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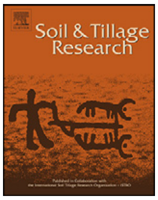

Effect of hydraulic and mechanical stresses on cyclic deformation processes of a structured and homogenized silty Luvic Chernozem

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ABSTRACT

The deformation behavior of soils is strongly affected by coupled mechanical and hydraulic stresses especially under cyclic loading. Contrary to static loading tests cyclic loading caused plastic deformation increments with ongoing loading cycles even for stresses in the re-compression range associated with alterations in the hydraulic stress state. The aim of this study was to proof the interference of hydraulic properties on the mechanical deformation behavior (cyclic compressibility) depending on soil structure and cyclic loading time. Cyclic loading tests with changing boundary conditions in terms of initial matric potential, loading time and magnitude on structured and homogenized silty soil samples were performed. Furthermore, pore water pressures during cyclic loading and the air conductivity of soil cores before and after cyclic loading were measured. The results indicated differences in the stress–strain response accompanied by typical hydraulic stress regimes. These were classified into five categories representing a typical development of pore water pressures according to soil structure and loading time. Predominantly at short-time cycles a built-up of pore water pressures with increasing number of cycles occurred resulting in a high cyclic compressibility of the homogenized soil. The loss of soil strength could be linked to the beginning of partial liquefaction processes induced by heavy soil loading of 150 kPa and by a higher initial matric potential. In contrast, the less compressible structured soil showed a better internal redistribution of pore water and faster dissipation of stress-induced pore water pressures compared to the homogenized soil. Finally, the influence of soil structure plays an important role in understanding hydro-mechanical relationships, especially since the reversal of pore water pressures back to the hydraulic equilibrium state was restricted by the time between repeated loading events.

1. Introduction

Soils are regularly exposed to different kinds of external loads, which are usually described as static but in fact are highly dynamic with variable loading time and magnitude. The cultivation of arable soils requires annually multiple wheel passes of agricultural machines. Various field operations and multiple number of axes (tandem axle, trailer combinations) represent such repeated loading situations. In several studies the effect of wheeling repetitions on soil deformation processes have already been analyzed by loading simulations in the field and laboratory (Okhitin et al., 1991; Slowiñska-Jurkiewicz and Domzal, 1991; Defossez and Richard, 2002; Horn et al., 2003; Pytka, 2005; Botta et al., 2006; Peth et al., 2010). While the first pass causes the highest irreversible volumetric change, further smaller plastic deformation increments after additional wheeling events could be observed, even if moderate machinery (e.g. light traffic according to Botta et al. (2006)) was used. This conflicts with the general assumption, that stress paths at the re-compression range are regarded to show almost fully elastic response. Thus, common mechanical parameters like the pre-compression stress were often not sufficient to describe cyclic stress–strain relations accurately (Krümmelbein et al., 2008) and it was recommended to distinguish between pre-compression stress values determined under static and cyclic loading (Peth and Horn, 2006). O'Reilly and Brown (1991) reported on the high uncertainty when estimating cyclic soil movements from static deformation behavior especially at high loading frequency like it is usually the case for applications in civil engineering. Moreover, there is a substantial risk for under-estimating soil degradation, if foundation elements are stressed cyclic compared to pure static loading for the same stress, even if the load is below the static bearing capacity (Malkus, 2000). Since plastic volumetric strain is always linked to proportional alteration in the three-phase system, hydraulic soil properties became an essential feature in geotechnical engineering with major interest in soil liquefaction processes. However, not only saturated soils are

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affected by liquefaction but also unsaturated soils (Khalili et al., 2008; Bian and Shahrour, 2009). While elastic or plastic deformations in water saturated soils under undrained conditions can be directly associated with changes in hydraulic stresses (pore water pressures) (Boyce, 1980; Yildirim and Ersan, 2007), the mechanical behavior of partial saturated soils requires the separation of independent stress variables, the net stress and matric potential as components of the effective stress concept described by Bishop (1959, cited in Fredlund and Rahardjo, 1993).

Most changes of hydraulic properties could be expected for stresses within the virgin-compression range (Horn et al., 2003) or are basically referred to changes in soil structure by compaction (Larson and Gupta, 1980; Richard et al., 2001). Consequently, in aggregated soils the effect of compaction is mainly related to the amount of water retained in structural pores by capillary forces at low matric potential ranging from <10 kPa (Matthews et al., 2010) to <100 kPa (Zhang et al., 2006). Even without detectable changes in bulk density, alteration in water retention properties of aggregates could also correspond to constrictions of intra-aggregate pores, which are increasingly narrowed by compaction (Tamari, 1994). Vice versa structural changes could refer well as an indicator for compaction impacts on hydraulic functions (Alaoui et al., 2011). Based on this, Peth et al. (2010) explained coupled hydraulic–mechanical processes and discussed the consequences of altered pore size distribution on matric potential changes of cyclic loaded soils. Krümmelbein et al. (2008) have also confirmed the impact of pore water pressures, which are more pronounced during cyclic compared to static stress conditions.

