^{\mu}$$

lv '-,) .i,.

Table 4
interpretation of the swelling indices according 10 the pedostructure soil water m()del

Index	Definition	Structure of sample initial starting point	Formulation of index according to the pedostructure model
COLE,,u	(L-s kPa- lu,y)llctry	Natural soil clods	(VE! - VA1)/3VA1 = (VMI - VN1)/3VN1 = Kh,1(WM - WN)/3(WN + YPmal + V,)
	(133 kPa ldry)ILdry	Near-saturation or -33 kPa matrix potential	(Vo1 - V,,,_1)/3VAI = (VMI - VN1)/3VN1 = Kh,I(WM - WN)/3(WN + VPmal + V,)
COLErod	(4.misi- ldry)/Ldry	Rod of remoulded soil paste	(Vu - VA2)/3VA2 = (VM2 - VN2)/3VN2 = Kb,2(WM - WN)/3(WN + Vp$_{111}$a2 + VJ
	(L33 kPn - ldry)/lctry	Liquid-limit estimated at - 33 kPa mallix potential	(VD2 - V,,d/3VA2 = (VM2 - VN2)/3VN2 = Kb,2(WM - WN)/3(WN + Vp$_{111}$a2 + V,) (with Kb,2 = I and Vp$_{111}$a2 = 0)
LS,,d	(LLL- Ldry)/LLL	Remoulded soil paste Liquid limit	(Vu - VA3)/3VL3 = (VM3 - VN,)/3VM3 = Kb,3(WM - WN)/3(WM + Vp,,,33 + V,) (with Kb,3 = 1 and VPma3 = 0)
LSmoo	(Ls kPa- ldry)lls kPa	Layer of <2 mm soil aggregates Near saturation (-5 kPa)	(VE4 - VA4)/3V1.-1 = (VM4 - VN�)/3VM4 = Kbs.i(WM - WN)/3(WM + VPma3 + VJ

The parameters in the last column have values different from one method to the other depending on the method of sample preparation.

and the specific volume at field capacity V_0:

$$CG = 3LS_{mod}V_{M4} \text{ and } V_D = V_{M4}$$

3.3. Construction of the SC from primary data of soil

These parameters, W_8, We and W_0 are approximated by water contents at permanent wilting point (Wrwp); water content at =90 kPa, the tension pressure limit of the water column in a tensiometer, W_{90}; and water content at field capacity (WFc) which is generally approximated by the water content at tensions varying between 5 and 40 kPa in the Richards pressure membrane test, depending on soil texture and mineralogy. These three points of the soil moisture characteristic curves can be obtained using porous pressure plate apparatus or evaluated from texture using PTFs (Donatelli et al., 1996). A comparison of W_8 and W_0 with the values of Wpwp and WFc calculated by nine PTFs is given below.

The slope of the basic shrinkage phase (Kbs), which lies between 0.1 and 1.2, is a structural feature of the assembly of aggregates according to the relation:

$$K_{bs} = dV/dV_{mi}$$

which represents the volume change ratio between the aggregated soil sample and the primary peds. The parameter depends on the apparent sand content with respect to argillaceous plasma and thus on the clay/sand ratio. A PTF based on texture is needed for this parameter.

The remaining parameters V_0 and VD could not be obtained from texture but rather from indicators of the soil swelling potential such as COLE or LS (linear shrinkage index). For example, according to their formulation in Table 4, both measurements of COLE,oc1 (on saturated paste) and LSrnod (on bed of aggregates <2 mm) would provide the following four SC parameters: VN·, VM', WM and WN. Adding WFc and WrFP (e.g., W_0 and W_8), the six parameters needed for modeling the *in situ* SC and consequently all the descriptive variables of the pedostructure can be obtained.

4. APPLICATION EXAMPLE

A pedological study in Tunisa of the irrigated perimeter of Cebala in the Low Valley of Majerda highlighted four types of alluvial soils. all located in the alluvial plain of the Delta of the Majerda River, at 10 km from the sea (Braudeau et al., 2001). These soils are differentiated by their behavior in four alluvial soil groups as: (a) vertic; (b) calcareous: (c) weakly saline; and (d) loamy. Table 5 shows the soil bulk density Db at point D, Db= $1/V_0$. The water content at field capacity and permanent wilting point were estimated as $\theta_{Fc} = W_0/\rho_w V_0$ and $\theta_{pwp} = W_8/\rho_w V_8$. The values in brackets refer to water contents of the horizon:

$$(\theta_{PWP}) = W_B/\rho_w V_B^{hor}.$$

4.1. Pedotransfer functions for calculating FC and PWP (W_0 and W1.1)

Nine different PTFs are proposed to calculate θ_{Fc} and θ_{PWP} from soil texture, the results of which are given directly in volumetric water coment (m³ m3)_They are

