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Non-invasive 3D analysis of local soil deformation under mechanical and hydraulic stresses by μCT and digital image correlation

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ABSTRACT

Soil deformation is a perpetual process in the pedosphere where besides physicochemical stresses primarily alternating hydraulic and mechanical stresses continuously re-arrange the configuration of solid particles. In this study we present a local strain analysis and changes in soil structure resulting from hydraulic and mechanical stresses based on X-ray microtomography data. Digital image reconstructions were used to quantify local structural pore space characteristics and local soil deformation by 3D morphological and correlation analysis of grayscale tomograms. Swelling and shrinkage resulted in a complex heterogeneous soil structure which proofed to be very stable when mechanical loads were applied. The mechanism of soil deformation for both structure formation by internal hydraulic stresses and structure degradation by external mechanical stresses were in both cases controlled by pre-existing (micro)-structures. Especially during wetting such structures served as a nucleus for subsequent structure evolution. The results demonstrate the potential of more detailed non-invasive micro-mechanical analysis of soil deformation processes which could improve the conceptual understanding of the physical behavior of soil systems.

1. Introduction

Soil deformation is a perpetual process in the pedosphere where besides physicochemical stresses primarily alternating hydraulic and mechanical stresses continuously re-arrange the configuration of solid particles. Soil structure formed during the process of particle re-arrangement is therefore highly dynamic and consequently all structure related soil functions are not constant with time. However, limited understanding of the complex mechanisms involved in structure evolution and dynamics yet often restricts the treatment of soils as static porous media (Or and Ghezzehei, 2002). This is a major flaw, especially with respect to modeling transport phenomena in soils, which are not adequately described by assuming rigid pore systems. To better predict soil responses to changes in environmental boundary conditions resulting from natural and anthropogenic factors such limitations have to be overcome.

Especially the upper soil layer, which is usually subject to tillage, is characterized by high particle mobility due to the mechanical homogenization which breaks up inter-particle bonding and loosens the soil reducing both cohesion and frictional resistance. Such soil layers undergo intensive structural changes in a consecutive sequence of (i) soil structure formation by repeated shrinking–swelling and bioturbation, (ii) deterioration of soil structure by compaction and shear deformation and (iii) subsequent structure re-formation by *biotic* and *abiotic* processes. The structural changes are further based upon the continuous change of the electrokinetic, also zeta-potential (ζ-potential = potential at the plane of shear between a charged surface and the electrolyte solution). This is due to change of soil water content and inflow/outflow of soil solution, eventually by inflow of external water. Therefore, (iv) the coagulation and dispersion processes of mainly clay particles have to be considered as a continuous structure modifying process, too (Baver, 1958; Kutilek and Nielsen, 1994; Probstein, 1994; Mashliyah and Bhattacharjee, 2006).

Within the natural soil structure formation processes also deeper soil layers are affected where prismatic to subangular blocky structures are formed which finally would result in the status of smallest entropy. This development also includes the continuous changes in pore rigidity because each strengthening can either be achieved by an increase in contact points or by an optimization of per contact area compensated external soil stress (Hartge and Horn, 1984). These interactions can be detected easily in topsoil layers and to a lesser extent also subsoil layers are characterized by non-rigid structures, even if structure formation by aggregation is often inhibited in compacted soil resulting from the use of heavy machinery (Peth et al., 2006). Nevertheless, in this case wetting and drying generates hydraulic stresses evoking

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shrinking and swelling and hence a modification of pore space architectures, which- although less pronounced than in loose topsoil layers- may significantly modify fluid and gas transport properties. The significant change of permeability with pore channel diameters is well known from *Hagen-Poiseuille's* law which states that the mean volume flow rate per unit area through cylindrical capillary tubes increases exponentially with the squared radius of the tube (Domenico and Schwartz, 1990; Jury and Horton, 2004).

Aggregated and homogenized soils show significant different physical properties and behave also differently with respect to structure dynamics (Horn, 1989) influencing numerous soil functions. Besides *abiotic* processes such as fluid transport also *biotic* functions depend on soil structure development and stability (Whalley et al., 1995; Horn and Peth, 2009). Mechanical loosening of the upper soil layer by tillage, for example, mainly aims at creating favorable conditions for plant growth. At the same time, however, the resulting loose structure is susceptible to collapse by internal capillary forces and external compressive stresses with concurrent changes in soil hydraulic, mechanical and thermal properties (Wiermann et al., 2000; Or and Ghezzehei, 2002) which in turn influence plant growth. The predominant change of structural porosity due to compression was partly studied by Assouline et al. (1997) and is well documented (Kutilek et al., 2006) on the representative elementary volume (REV) scale by water retention curve analysis. Apart from the hydraulic effects on plants the presence of zones of high mechanical resistance is one of the most common physical limitations to soil exploration by roots (Hoad et al., 1992). To date, the majority of studies on roots have ignored the heterogeneity of soil conditions, leaving serious gaps in our understanding of plant functioning under field conditions (Hutchings and John, 2004). This is particularly true for local mechanical strength which determines the accessibility of reaction sites (Horn and Kutilek, 2009) and the propagation of plant roots (Bengough and Mullins, 1990). Further, local mechanical soil strength of the different hierarchically organized structural units not only guards root growth but lately is considered to play a key role in carbon cycling and sequestration by physical stabilizing soil organic matter within aggregates (Six et al., 2000; Denef et al., 2001; Blanco-Canqui and Lal, 2004; Smucker and Hopmans, 2007). A detailed spatial quantification of the dynamics of soil structure due to modified hydraulic and mechanical stress states could help to overcome some of the above mentioned limitations.

