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Article Title

00243 Shrink-Swell processes in soils

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Abstract

Soil shrinking and swelling with water, leading to crack formation, is the primary abiotic soil structure forming process. Shrinking is mostly due to the soil colloids forming the soil *plasma*, which produces a characteristic shrinkage curve (SC) on drying. Soil shrinkage has physical, geotechnical and pedological applications with relevance to (i) its impact on soil hydrodynamics (preferential flow in cracks and changes in the hydraulic characteristics) and (ii) improved impact diagnosis and upscaling of physical properties by deterministic SC modelling. In natural soils, organic matter and aggregation affect shrinkage and therefore the development of soil structure by drying and wetting.

Keywords

Colloids, non-rigid soils, plasma, shrinkage, structure, structural pores, hydrodynamics, by-pass flow, modelling

Key points

- All soils containing colloids show a shrinkage curve
- The characteristic shrinkage curve (SC) on drying should be considered in the hydrodynamics of non-rigid soils
- SC deterministic modelling allows characterization of the plasma and structural pore systems
- SC analysis allows improvement in the soil physical characterization of the soil
- Applications in hydrodynamics: non-rigid soils, by-pass flow
- Applications in structure characterization, compaction diagnosis
- Spatialization and dynamics of soil physical properties

Glossary

COLE: Coefficient of linear extension
Plasma: That part of the soil solid material that is easily deformed, reorganized or concentrated by the processes of soil formation. It includes all the material, mineral or organic, of colloidal size and relatively soluble material that is not contained in the skeleton grains.
Structural porosity: pore system made of the biopores, the cracks and the packing voids.

Introduction

Most soils show shrink-swell behaviour, induced by the forces resulting from changes in water content and their impact on pore volumes. The extent of soil shrinkage is generally defined as the bulk density or specific volume change of soil relative to its water content (Haines, 1923). It is, therefore, a physical property of undisturbed soil structure that has a large impact on a range of soil processes, especially pore structure dynamics and transport. The volume change with water content is due to the shrinking and swelling of soil constituents and their structural arrangement.

Soil shrinkage has been studied for more than a century and was first considered as an indicator of soil structural stability. It is evident in some soils by the creation of cracks, which is considered as the primary and major abiotic process of soil structure formation (see Soil Structure section). Vertisols, for instance, shrink extensively during drying, which provides one of the key diagnostic features of their classification. During the 20th century, the scope of interest in soil shrinkage widely increased in soil science and civil engineering. In engineering applications, the question is mostly related to heavy swelling-clay soils whose shrinking properties may severely damage buildings. In soil science, the investigations covered a wide range of topics, ranging from a fundamental understanding of pedogenic processes to applications in understanding water flow, structural stability or pore structure dynamics. Soil scientists have explored the role of soil constituents in soil shrinkage, observing a characteristic shrinkage curve (SC) that relates specific volume (or bulk density) of the soil to its water content. Using the shrinkage curve in modelling and analysis has applications in soil physics and soil physical characterization from the aggregate to field scale. There is capacity with soil shrinkage modelling to bridge the knowledge on soil fabric, soil constituents and soil hydrodynamics. In shrinking soils, hydrodynamics is affected by both matric potential draining soil pores and changes to the size of pores from shrinkage. Although the former process is studied extensively in soil physics, the second process is often overlooked, so soil shrinkage modelling plays an important role in overcoming a major limitation faced by soil physics.

Origin of soil shrinkage

If we revisit the example of Vertisols, their large macroscopic shrink-swell behaviour is closely related to their large content of swelling clays (see Pedology section in this Encyclopedia). Seasonally dependent crack networks develop in these soils with cycles of wetting and drying. Smaller concentrations of swelling clays and other colloids observed in other soils results in less shrinkage, leading to smaller size cracks whose network may only be observable on thin sections. Mineral soils are formed of voids, skeleton grains, and colloids, namely clay minerals bound to soil organic carbon (SOC) and oxides forming the soil *plasma* ("Glossary of Soil Science Terms | Soil Science Society of America," 2020). The plasma consists primarily of domains of silt- and clay-size particles coated with SOC and oxides. It comprises small (nm to μm) interparticle pores. Because clay particles are major constituents of the plasma, it is also referred to as the clay matrix, clay phase, or organo-mineral complex. Clay minerals and SOC shrink and swell with changes in water content. The shrinkage behaviour of clay pastes has been well described and depends on the clay mineral properties (e.g.Tessier, 1990). The shrinkage of the soil, therefore, depends on the clay content, clay type,
SOC and oxides acting as binding elements, thus limiting the shrinkage of the plasma (Boivin et al., 2009, 2004; Goutal-Pousse et al., 2016).

