Pore rigidity in structured soils – only a theoretical boundary condition for hydraulic properties?

R. Horn[A], S. Peth[A], T. Baumgartl[B], S. Gebhardt[A], H. Fleige[A], J. Doerner[C] and XH. Peng[D]

[A]Institute for Plant Nutrition and Soil Science, Christian Albrechts University zu Kiel, Olshausenstr. 40, Kiel, Germany, Email rhorn@soils.uni-kiel.de
[B]CMLR, University of Queensland, Brisbane, Australia
[C]Universidad Austral de Chile, Valdivia, Chile
[D]Institute of Soil Science, CAS Nanjing, China

Abstract

The quantification of fluxes in structured unsaturated soils requires rigid pore systems as the key background parameter. Swelling and shrinkage, chemical, mechanical, and biological processes alter the internal soil strength and consequently also the pore diameter, continuity and pore functions as soon as the structural shrinkage, or precompression stress is exceeded by a more intense drying, or the corresponding stresses applied. The absolute error in quantifying the water retention functions for sandy, silty, clayey, as well as peat soils will range in between 3–10 vol. % water which also results in a variation of the hydraulic conductivity/matric potential relation of up to 2–4 orders of magnitude up to pF 3.

Key Words

Rigidity of pores, water retention curve, hydraulic conductivity, shrinkage, soil aggregation

Introduction

Darcy's Law describes the 1-dimensional water flux under given boundary conditions which have to be fulfilled. Apart from this 1-dimensionality, also the laminar flow, inert properties, and complete pore rigidity are required in order to obtain validated results. Thus, these restrictions limit the applicability of the Darcy's Law mostly to coarse textured or coarse sandy soils (if no turbulent flow occurs), while silty, loamy, and clayey textured substrates mostly would not fulfill these boundary conditions. Most current approaches for calculating water flow are based on a mass balance equation and Darcy's Law. The use of material coordinates, instead of fixed spatial coordinates such as normally used for nonswelling soils, leads to a flow equation analogous to the Richards equation (Smiles, 2000). Thus, Darcy's Law relates the volume flux of water, q, to the gradient in the hydraulic potential and the soil hydraulic conductivity.

If arable, forest, or anthropogenic soils are considered it is obvious that aggregate formation due to wetting and drying as well as due to biological activity occur as soon as soils contain some clay, but even if soils are coarser but more saline or have more expansive clay minerals also remarkable cracks are to be detected and proof that volume changes and reformation of pores generally occur.

Generally, when matric potential decreases, menisci forces pull adjacent soil particles closer to each other and consequently decrease soil volume. Based on the findings of Baumgartl (2003), who described the parallelism of mechanical stress–strain curves and hydraulic stress (matric potential) and volume change behavior, Peng *et al.* (2007) showed that the link between the mechanical and the hydraulic prestresses result in nearly identical shrinkage curves. Additionally, Baumgartl (2003) explained the differences between the mechanically induced collapse and the matric potential dependent shrinkage pattern by the dimensionless X factor. Stange and Horn (2005) showed the effect of nonrigidity on hydraulic functions as well as they developed corrected model equations for homogenized substrates. In the present paper we therefore discuss the following hypotheses: 1) soil hydraulic properties are only reliable in the preshrinkage i.e. structural shrinkage range and depend on the in situ hydraulic history; and 2) exceeding the structural shrinkage range results in a new 3-dimensional volume decline and altered retention curve and conductivity pressure head relations.

Material and Methods

Several disturbed and undisturbed soil samples were taken from various soil profiles with different geological origin in Northern Germany under arable and pasture conditions: Stagnic Luvisol (*SS-LL*), Gleysol (*GGn*), Stagnosol (*SSn*), Tschernosem (*TTn*), Lowland peat (*HNn*), Histic Gleysol (*HN-GH*). Table 1 informs some physical properties of the investigated sites. Both the water retention and the shrinkage characteristics of these undisturbed soil core samples (v = 470 cm³) were determined after complete saturation by capillary rise and drainage to fixed soil moisture tensions.

