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Controlled vertical stress in a modified amplitude sweep test (rheometry) for the determination of soil microstructure stability under transient stresses

Dörthe Holthusen [a,]*, Patricia Pértile [a], José Miguel Reichert [a], Rainer Horn [b]

[a] Department of Soil Science, Federal University of Santa Maria, Roraima Avenue, 1000, 97105-900, Santa Maria, RS, Brazil
[b] Institute of Plant Nutrition and Soil Science, Christian Albrechts University Kiel, Hermann-Rodewald-Str. 2, 24118 Kiel, Germany

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ABSTRACT

Although there are evidences that most, if not all, soil physical and mechanical processes on larger scales have their origin in processes and properties at the microscale, the range of methods to investigate micro-scaled soil behavior directly is limited. One method to detect flow and deformation behavior under steady and transient stresses is rheometry. This method is well established by means of the amplitude sweep test (AST) to detect viscoelastic properties of soils, i.e. stress-strain relationships under transient stresses that occur due to wheeling or trampling. This test is based upon a soil sample positioned between two parallel plates, where the upper plate rotates in an oscillatory manner with increasing stress or strain amplitude, and the lower plate is fixed. Depending on the retardation of the sample's shear stress reaction, viscous and elastic strain proportions are defined with the help of storage and loss modulus (G′ and G″), and their ratio (tan δ). However, the AST is strongly susceptible to sample preparation and the vertical force of the upper plate. Either a low force (e.g. 1 N) was applied or samples with forces beyond a critical limit (e.g. 12–15 N) were excluded. We used controlled force of 1, 3 and 10 N, equivalent to compressive stresses of 2.04, 6.11 and 20.37 kPa, to find the optimum settings to run the AST. The selected forces/stresses are either low, intermediate or high compared to those observed under undefined conditions in two South Brazilian soils (A and B horizon of a Typic Hapludox – Oxisol, and an Oxyaquic Hapluderts – Vertisol). Furthermore, field density and a common (high) density were applied to the homogenized soil material. The variability of the results generally decreased with increasing compressive stress level, and at highest stress variability was lower than under variable force/stress. The microaggregation of the Oxisol based upon iron oxides and hydroxides (pseudosand) and high kaolinite content in the B horizon resulted in a smaller range of recoverable elasticity than in the Vertisol. However, at large strains the elasticity was higher in the Oxisol, while the Vertisol exhibited alignment of the soil particles. The Oxisol generally showed a brittle rupture by means of a maximum shear stress; while in the Vertisol yielding occurred due to expandable clay. High compressive force and density simultaneously reduced the share of elastic deformation and promoted plastic yielding. The results do not allow yet defining an optimum compressive stress. Thus, we suggest investigating further force or stress levels and to test more soils, e.g. of high soil organic matter content and/or high or low clay, silt or sand content.

1. Introduction

Many mechanical processes exhibited by soils on a larger scale (pedon to plot scale) originate in the micro or particle scale (Ghezzehei and Or, 2001) or physical properties are repeated in a fractal-like manner, as found by Williams and Petticrew (2009), i.e. soil of high bulk density consisted of more stable aggregates which in turn fragmented into even more stable micro-aggregates. Consequently, recent research also includes investigations at the microscale, e.g. with the help of non-invasive X-ray computed microtomography. However, the micromechanical aspects are only poorly investigated.

Soil deformation generally is based on elastic (reversible) and plastic (viscous and irreversible) deformation as a reaction to an external stress (Kézdi and Réth± 1974). While elastic deformation and viscous flow are separated by different stress magnitudes (with the yield stress or precompression stress being the threshold) during steady stress, transient (or cyclic) loading causes simultaneously elastic and viscous deformation (viscoelasticity, Ghezzehei and Or, 2001). The reason is a lack of time for complete dissipation of the energy input, e.g. via a re-distribution of excess pore water, which causes energy to be temporarily stored and released upon relaxation (Ghezzehei and Or, 2001). Consequently, e.g.

* Corresponding author.
E-mail address: doerthe.holthusen@web.de (D. Holthusen).

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Peth and Horn (2006) proved that repeated stresses, although below the soil's bearing capacity (i.e. precompression stress), caused further compression. Furthermore, although the precompression stress during repeated stresses appears to be higher due to the incompressibility of trapped pore water, the soil shear resistance is profoundly lower due to the lack of apparent cohesion (Krümmelbein et al., 2008).

With the help of rheometry and an amplitude sweep test (AST), we can simulate transient shear stresses and if desired, at the same time, compressive stresses at the particle scale. In a rheometer (Fig. 1a and b) a soil sample between two parallel circular plates is subjected to oscillating strain of increasing amplitude. Both tests with controlled shear stress as well as with controlled strain exist. The corresponding rheological parameters are well described (e.g. by Vyalov (1986) and Barnes et al. (1989), and more recently by Mezger (2006)). We will elaborate them further in section 2. The main benefit of the AST is the knowledge of viscoelasticity (share of elastic or viscous deformation). With small sample volume (few cm^3), high resolution of oscillation (1 μrad) and torque to register the shear stress (0.002 μNm, both values for the rheometers of the MCR series by Anton Paar, Ostfildern, Germany), the AST is used to detect the stability of the soil microstructure as influenced by inter-particle forces (Markgraf et al., 2006). The method is well established, but past results point out relatively high variability of supposedly similar (because homogenized) soil samples, e.g. by means of an coefficient of variation of 5–20% in general and occasionally up to 40% (Baumgarten et al., 2013; Baumgarten et al., 2012; Holthusen et al., 2012c; Markgraf et al., 2012a, 2012b). Furthermore, especially dense and/or sandy soils are mostly not possible to investigate with this method as the technical restriction of the rheometer (vertical force < 50 N) is exceeded (as experienced by the authors in previous research unpublished). Similarly, Markgraf et al. (2006) mention a restriction to "fine-grained (<630 μm and/or low sand content)" samples and samples of "homogeneous consistency (grinded and sieved)".