As a structured medium, the soil has a porosity. Various classifications of soil pores based on size classes have been proposed (see Soil Structure section). Size classes are user, tool, and scale dependent. Therefore, they do not reflect intrinsic properties of the structured soil and its materials. Soil shrinkage occurs at the expense of soil porosity and is, therefore, related to the nature and behaviour of the soil pores. Soil pore size distribution, shape, and connectivity have been investigated for their implications in transport properties or as habitat of soil biota.

At its simplest, a rigid, homogeneous, and uniform pore network has been assumed in water transport modelling, but structural complexity of the pore network has become increasingly appreciated and feasible to model with higher speed computers. The deformation of the structure, especially its changes due to shrinkage, is often overlooked.
The solid material (either minerals or organic matter) and pore system together constitute the soil fabric. The physical structure of the soil fabric was long ago described by micromorphologists (e.g., Brewer, 1964), which allowed identification of two categories of soil pore systems, based on their origin, shape and function; namely the structural pores and the plasma pores. Plasma pores are equivalent to textural porosity, which refers to the clay pores and the lacunar voids between skeleton grains and the clay matrix. Taking this approach, the structural porosity includes cracks, biopores, packing voids and vughs. Because of their origin, plasma pores are sub-µm, while the volume of structural pores is mostly represented by pores larger than 5 µm.
The structural and plasma pores show distinct shrink-swell behaviour upon changes in soil water content. From saturation to the *Air Entry (AE)* point, no air entry occurs in plasma pores (Tessier, 1990). Therefore, the plasma pores remain saturated along the corresponding water content range, and the clay paste volume follows a 1:1 line with the water content (Figure 1), until AE is reached, which may account for a large soil shrinkage in swelling clay soils. In contrast, air enters into the structural pores upon soil drying, and water menisci exert a shrinkage pressure on the soil by Jurin's law of capillarity and approximated by the Laplace equation.

a supprimé: Figure 1

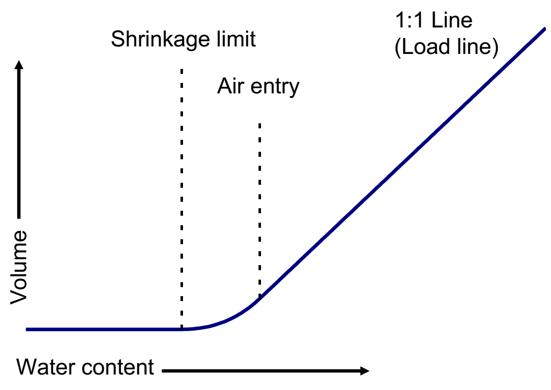

Figure 1 Schematic shrinkage curve of a clay paste.

Basics of soil shrinkage

Soil shrinkage was studied early in the early 20th century for its impact on soil structure, including disputed roles of colloidal coatings (Haines, 1923; Hardy, 1923). Later, soil shrinkage was investigated for geotechnical problems like foundation integrity or in soil science as an indicator of structure stability (McGarry and Daniells, 1987). The concept of linear extensibility was introduced to characterize the one-dimension change of soil with water content, which is usually quantified with the Coefficient of Linear Extensibility (COLE) (Grossman et al., 1968):

$$COLE = \frac{L_m}{L_d} - 1 \qquad \text{Eq. 1}$$

where L_m is the length of the moist soil unit and L_d is the length of the dry soil unit. COLE indicates the potential of the soil to shrink and swell with water. As the extent of shrinkage can results in soil layer cracking and soil subsidence, there is a great interest in measuring COLE for engineering or preferential flow modelling (Coppola et al., 2015). COLE is used in soil classification to categorise shrinking soils such as Vertisols, which require at least 0.06 mm m^{-1} linear shrinkage in their characterisation. Testing of COLE is simple. It involves filling a trough of soil with a remoulded soil paste and then measuring the length change after the soil has been dried. However, shrinkage is a volumetric, so the volume change is related to the COLE by:

$$\frac{dV}{V} = \left(\frac{dL}{L}\right)^n \qquad \text{Eq. 2}$$

with V, the soil specific volume ($cm^3\ g^{-1}$), L the soil length, and n the geometric factor (Towner, 1986) with n= 3 in case of isotropic shrinkage.