Table 1. Soil types, texture (according to the German classification system), structure, and bulk density of the investigated sites.

abbreviation	texture	Structure	ρt	clay	fine	middle silt	coarse	fine	middle sand	coarse
				< 2	< 6,3	< 20	< 63	< 200	< 630	< 2000
			[g cm^{-3}]				[µm]			
SS-LL (15, 25)	**Su3**	**coh - subangular blocky**	1,59	7,4	4,3	6,6	16,5	29,7	29,0	6,5
SS-LL (35)	**Su2/Su3**	**platy**	1,73	4,3	2,6	7,6	14,3	31,1	32,8	7,3
SS-LL (50)	**Ls3**	**Subang. blocky**	1,68	20,4	8,6	11,9	18,1	22,1	15,1	3,8
SS-LL (75)	**Sl3**	**blocky– prism**	1,77	8,1	2,1	6,3	14	29,5	34,5	5,5
GGn (40)	**Tu3**	**coh– blocky**	1,46	34,9	17,1	20,5	20,1	5,8	1,4	0,2
SSn (50)	**Ts2/Tl**	**coh – blocky)**	1,72	64,9	9,1	3,7	2,2	8,7	10,4	1,0
TTn (40)	**Ut4**	**Subang. blocky**	1,45	19,24	23,54	44,19	97,93	98,64	99,49	100
HN (30)	**Torf**		0,81							
HN-GH (40)	**Lt3**	**Coh**	1,08	39,9	11,5	15,9	6,7	17,8	7,8	0,4

Key: SS-LL: Stagnic Luvisol, GGn: Gleysol, SSn: Stagnosol, TTn: Tschernosem, HNn: Lowland peat,
HN-GH: Histic Gleysol.

The used drainage steps were -3, -6, -15, -30 und -50 kPa with ceramic suction plates, 300, 600 und 1500 kPa with pressure chambers and 105°C in the oven. After each drainage step, the weight of every sample as well as the volume decrease due to shrinkage was measured assuming an isotropic i.e. identical vertical and horizontal deformation. The vertical height change was determined by a digital measuring caliper with an accuracy of 0.05 mm at eight fixed point at the sample surface. The total height change was then calculated from the arithmetic mean of these eight values. The change of sample height multiplied by the actual surface area gives the vertical volume change. The saturated hydraulic conductivity was determined under instationary conditions (Hartge 1966). The hydraulic conductivity/ matric potential ratio was determined and calculated for undisturbed samples via 2 microtensiometers and 2 TDR probes inserted in a vertical distance of 2 cm.

Results

In order to test the assumption that the 3-d shrinkage can be taken as isotropic, we chose the weakest soil samples from the Histic Gleysol with coherent structure (Figure 1). It is obvious that the pattern of the retention curves without consideration of the volume loss due to soil shrinkage results in a complete misinterpretation of corresponding ecological data for the soil volume like the air capacity (from saturation to pF 1.8) or plant available water capacity (from pF 1.8–4.2). If the vertical shrinkage is considered the air capacity values decrease while the amount of plant available water increases. If finally the 3-d shrinkage is determined and included in the calculations we can find a further decline in the air capacity and even in the plant available water capacity values, while the amount of fine pores in the soil sample increases.

The shrinkage curves for all analyzed soil samples are shown in Figure 2. The Stagnic Luvisol SS-LL (15–75) had the smallest shrinkage behavior at all depths (not shown) but the 4 shrinkage ranges can still be differentiated. Thereby the samples taken from the ploughed layer SS-LL (15, 25) are more sensitive to volume changes while with increasing bulk density and/or stronger aggregation the volume reduction decreases. With increasing clay content (> 30%) very pronounced shrinkage curve ranges can be detected (Figure 2). It becomes obvious, that the moisture ratio ranges for the structural shrinkage differ with soil aggregation and therefore also with the previous drying history derived from the general description of the sites. The Axh horizon from the Tschernosem with subangular blocky structure is characterized by a large structural shrinkage range, i.e. it shows a very rigid pore system, followed by a small proportional shrinkage and a well defined residual and zero shrinkage range, while both the Gleysol samples and especially those of the Stagnosol show a very pronounced proportional shrinkage range but only a small structural shrinkage behavior. Both curves show similar residual and zero shrinkage patterns.

