SOIL MICROMORPHOLOGY, SOIL STRUCTURE STABILITY AND SOIL HYDRAULIC PROPERTIES

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Abstract

Soil micromorphological properties were studied to explain soil structure stability and define configuration of a soil porous system that is reflected in a shape of soil hydraulics properties. The study was performed in six soil profiles. Micromorphological properties characterizing soil horizons specified for each soil type were studied on soil thin sections prepared from large soil aggregates. The stability of the soil structure was investigated using two different methods that are usually used to study aggregate stability under the different destruction mechanisms. Soil structure stability varied within the soil profiles depending on organic matter content, presence of clay coatings and fillings, existence of different forms of CaCO₃ and presence of iron oxides. The ARCGIS raster processing tools were used to analyze pore areas and perimeters on soil images taken at one magnification at resolution of 300 dpi. The shape factors were calculated to divide pores into different shape groups. The micromorphological study of soil porous systems in many cases discovered multimodality of soil porous system. Soil water retention curves were determined using the sand tank and pressure plate apparatus. The saturated hydraulic conductivities were measured using the constant head test. The multi-step outflow method was applied to estimate soil water retention curves and unsaturated hydraulic conductivity curves via numerical inversion. Some of the retention curves display multimodality. One application of the single-porosity and dual-permeability model in HYDRUS-1D (Šimůnek et al., 2003, 2005) for description soil water flow and soil hydraulic properties is shown in this study.

Keywords: soil micromorphological properties, soil structure stability, soil porous system, soil hydraulic properties, single-porosity and dual-permeability models

Introduction

Different compositions of varying soil structure components resulted from pedogenesis and soil management are reflected in many soil properties including the aggregate stability, configuration of the soil porous system and soil hydraulic properties. Soil aggregation is under control of different mechanisms in different soil types. Flocculated clay particles, or their complexes with humus (organo-mineral complexes) and soil organic matter act as main cementing agents in soil aggregates development. The cementing effect of free Fe and Al oxides is important in soils with low organic matter content (Six et al., 2002). Generally, level of aggregation and stability of aggregates increases with increasing organic matter content, surface area of clay minerals and cation exchange capacity

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Next to the soil properties, soil management has also very important influence on soil structure stability. By tillage the topsoil is mixed and still new aggregates are exposed to different breakdown mechanisms (Six et al., 1998). Soil processing at improper soil moisture, crossing of heavy machinery, irrigation, and peptisation effect of fertilizers has also negative influence on soil structure (Pagliai et al., 2003, 2004 and Servadio et al., 2004).

Soil porous systems are influenced by similar factors, including the mineralogical composition, stage of disintegration, organic matter, soil water content, transport processes within the soil profile, weather, plant roots, soil organisms, and management practices. Shapes and sizes of soil pores may be studied on images of thin soil sections, taken at varying magnifications. Pore systems with macropores and their impact on saturated hydraulic conductivities, $K_s$, were previously explored by Bouma et al. (1977, 1979). Differently shaped pores in soils under different management practices and their $K_s$ values were studied by Pagliai et al. (1983, 2003, 2004).

Soil structure stability and configuration of soil porous system affect the entire shape of the soil hydraulic properties. Soil water retention curve $h(\theta)$ and unsaturated hydraulic conductivity curve $K(h)$ have been usually assumed to have a single S-shape. The multimodality of soil porous system is reflected in multiple S-shaped curve, e.g. curve with more then one inflection point. The multimodality of soil hydraulic properties was previously discussed by Othmer et al. (1991), Durner (1994), Durner et al. (1999) or Kutílek (2004). However, they only used the multimodal concept for description of the soil hydraulic properties without considering flow and transport. On the other hand, the two continuum approach may be applied to describe a non-equilibrium flow and transport.