Using a remoulded paste, however, destroys soil structure. Because of the strong relationship between soil structure and soil SC, COLE is much more descriptive of realistic field conditions if it is measured on undisturbed soil, contrary to what is sometimes practiced in geotechnical engineering for clayey materials.

COLE measures the extremes of shrinkage between maximum wetness and dryness. The availability of quasi continuous SC measurement techniques over a range of water contents on undisturbed soil cores allows for the general shape of the soil SC to be split into different linear domains with curvilinear transitions (Braudeau et al., 2004) (Figure 2). These main domains, from water saturation to air dry, are the structural, basic and residual shrinkage domains. In some soils, however, an additional swelling domain is observed close to water saturation and was interpreted as a property of poorly aggregated soil. Another sharp shrinkage domain has been observed near to the air-dry state in Swiss and Canadian soils with large SOC content (unpublished). Despite these possible additional domains at the two ends of the SC, most of the water content change is observed from structural to residual shrinkage. The magnitude of these domains depends on soil type and colloid content, though the S-shape is characteristic of many soils e.g., in Vertisols, Calcisols, Cambisols, Luvisols, Ferralsols etc.

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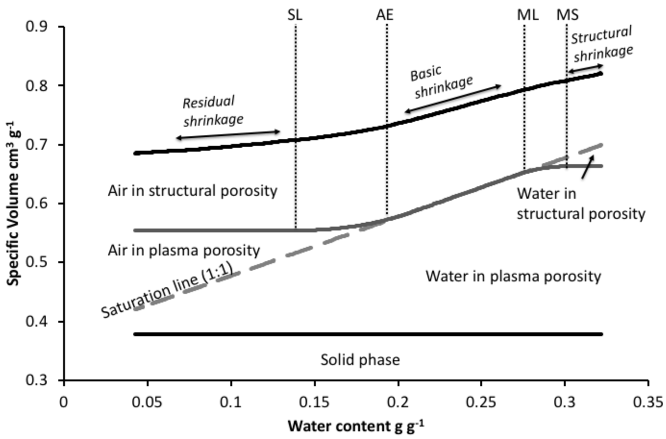

Figure 2 Cambisol shrinkage curve showing the typical S shape, soil shrinkage domains, water saturation line and distribution of air and water in the pore systems (Braudeau et al., 1999).

The structural shrinkage occurs primarily due to the drainage of structural pores. Its slope has been related to soil structural stability since it depicts the capacity of the structure to withstand the menisci forces. The basic shrinkage (Figure 2), also referred to as proportional shrinkage (Mitchell, 1992), is related to the proportional shrinkage of the clay. For clay, this slope is equal to 1 (Figure 1), but for structured soil it usually ranges from less than 0.1 to more than 1.5, depending of the tendency of the structure to collapse or to remain rigid upon plasma shrinking. Therefore, for the same plasma shrinkage, the lower the soil shrinkage slope, the denser the crack network in the soil and the greater its volume.

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Shrinkage measurement

Soil shrinkage can be measured *in situ* using displacement transducers that record the movement of gauges inserted at different depths (Coquet et al., 1998), though this is technically demanding and difficult to interpret. However, shrinkage is mostly measured on extracted undisturbed cores or clods. Once soil is removed from its environment, however, the overburden pressures of the overlying soil layers is not accounted for. Different devices have been proposed in the last decades to measure the shrinkage of clods, allowing high accuracy and quasi continuously measurement of SC. Examples include laser barriers (Braudeau et al., 1999), displacement transducers (Figure 3) (Boivin et al., 2004; Schindler et al., 2015) and X-Ray CT (Peth et al., 2010). Linear or circumference changes are converted into volume change using Eq. 2, with estimation of the geometric factor when the soil wet and dry volumes are measured. The geometric factor of soil cores has been generally reported to be close to 3 on average, though its value changes along the SC (Boivin, 2007).