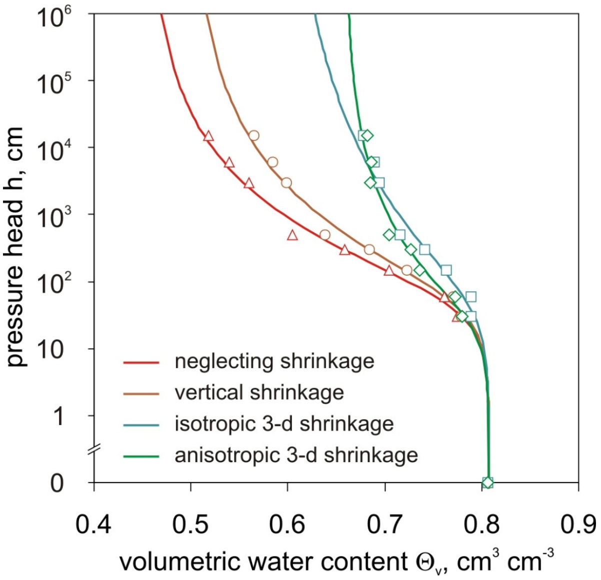

Figure 1. Effect of soil shrinkage on the pattern of the water retention curve of the peat clay (HN-GH). The differences in the water contents at given matric potential hPa (i.e. pressure head cm) is obvious and also proves the assumption of nearly identical curves for the 3-d shrinkage behavior.

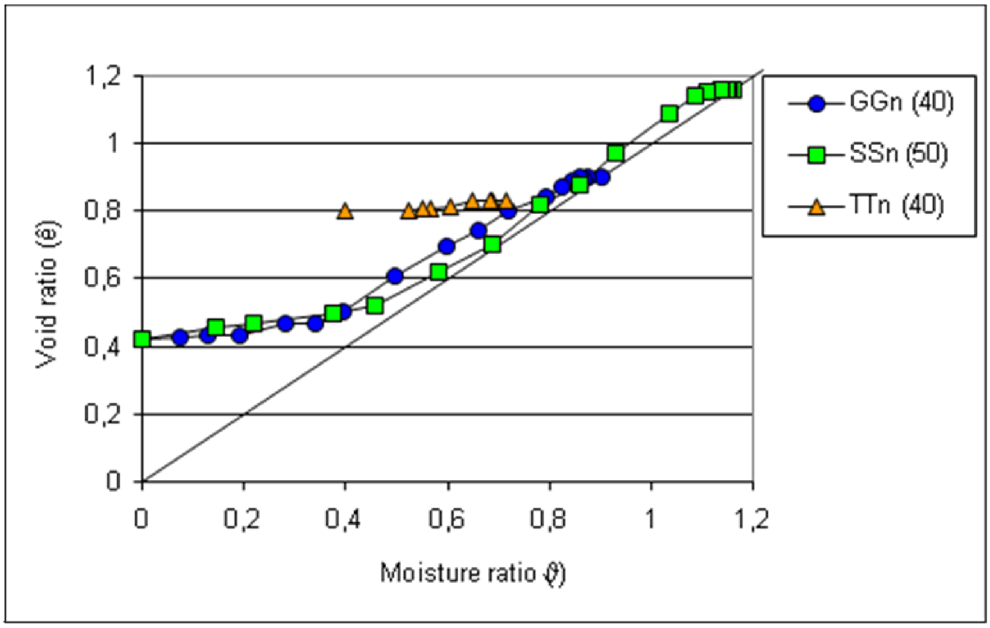

Figure 2. Shrinkage curves of selected soil horizons of the Gleysol (GGn), Stagnosol (SSn) and the Tschernosem (TTn). The number behind the abbreviation defines the soil depths.