Mathematical description of the equilibrium water flow and solute transport assumes a single continuum approach. To describe the non-equilibrium water flow and solute transport in soils, numerical models that assume two continuum approach have been developed. Soil porous system is in such models divided into two domains. Each domain is characterized with its own set of transport properties and equations describing transport processes. Dual-porosity approach defining a water and solute transport in systems consisting of domains of mobile and immobile water was presented by Phillip (1968) and van Genuchten and Wierenga (1976). The dual-porosity formulation for water flow and solute transport is based on a set of partial differential equations describing water flow and solute transport in the mobile domain and mass balance equations describing moisture dynamics and solute content in the immobile domain. On the other side, dual-permeability approach assumes water flow and solute transport in both domains. The dual-permeability formulation for water flow and solute transport is based on a set of equations describing water flow and solute transport separately in each domain (matrix and macropore domains). Different equations may be used to simulate water flow in the mobile and macropore domains. A kinematic wave approach was used by Germann (1985), Hermann and Beven (1985) and Jarvis (1994) to describe flow in macropores. The Richards equation was used by Gerke and van Genuchten (1993, 1996) to describe flow in both matrix and macropore domains. Other approaches can be based on Poiseuille equation (Ahuja and Hebson, 1992), and Green-Ampt or Philip infiltration equations (Ahuja and Hebson, 1992; Chen and Wagenet, 1992).

Study presented here was performed to utilize micromorphological properties for assessment of soil structure stability, evaluation of soil porous system and subsequently for analysis of the soil hydraulic properties.

**Material and methods**

**Soil type definition**

This study was performed in four different soil types. Undisturbed large soil aggregates, undisturbed 100 cm$^3$ soil samples and disturbed soil samples were taken from each horizon that were specified for each soil type. Micromorphological properties characterizing soil porous structure were studied on the soil thin sections prepared from the large soil aggregates. The soil properties like particle size distribution, organic carbon content, cation exchange capacity, pH$_{KCl}$ were studied on disturbed samples.
Soil structure stability

The stability of the soil structure was studied using two different methods. First the water stable aggregates were determined using the following procedure (Nimno and Perkins, 2002). Four grams of air dry soil aggregates (segregates) of size 2 – 5 mm were sieved 3 minutes in distilled water (sieve 0.25 mm). Next the aggregates remaining on sieve were sieved in sodium hexametaphosphate until only sand particles were left on the sieve. The indexes of water stable aggregates were determined as the weight of aggregates dispersed in dispersing solution divided by sum of the weight of aggregates dispersed in dispersing solution and the weight of aggregates dispersed in distilled water. The method proposed by Le Bissonnais (1996) was also used to study destruction mechanisms like slaking due to compression of entrapped air, micro cracking due to different swelling, mechanical breakdown, physico-chemical dispersion due to osmotic stress. The fast wetting, slow wetting and shaking after pre-wetting tests were applied. However results of those tests are not shown in here.

Soil porosity

The soil porous system was analyzed using the similar procedure that was presented by Rösslerová - Kodešová and Kodeš (1999). Images of the investigated soils were taken at one magnification at resolution of 300 dpi. To detect pores, image-processing filters were used. The ARCGIS raster processing tools were used to analyze pore areas and perimeters. The shape factors \( \frac{\text{perimeter}^2}{4\pi \text{area}^2} \) proposed by Pagliai et al. (1983) were calculated to divide pores into different shape groups. The results for one soil type are shown here.

Soil hydraulic properties

Soil hydraulic properties were studied in the laboratory on the undisturbed 100 cm\(^3\) soil samples. Soil water retention curves were determined using the sand tank and pressure plate apparatus. The saturated hydraulic conductivities were measured using the constant head test. The multi-step outflow method was applied to estimate soil water retention curves and unsaturated hydraulic conductivity curves via numerical inversion. The soil water retention curves were also obtained using the water balance calculated for the soil sample subject to the multi-step outflow experiment. The results for one soil type are only shown here. In addition one application of the single porosity and dual permeability model (Gerke and van Genuchten, 1993) in HYDRUS-1D (Šimůnek et al., 2003, 2005) is shown to reveal impact of multimodality of soil porous system on soil hydraulic properties. The van Genuchten functions (1980) were used to describe both hydraulic properties.

Results and discussion

Soil type definition

Soil profiles of studied soils and micromorphological images characterizing the soil structure in different horizons are shown in Figs. 1-6. The resulting organic carbon content, clay content, cation exchange capacity and pH\(_{\text{KCl}}\) are shown in Fig.7. Based on the soil profile description, micromorphological images and soil properties of soil types were defined as follows: Haplic Chernozem on loess, Haplic Luvisol 1 on loess, Haplic Luvisol 2 on loess loam, Haplic Cambisols on paragneiss, Dystric Cambisol on orthogneiss and Greyic Phaeozem on loess.
Fig. 1. Haplic Chernozem on loess – soil profile and micromorphological images.

Fig. 2. Greyic Phaeozem on loess – soil profile and micromorphological images.
Fig. 3. Haplic Luvisol 1 on loess – soil profile and micromorphological images.