Table 5
Physical properties of the four alluvial soil

	Clay (%)	Fine silt (%)	Coarse silt (%)	Fine sand (%)	Coarse sand (%)	Db (kg dm-')	Or,c (m3 m 3)	OP>I' (m3 m-3)
Chalcareous	25	41.5	16.5	II	2	1.14	0.41	0.12(0.13)
Weakly saline	28.6	32.4	16	18.4	1.4	1.32	0.38	0.12 (0.13)
Loam	23.6	18.4	19.4	34	1.6	1.4	0.34	0.1I (0.11)
Vertie	31.4	53.8	6.4	5	0.67	1.24	0.43	0.15 (0.16)

Values in brackets correspond to 0pfp of the horizon at point B.

estimates of -33 kPa and -1500 kPa pressure plate water content, respectively. Results of these nine PTFs estimates for both moisture levels will be compared to the values of W_0 and W_8 derived by retractometry for the four soil types of Table 5. Results are shown in Figure 4. The volumetric water contents at field capacity (33 kPa) and wilting point (1500 kPa) for the four soil types using nine PTFs are presented along with the results given by retractometry (Table 5). The SOILPAR computer code (Acutis and Donatelli, 2003) was used to generate the soil moisture values with nine PTFs. In the figure, SC(!) represents the volumetric water content of the pedostructure (W_0/V_0 and W_8/V_8); and SC(2) represent�the volumetric water content associated with the volume of the horizon (W/Vhor with Vhor (2Vo + V)/3).

4.2. Values of LSmod for the four types of soil

LSmouwas calculated using the SC measurement instead of the standard test described by McKenzie et al. (1994). The specific volume of the wet sample cVmoi<1) in the LS_{11100} measurement is. in fact. the volume of the measuring cell divided by the weight of dry soil.

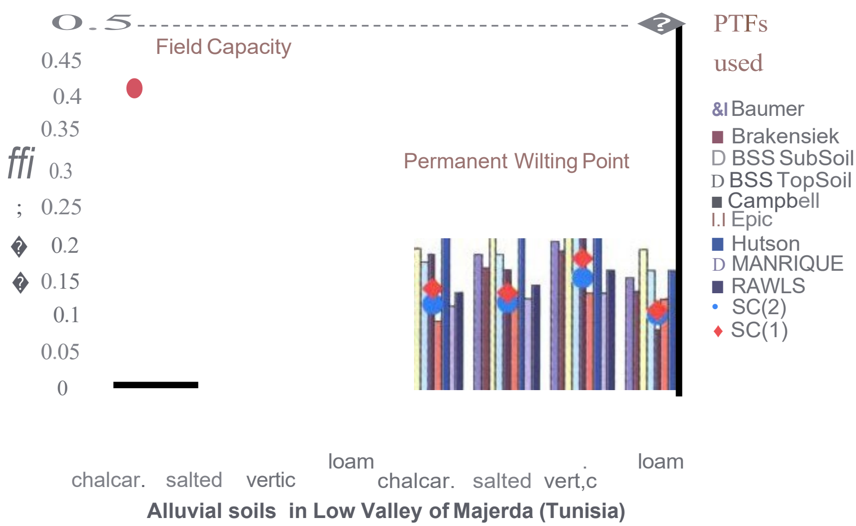

Figure 4. Comparison of field capacity and pennanent wilting point values calculated using the nine PTFs proposed by SOILPAR (Acutis and Donatelli, 2003) with those determined by the SC (Braudeau and Donatelli, 2001).

Thus, two parameters, Vu(= VA = $VN_,$), and VE(= V_0 = $VM_,$) are obtained as result of the test, instead of only $LS_{111}od$ = (Lmoisi -Ldry)/Lmoisi·

4.3. Value of Kbs as a function of texture

The multiple regression carried out in the pedological study of the irrigated perimeter ofCebala (Braudeau et al.. 2001). between K_{bs} and clay (<2 mμ) and silt (<50 mμ)and sand (> 50 mμ) contents yielded:

$$Khs = 0.0 I?(Clay+ silt)+ 0.006sand - 0.36$$

with a coefficient of regression R^2 = 0.89 for 26 observations. This relation can be used as a PTF for Kbs·

4.4. Equations used to build the shrinkage curve

Equations relating the parameters of the SC which make it possible to calculate the six basic parameters, *VN'*, VM,, *WN, WM, kN,* and *kM,* to model the SC arc derived from the relationships between shrinkage characteristics given in Table I (Braudeau et al., 2004; Braudeau and Donatelli, 200I):

$$WM= 0.42WI) + 0.58Wc \qquad WN = 0.42WA + 0.58Ws$$

$$kM = 3.46 \log 2/(Wc - WM) \qquad kN = -4.8 \log 2/(WA - WN)$$

$$Ws/Pw = 0pwpVB \qquad W_D/\rho_w = \theta_{FC} V_{M'} \qquad (V_{M'} - V_{N'})/(W_M - W_N) = K_{bs}$$

$$W_C = W_M + (V_C - V_{M'})/K_{bs} \qquad W_B = W_M + (V_B - V_{M'})K_{bs}$$

EAW = I /3 UW (estimated using the agronomic relation used between the easily available soil water and the useful soil water) *(0c -* 08) = 1/3(0D - 08) that