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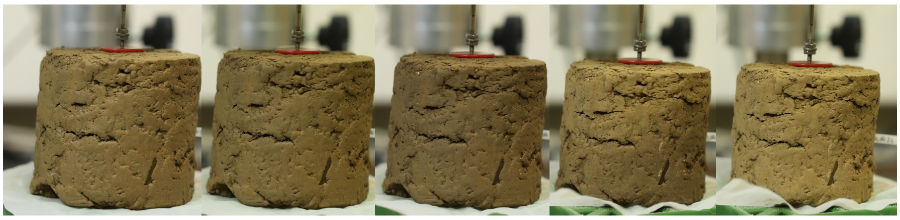

Figure 3 Undisturbed cambisoil sample shrinking from -10 hPa (left) to air-dry (right) in a shrinkage apparatus (Schäffer et al., 2008). *Note the displacement transducer on the top of the sample (picture C. Deluz).*

Shrinkage modelling

Shrinkage modelling was performed early in soil science, with the aim of quantifying the structural stability of the soil. In past decades models were proposed that took benefit from the high quality SCs obtained with quasi-continuous SC measurement devices. Two categories can be distinguished. One category of equations aims to reproduce quantitatively the SC, for instance to account for its influence on hydraulic conductivity (Horn et al., 2014). Due to the characteristic S-shaped curve of the SC, one approach modified the Van Genuchten equation. Another category is deterministic models based on considerations of the nature and behaviour of soil pores, accounting for the properties of plasma and structural pores with decreasing water content, as presented above. In the first category of equations, the number of parameters conditions the ability of the model to reproduce the observation, which opposes the objective of using a minimum number parameter.

Deterministic models have been proposed from particle scale to layer scale, with special emphasis on clod scale. The most developed models (Braudeau et al., 2004, 1999; Chertkov, 2012) are based on common concepts, namely soil SC accounting for the combined effect of shrinkage of plasma (that can be referred to as clay matrix or microporosity) and structural pores. The shrinkage of plasma is considered, as depicted in Figure 1, and that of the structural porosity, including cracks, drains with soil drying with limited deformation, being accounted for by the slope of the structural shrinkage (Figure 2). To our best knowledge, model comparisons have rarely been performed on high resolution SCs (Boivin et al., 2006), therefore, we will not discuss this aspect further.

In Boivin (2007), the clay pastes sub-model of Chertkov (2012) and Braudeau et al. (1999) were found to be extremely close, thus implying a similar modelling of the complementary structural porosity volume for successful fitting. However, only the XP model (Braudeau et al., 1999) has been successfully applied to a large number of undisturbed sample series from different soil types. The thermodynamic formalism of the soil shrinkage proposed by Braudeau et al. (2014) is based on previous research starting with Sposito (1972). Based on the two-pore systems description, it yields results close to those obtained with XP. Note that overburden is not taken into account in this model, thus applicable to isolated soil structure units.

Properties and processes affecting shrinkage curves

Soil shrinkage is affected by clay type, clay content, iron and aluminium oxides, SOC content (see above) and carbonate content (Zolfaghari et al., 2016). These factors show linear relationships with the shrinkage parameters as determined with the XP model, or modified Van Genuchten equation of shrinkage. For instance, shrinkage increases with clay content and decreases with SOC and iron oxides contents, whereas the structural pore volume and the readily available water increase with SOC content. In that respect, the spatial variability of soil colloids allows one to account for the spatial variability of soil physical properties. Moreover, the coefficients of variation (CV) of the SC parameters (XP model) are very small

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(from 7 to 14%, Boivin, 2007; Boivin et al., 2006) compared with CVs for most soil physical parameters reported, thus opening the door to effective mapping of the soil shrinkage properties and derived pore systems parameters.
Soil shrinkage is also affected by external factors such as cropping practices, trafficking or biological activity, and shrinkage modelling has been used to determine structure degradation indicators (Johannes et al., 2019), to characterize tillage effects (Mallory et al., 2011), soil compaction (Peng et al., 2009) and structure recovery (Fell et al., 2018; Goutal-Pousse et al., 2016), or the effect of soil biota on soil structure (Milleret et al., 2009). Fitting XP on soil SCs allowed a distinction to be made between the effect of soil constituents, their variability, and factors such as trafficking on biological activity, thus allowing for improved field diagnosis.