Another important factor controlling the soil deformation process is the loading time, which primarily determines the consolidation rate in two ways, i.e. first soil settlement as an inherently time dependent process and second the mobilization of pore water under pressure (Biot, 1941). Hence, the interaction between solid deformation processes and water movement is related to the soil specific compressibility and the hydraulic permeability (Schmidt, 2006). It can generally be assumed, that short-time stress-inputs lead to smaller total soil settlements (Rézdi and Kinze, 1969) due to the fact, that consolidation processes cannot be fully completed. In terms of agricultural traffic it was shown, that on the one hand an increasing wheeling speed could lower compaction effects (Dexter and Tanner, 1974; Horn and Hartge, 1990) while on the other hand, the dynamic character of wheeling plays an important role in understanding stress–strain relations (Peth et al., 2010). Considering this, for a load that is allocated on multiple axes, even with increased wheeling speed one single pass will represent short-time loading–unloading sequences that will alter not only mechanical but also hydraulic equilibrium conditions and hence the internal stress situation.

The practical relevance was pointed out by Peth and Horn (2006), who calculated wheeling frequencies for a time period of 5 years and for 85% of an arable crop field, that amounted to more than 50 machinery passes and would rise up to 100 times by using permanent traffic lanes. Estimations of related compaction effects at given number of wheeling repetitions become very complex if axle loading and time of loading and unloading vary, especially because the internal strength of soil changes with time depending on soil moisture dynamics (Okhitin et al., 1991; Défossez et al., 2003).

For understanding coupled hydro-mechanical phenomena, the simultaneous behavior of solid and fluid phases has to be analyzed connectedly and in combination with other parameters like the degree of saturation, coefficient of water compressibility and permeability (Ghassemi et al., 2010). Considering cyclic loading as a highly coupled hydraulic–mechanical process, the main objective of this work was to proof, how the cyclic deformation behavior of structured and homogenized soil samples is controlled by hydraulic stresses (e.g. initial matric potential and stress-induced changes of the matric potential). This was investigated by cyclic loading tests with changing boundary conditions in terms of loading magnitude and loading time.

2. Material and methods

2.1. Sampling of undisturbed soil

Undisturbed soil (intact soil cores, $h = 5$ cm, $d = 10$ cm) was sampled in 2002/2003 from experimental field plots of the Institute of Sugar Beet Research in Harste near Göttingen from 12, 40 and 60 cm depth under two different treatments ("mulch" and "ploughed") with 2 replicate field plots, respectively. These plots were established for long-term investigations with conventional and conservation tillage systems since 1992. Half of the samples were obtained from plots additionally wheeled once and for the first time with a heavy sugar beet harvester (35 mg Holmer Terra Dos). The soil type is a Luvic Chernozem derived from loess. More detailed information on site and soil properties are given in Fazekas (2005) and Peth et al. (2010). This sample series was labeled as "structured cores" (SC).

2.2. Homogenized soil samples

Additional homogenized soil samples were made under standardized conditions using a loading frame (Dual Column Tabletop Testing System 5569, Instron Company, USA). Two different homogenized sample series were produced for the cyclic loading test:

1. *Homogenization of structured cores (SC^H)*: In order to evaluate the effect of soil structure for soils under cyclic loading, structured cores from the field (SC) (see Section 2.1) were homogenized after the cyclic loading test was finished. The homogenized material was refilled into each steel cylinder and compacted to achieve the same bulk density as it was present in the field (1.52 ± 0.06 g cm^{-3}). Depending on the desired bulk density compressive stresses applied by the loading frame ranged from 80 to 707 kPa. Each cylinder was subsequently used for a second cyclic loading test.
2. *Homogenized cores (HC)*: Disturbed soil material was taken from the Ap–horizons under conservation management and compacted to a bulk density of 1.28 ± 0.03 g cm^{-3} in steel cylinders ($h = 3$ cm, $d = 10$ cm).

2.3. Cyclic loading test

The cyclic loading test simulates a vertical compression of soil cores under drained conditions using a programmable pneumatic multistep oedometer. A detailed description of the apparatus can be found in Peth et al. (2010). Three different loading times were chosen and mechanical stresses ranging from 30 to 150 kPa were applied over 20 up to 300 cycles varying between the samples set (Table 1). To represent load magnitudes close to field conditions SC and SC^H samples were loaded with 80 kPa in relation to contact area pressures, which are common under field practice leading to stresses occurring even in subsoil layers (Fazekas, 2005). For the experiments with homogenized topsoil material (HC) the numbers of cycles have been reduced with increasing loading time in order to shorten the total runtime of a single experiment. A single cycle corresponds to a loading and a following unloading phase of same time length (Table 1). Also pore water pressures (matric potential) were measured during the cyclic loading test by a microtensiometer inserted into the soil from below.