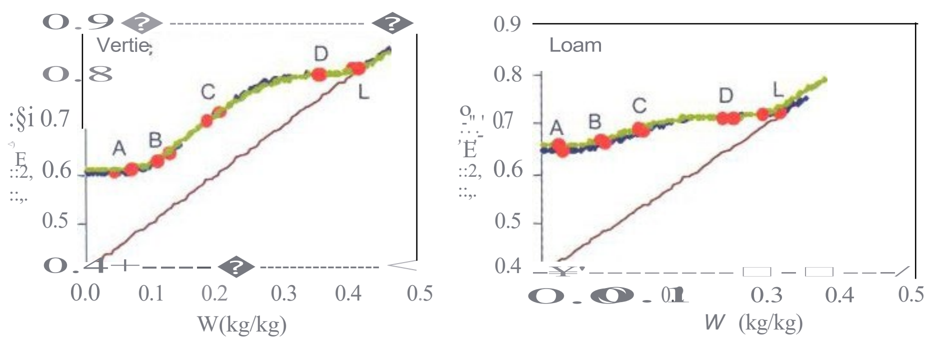

Figure 5. Superimposed observed (blue) and simulated (green) shrinkage curves from texture data, bulk density, and COLErod• The observed and calculated transition points are also shown.

corresponds to

$$W_C/\rho_w = \theta_C V_C = (W_D + 2W_B)/3$$

that gives IO equations with 15 unknowns.

Five variables have to be estimated to determine the others. That can be 0rwr, 0Fc and Kb, using texture, and the most and dry specific volumes (V,111, *VN')* using the linear swelling index (LSm00).

Figure 5 gives examples of the curves observed and simulated from primary data: the specific volume of the sample to V_0, at the holding capacity, COLE,00 and texture; V, is taken equal to 0.4 dm^3 kg- i. The �c and the Or,wr were calculated by the most suitable methods defined on Figure 4 (BSS TopSoil and Rawls).

5. CONCLUSION

A systemic, process-based conceptual model of the soil SC for characterizing and parameterizingthe soil-water medium is presented. The model demonstrated a unique link between soil water properties of non-rigid aggregated soil medium and its internal volume change. This leads to a physically based and functional model of the soil medium which can be used to accurately define and quantify commonly used field scale agronomic properties.

In this chapter, the required parameters for modeling the *in situ* soil hydro-structural properties are defined and calculated from the continuously measured SC. For cases where SC data is missing, approximate estimation of the soil-water medium parameters was developed and evaluated using texture, COLE, pf curve, field capacity and wilting point. Comparison of the SC estimates of agronomic parameters with some PTFs estimates of these parameters was presented.

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APPENDIX A. LIST OF PARAMETERS AND ABBREVIATIONS USED

The definition of the pedostructure variables and characteristics were presented in Braudeau et al. (2004), they are:

V	Pedostructure specific volume (dm^3 per kg of dry soil horizon)
Vm;	Primary peds specific volume (dm^3 per kg of dry soil horizon)
V,	Solids (primary particles) specific volume (dm^3 per kg of dry soil horizon)
Vp	Pedostructure pore specific volume (dm^3 per kg of dry soil horizon)
Ypma	Macro-pore specific volume of pedostructure (dm^3 per kg of dry soil horizon)

V_{pm};	Micro-pore specific volume of pedostructure (dm^3 per kg of dry soil horizon)
W	Pedostructure water content (soil moisture) (kg per kg of dry soil horizon)
W_{mi}	Primary peds water content (kg per kg of dry soil horizon)
W_{ma}	lnterpedal water content (kg per kg of dry soil horizon)
W_{rc}	Pedostructure residual water pool (kg per kg of dry soil horizon)
W_{bs}	Pedostructure basic water pool (kg per kg of dry soil horizon)
W_{st}	Pedostructure structural water pool (kg per kg of dry soil ho,izon)
W_{ip}	Pedostructure interpedal water pool (kg per kg of dry soil horizon)
A, B, C. D, E, F	Shrinkage transition points of the SC defined by the XP model
N'. M', L'	Intersection points of the tangents to the SC at the linear phases
N. M, L	Characteristic points of the SC at the vertical (y-axis) of **N', M',** L'
I_{st}, I_{bs}	Inflection points of structural and basic shrinkage phases
W_A, W_B... W_F	Pedostructure water content (kg kg^{-1}) at points A, B... F
W_N, W_M, W_L	Pedostructure water content (kg kg^{-1}) at points N, M, L
V_A, V_B... V_F	Pedostructure specific volume (dm^3 kg^{-1}) at points A, B... F
V_N, V_M, V_L	Pedostructure specific volume (dm^3 kg^{-1}) at points **N, M, L**
$V_{N'}$, $V_{M'}$, $V_{L'}$	y-axis values (dm^3 kg^{-1}) of points N', M', L' in the SC graph
K_{re}, K_{bs}, K_{st}, K_{ip}	Slopes of the SC linear phases (dm^3 kg^{-1})
k_N, k_M, k_L	Shape parameters (kg kg^{-1}) of the SC equation

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