1.1. Interaction of mechanical and hydraulic stresses

Mechanical and hydraulic stresses are closely linked. Every change in mechanical stress results immediately in a change in hydraulic stress. On the other hand mechanical stresses and soil strength in unsaturated soils are also influenced by hydraulic stress which is described for example by Bishop's effective stress equation (e.g. Fredlund and Rahardjo, 1993). A detailed concept of the coupling of hydraulic and mechanical stresses has been presented in various theoretical and modeling contributions (e.g. Richards, 1992; Horn et al., 1998; Horn, 2003; Richards and Peth, 2009) and shall not be repeated here except for the following few principles: (i) Hydraulic stresses are exerted via capillary pressure in water menisci at inter-particle contacts. During the first period of drying (decreasing pore water pressure) shrinkage is induced where mineral particles are pulled together by capillary forces consequently generating cracks. Both crack volume and morphology depend on the local stress field, structure and moisture induced strength of the soil. Shrinkage increases the number of points of inter-particle contacts within the newly formed aggregates resulting in higher bulk density and higher mechanical strength due to an increased frictional resistance. It has been found that the mechanical conditions of granular systems such as shearing, compaction and the transmission of stress are greatly influenced by microstructural characteristics, e.g. the spatial distribution of particle contacts (Al-Raoush, 2007). During the process of hydraulically induced crack formation the soil becomes more heterogeneous but mechanically also stronger at the same moisture level compared to the homogenized condition. Upon wetting (increasing pore water pressure) previously formed cracks will partially close by swelling. However, a residual deformation known as structural shrinkage (Peng and Horn, 2005) remains. (ii) Externally applied mechanical loads generate compressive and shear stresses in the soil resulting in soil deformation predominantly in the vicinity of the larger inter-aggregate pore space since here particles and smaller aggregates are less stabilized by neighboring particles/aggregates that could support the load (Horn, 1989). Soil deformation by external mechanical loads additionally depends on the prevailing pore water pressure (matric potential) and its change during the loading process which in turn is influenced by the spatio-temporal modification of the local hydraulic conductivity. However, the wetter the soil the smaller is the inter-particle friction and therefore the higher is the soil deformation and finally the deterioration of soil structure.

Traditional methods for investigating soil deformation and structure are usually based on bulk soil measurements. For instance the overall soil compression or shear displacement is measured at the specimen boundary and associated soil structural changes are described by changes in pore size distributions derived indirectly from water retention curves. In this way, local displacements and (micro-)structural changes are averaged statistically over the total volume assuming stress–strain relationships to be homogeneous with uniform strain throughout the soil sample. This totally neglects the complex modification of internal pore morphologies as a result of locally changing stress conditions. Verveckaite et al. (2007) noted that knowledge of the real micro-scale distribution of stress and strain would allow a better description of soil strength and deformation parameters and provide a more precise way of rating the influence of different factors on soil properties. This would also facilitate the development of more enhanced models accounting for the spatial heterogeneity and dynamics of soil pore systems and functions which are controlled by local mechanical properties.

1.2. Measurement of localized deformation in composite materials

Recently, a new system for measuring localized soil deformation in geotechnical testing based on digital photography was presented by White et al. (2003). The technique is referred to as particle image velocimetry (PIV) where the local displacement of patches of pixels is measured by cross-correlating sequential images. Local strain is calculated from the coordinates of the changing patch positions. The technique, which was originally developed in the field of experimental fluid mechanics (Adrian, 1991), was also applied to measure local surface strain rates of plant roots from time-lapse images taken during tensile loading (Hamza et al., 2006). A three-dimensional extension of two-dimensional digital image correlation techniques has been developed by Bay et al. (1999). Using X-ray tomography images they calculated the strain tensor field of a trabecular bone under load. Three-dimensional digital image correlation techniques were also developed by Crostack et al. (2008) for strain measurements in microstructures of metal matrix composites. However, to our knowledge only little work has been done using X-ray tomography data in conjunction with digital image correlation techniques for the study of localized soil deformation. In this study we present a local strain analysis and changes in soil structure resulting from various hydraulic and mechanical stresses. The analysis is based on