Significance

Many developments in soil physics require assumptions about the pore network, such as homogeneity and rigidity, to simplify the numerical solution of the equations. These assumptions oppose the known behaviour of structured soils containing colloids, i.e., non homogeneous and uniform pore network, and geometry changes with water content. This has raised many issues in application, particularly in parameter estimation and mapping. The physical properties, as determined according to mechanics theories, exhibit large variability, unstable variances with measurement device size, and poor correlation with the distribution of soil constituents. The developments of pedotransfer functions (Bouma and van Lanen, 1987) are aimed at bridging the resulting gap between soil physical properties and easy to map soil properties, in particular colloid content, by establishing local correlations. To some extent this can be considered doomed to failure owing to the fundamental contradiction between soil mechanics assumptions and soil properties. With that respect, one may consider the development of shrinkage modelling as a promising way to bridge this gap.
Fluid transfer modelling equations including the shrink-swell properties of the soil were proposed (Garnier et al., 1997). However, the soil volume change with water remains seldom considered in fluid transfer modelling despite its strong impact (Horn et al., 2014). The introduction of shrink-swell properties in water transfer models allows the dynamic accounting of preferential flow at layer scale (Coppola et al., 2015). A full modelling method including (i) overburden (Smiles and Raats, 2005), (ii) preferential flow in cracks and (iii) the dual porosity (accounting for transfers between plasma aggregates and structural pores) is still to be formulated.
Significant progress in soil structure characterization has been gained with shrinkage analysis. In the context of climate change, and SOC depletion leading to poor quality soils, it is of key importance to improve our capacity to monitor and model changes in soil physical properties. For instance, shrinkage analysis allowed to emphasize the role of SOC in soil structure and soil porosity development (Boivin et al., 2009), to propose improved soil compaction diagnosis (Goutal-Pousse et al., 2016; Schäffer et al., 2008) and effective structure degradation indicators (Johannes et al., 2019).

Perspectives

In re-designing water transfer models at profile scale, taking into account soil shrinkage is essential. Addressing this challenge requires growing interest in developing deterministic shrinkage models, which include the two-soil pore-systems (structural and plasmic) and their response to changes in soil constituents (particularly SOC content). This opens the door to models that are capable of dynamic adaptation of soil physical properties to e.g., soil management, and to sharply improve model parameter spatialisation.
To do so, research is needed that can fill the known and suspected knowledge-gaps remaining. For example, the deterministic models of shrinkage include a transfer of water from plasma

porosity to structural porosity, which needs to be further investigated (Barbosa et al., 2022), and overburden should be included in the description of water potential and confining stresses from the surrounding soils that would be found in the field.
Another perspective is to improve our understanding of soil complex processes. The role of structural porosity in microorganism activity and the related carbon or nitrogen cycles has started to be deciphered, in particular with imaging technology (Kravchenko et al., 2019). Changes to soil pore structure with shrinkage is likely to have a large impact on microbial habitats, activity and physical protection. Such a fundamental knowledge is key to our understanding of soil ecosystem services management, particularly in cropland, but it is hard to study *in situ* and at large scale. On the other hand, shrinkage analysis does not allow the capture of fine structural pores architecture, but it does allow precise, inexpensive quantification of fine structural pore volume, size distribution, and their relationships with constituents and practices at large scale. Therefore, research on the links between fine structural porosity architecture and the shrinkage signature of soil structure should be worked out. The impacts extend beyond physical processes, including the capacity of soil pores to support biological activity and diversity, but shrinkage impacts have been overlooked.
Finally, though deterministic modelling of soil SC seems more promising, the models are based on assumptions that have been only partially validated, at best. If the above perspectives stand, it is of critical importance to progress in deterministic SC modelling associated with a fully validated physical formalism of the underlying processes.

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