Fig. 4. Dystric Cambisol on orthogneiss – soil profile and micromorphological images.
Fig. 5. Haplic Luvisol 2 on loess loam – soil profile and micromorphological images.

Fig. 6. Haplic Cambisol on paragneiss – soil profile and micromorphological images.
Fig. 7. Organic carbon content, clay content, cation exchange capacity and pH$_{KCl}$. 
**Soil structure stability**

The resulting indexes of water stable aggregates within the soil profiles are shown in Fig. 8. Soil aggregate stability was in A horizons higher than in horizons bellow (B, C) in both Cambisols and Haplic Luvisol 2 due to higher organic carbon content. High aggregate stability was found in both Cambisols in spite the micromorphological images have shown weakly developed soil aggregates. This was probably caused by presence of free iron oxides in these soils. In the case of Haplic Chernozem, soil aggregates stability increased in the Ah horizon in comparison with Ap horizon even if the organic carbon content was lower. It can be due to higher content of clay and different forms of CaCO₃, and no effect of tillage. In the case of Haplic Luvisol 1, the most stable aggregates were found in the Bt-horizon, presumably because of presence of clay coatings in this horizon. An impact of tillage and clay coatings on soil structure stability within the soil profile is also evident in Greyic Phaeozem. The highest aggregate stability was found again in the Bth-horizon.

**Soil porosity**

Depending on type of pedogenesis, the soil porous systems exhibit different shape factors, different size classes, and different pore-size distributions that are mono- or multi-modal with random or hierarchical distribution of pore-sizes. The sizes and shapes of pores having impact on soil hydraulic functions are affected by coatings and fillings. Pores in the Ap horizons of all soil types apart from Greyic Phaeozem are not affected by coatings. Pores in subsurface horizons are affected by clay coatings in both Haplic Luvisols and Greyic Phaeozem and also by coatings of amorphous forms of CaCO₃, calcite needles and calcite rhombohedras in deeper horizons of Haplic Luvisols 1, and Greyic Phaeozem. Coatings and fillings of amorphous forms of CaCO₃, calcite needles and calcite rhombohedras affect pores in subsurface horizons in Haplic Chernozem. Pores in both Cambisols are not affected by any coatings and fillings.

Soil porous systems and detected image porosities in varying horizons of Haplic Luvisol 1 analyzed using the image processing filter and ARCGIS are shown in Fig. 9. The detected image porosity initially decreases with depth (in Ap2 horizon) and then again increases. Assuming the shape factor (SF) classification proposed by Pagliai et al. (1983) [regular SF=1-2, irregular SF=2-5, elongated SF>5] the percentages of different shape groups are as follows: regular pores represent 59.3, 54.4, 64.5, 58.6 and 59.7% of the pores in the Ap2, Bt1, Bt2, BC and Ck horizon, respectively, irregular pores 37.9, 39.2, 33.6, 37.8 and 36.5%, and elongated pores 2.8, 6.4, 1.9, 3.6 and 3.8%. The soil porous system in Ap1 is highly connected creating the large pore clusters. The pore irregularity increases with increasing pore sizes. The majority of detectable pores correspond to the pressure head range between −2 and −70 cm. It is evident from presented images that analyses of smaller pores
would require higher magnification (finer resolution) and that the different pore-size distribution would likely be obtained for pressure heads below −70 cm.