The calculated theoretical water content loss due to shrinkage reveals severe differences between the analyzed soils. We can find for the soils with higher clay content and/or less pronounced soil aggregation an increased “misinterpretation of the retention data as soon as the soil samples dried out more than to -200 hPa.(Fig.3) The Axh horizon of the Tschernosem with a subangular blocky structure showed a strong rigidity with negligible small shrinkage induced “water loss”, while the actual shrinkage induced changes in the available pore space approached even 12% at pF 4.2 for samples with smaller aggregate strength (e.g. coh) and increasing organic carbon content. The high values for the lowland peat samples with more than 10% at pF 4.2 demonstrated also the influence of the low bulk density on shrinkage induced misinterpretation. If the HNn and the SSn curves are compared it becomes obvious that even a very high bulk density does not always coincide with high internal soil strength (cf. bulk density 0.81 and 1.72 g/cm³ in Table 1).

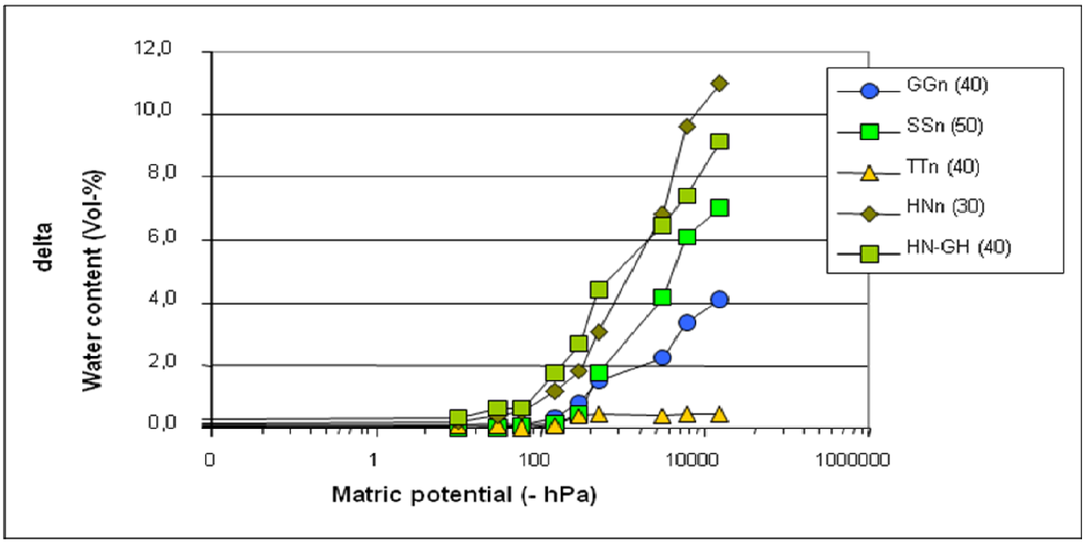

Figure 4. Calculated water loss due to shrinkage as a function of matric potential.

At a given bulk density of approx. 1.45 g/cm³ is the shrinkage induced volume loss (calculated as water loss) more pronounced in the GGn with up to 4% due to a weaker soil structure as compared with the TTn samples.

These nonrigidity effects also alter the pattern of the hydraulic conductivity matric potential curves revealing that if curves are derived from alpha, n and m values together with the measured ks value (van Genuchten/Mualem approach) a strong discrepancy to measured curves occurs.

Three general effects can be defined for these curves:

- If soils are mostly rigid (demonstrated e.g. by the SS-LL and TTn samples) we cannot detect any effect of shrinkage on the calculated curves as they are identical. The introduction of reduction factors for ks only results in a parallel shift of the curves.
- If shrinkage induced changes in the soil/or pore volume and pore size distribution occur, differences between the measured curves with and without actual shrinkage consideration result in a pronounced curve pattern variation. Thus, some remarkable differences can be derived. If shrinkage is neglected in the measured curves, the pattern is mostly parallel to the calculated ones, while if the actual shrinkage process is included when calculating the actual curves, they bend only intensely after exceeding the structural shrinkage range. This matric potential can be therefore also considered as a rigidity index.
- At the transition to the proportional shrinkage range we can also find a corresponding increase in the number of grain contact points.

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