**Soil hydraulic properties**

Soil water retention curves obtained from water volume balance in the soil samples of Haplic Luvisol 1 from the multi-step outflow experiment data are shown in Fig. 10. The soil porous system in many cases displays multi-modality of the pore-size distribution that resulted in a multiple S-shaped curve. Here we present analysis of one multi-step outflow experiment data set for Bt2 horizon, where the multimodality was the most evident, using the single porosity and dual permeability approach. Those results will be also published in Kodešová et al. (2006). The single-porosity model in HYDRUS-1D was used first to analyze multi-step outflow data and to obtain soil hydraulic parameters assuming uniform flow (single continuum approach). Points of the soil water retention curve were also utilized in the inversion. While the saturated soil water content, θ_s, was set to the measured value of 0.401 cm$^3$/cm$^3$, the soil hydraulic parameters θ_r (the residual water content), α (reciprocal of the air entry pressure), n (related to the slope of the retention curve at the inflection point), and K_s (the saturated hydraulic conductivity) were optimized (Tab. 1). The resulting soil water retention curve does not fit the experimental data satisfactorily (Fig. 11a). Also the measured and simulated outflow data do not correspond well (Fig. 11b). The dual permeability model in HYDRUS-1D was then applied to improve numerical inversion results and to obtain parameters characterizing two flow domains defined as matrix (m) and larger pores (f) (two continuum approach). The fraction of the larger pore domain was estimated based on the micromorphological images (elongated pores corresponding to pressure heads between −2 and −70 cm). Values of θ_m and θ_f (saturated water contents of the matrix and macropore domains, respectively) were set assuming that the sum of their values multiplied by domains ratios ($w_m = 0.075, w_f = 0.075$) was equal to the measured θ_s value. Values of θ_m and θ_f (residual water contents of the matrix and macropore domains, respectively) were set equal to θ_r for the single porosity model and zero, respectively. Considering that the larger pores control saturated flow, the saturated hydraulic conductivity of the macropore domain, K_s,f, was defined as the ration of the K_s value (0.496 cm/hour), obtained using the constant head experiment on the same soil sample, and the domain ratio ($w_f$). The n_f parameter was set equal to 3 assuming a step-like shape of the soil water retention curve for the macropore domain. The effective saturated hydraulic conductivity, K_e, for the mass transfer between the matrix and the macropore domains was set equal to a low value of 0.00001 cm/hour due to the presence of clay coatings. Parameters α_m, n_r, n_m, K_s,m were optimized (Tab. 1). The resulting total soil water retention curve was obtained as the sum of soil water retention curves for the matrix and macropore domains multiplied by their corresponding fractions. The total soil water retention curve and simulated outflow data are presented in Fig. 11. Agreement between the measured and optimized retention curves and outflow data using the dual-permeability model exhibits significant improvement, especially for the pressure head range corresponding to pores detected in the micromorphological image.

**Conclusions**

It was shown that the soil micromorphology is together with usually investigated soil properties like organic carbon content and clay content very useful technique for explanation of soil structure stability. Soil structure stability varied within the soil profiles depending on organic matter content, presence of clay coatings and fillings, existence of different forms of CaCO$_3$ and presence of iron oxides. The soil micromorphology helps to describe pore configuration and explain flow processes in different flow domains and possible interactions between these flow domains. The micromorphological study of soil porous systems discovered in many cases the multimodality of the pore system. The soil water retention curves also displayed in many cases multimodality. The dual-permeability model was successfully applied for description of soil hydraulic properties and water flow in multimodal soil porous system.
Fig. 9. Detected pores in Haplic Luvisol 1 on loess.

Fig. 10. Soil water retention curves in Haplic Luvisol 1 on loess.
Fig. 11. Soil water retention curves (a) and multi-step outflow data (b) obtained on the soil sample characterizing the Bt2 horizon at depths of 75 - 102 cm in Haplic Luvisol 1 on loess.

Tab. 1. Parameters of the van Genuchten functions for the single porosity and dual permeability models for the soil sample characterizing the Bt2 horizon at depths of 75 - 102 cm in Haplic Luvisol 1 on loess.

<table>
<thead>
<tr>
<th>Model – flow domain</th>
<th>$\theta_s$ [cm$^3$/cm$^3$]</th>
<th>$\theta_r$ [cm$^3$/cm$^3$]</th>
<th>$\alpha$ [1/cm]</th>
<th>$n$ [-]</th>
<th>$K_s$ [cm/hour]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Porosity</td>
<td>0.401*</td>
<td>0.254*</td>
<td>0.041</td>
<td>1.214</td>
<td>0.310</td>
</tr>
<tr>
<td>Dual Permeability – Larger Pores</td>
<td>0.410*</td>
<td>0*</td>
<td>0.036</td>
<td>3*</td>
<td>6.5*</td>
</tr>
<tr>
<td>Dual Permeability - Matrix</td>
<td>0.400*</td>
<td>0.253*</td>
<td>0.009</td>
<td>1.240</td>
<td>0.0032</td>
</tr>
</tbody>
</table>

* not optimized
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References:


PŮDNÍ MIKROMORFOLOGIE, STABILITA PŮDNÍ STRUKTURY A HYDRAULICKÉ VLASTNOSTI PŮD

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Klíčová slova: mikromorfologické vlastnosti půd, stabilita půdní struktury, pórový systém půd, půdní hydraulické vlastnosti, modely jednoduché pórovitosti a duální propustnosti