On the one hand, test performance depends on sample preparation, where slight variation in sample height occurs. In an experimental setup with a fixed gap size of the parallel plates (generally 4 mm), this causes subsequent variation in vertical stresses. Hence, we relate the variability of the rheological parameters to strong variability in the vertical (normal) stress acting on the samples during an AST. In this paper, by controlling the vertical stress, we aim to:

- Increase the representativeness of the existing test.
- Allow for an increased range of soil materials to be investigated.
- Transfer between rheological and macroscale processes and parameters.

As material we chose two different South Brazilian soils (Typic Haplodux and Oxyaquic Hapludert) to execute a modified amplitude sweep test, where the gap size is not fixed but the normal stress is kept constant. Thus, the gap size is adjusted to the sample's a priori compressibility, enabling also dense or sandy soils to be investigated. Furthermore, as several macroscale parameters are based upon defined vertical stresses (precompression stress, time-dependent settling, shear parameters gained by shear frame tests under controlled vertical stress situation etc.), the results of the modified AST can be related directly to those soil properties, unlike to the unmodified test.

2. Theoretical considerations

2.1. Viscoelastic soil strength and its detection with the help of rheometry

Generally, the deformation of soil occurring due to an external steady stress (consolidation), e.g. by a permanent load, was found by Terzaghi (1925) to be a function of the slow drainage of pore water and accompanying translocation of particles into a denser packing. This hydrodynamic approach, however, becomes invalid, where the shear strength of the soil is exceeded, which is following Wilson (1974) true especially for soft soils, where the shear strength is low and the water permeability is lessened rapidly. Hence, viscous flow is initiated. Vyalov (1986) related this phenomenon to the Bingham model (amongst others), where plastic (or viscous) flow (i.e. flow according to Newton's law, that is linear to the stress) occurs only at stresses beyond a critical (yield) stress.

Stresses of short duration, i.e. transient stresses like several passages of wheels or trampling (cf. Peth and Horn, 2006), do not allow the soil to re-gain a new equilibrium in-between the single loading events and thus both viscous or plastic and elastic deformation occur at the same time. In a perfectly elastic material, represented by the example of a spring, the shear stress τ (Pa) is linearly related to the strain γ (%) according to Hooke's law with the shear modulus (or modulus of rigidity) G (Pa) as the proportionality factor (Eq. (1)).

$$\tau = G\,\gamma \quad (1)$$

On the other hand, the stress-strain relation of a perfectly viscous material (e.g. water) follows Newton's law of proportionality of shear

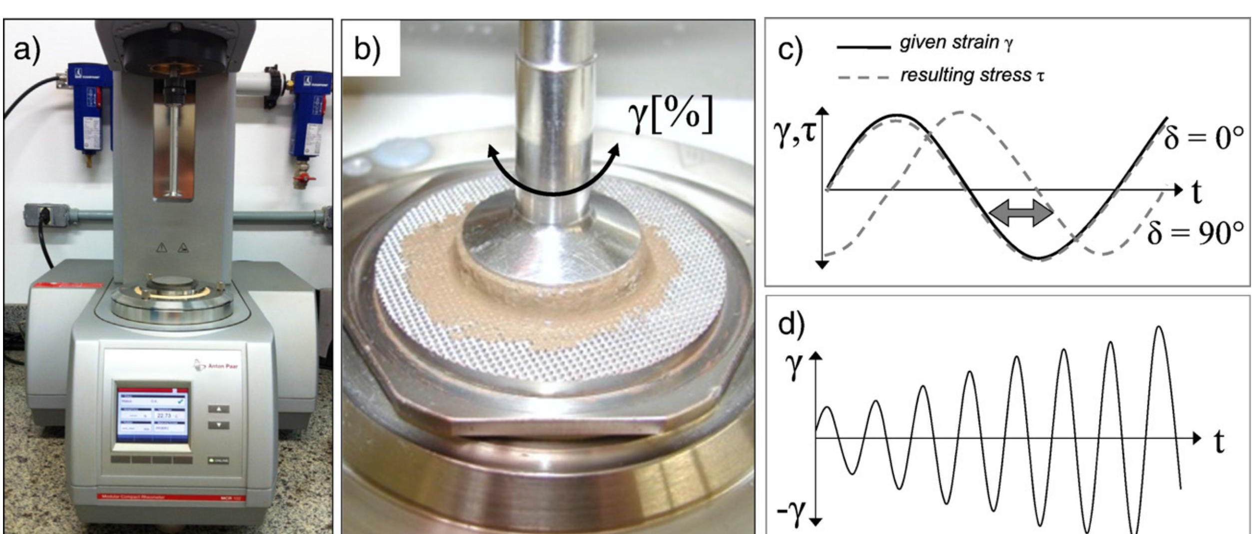

Fig. 1. Images and schematic drawings of the equipment and the test used: a) modular compact rheometer MCR 102 by Anton Paar GmbH, Ostfildern, Germany, b) plate-plate measurement system with roughened surface, c) given and resulting parameters in oscillatory modus, here shown for given strain γ and resulting stress τ that are either in line ($\delta = 0°$) for a fully elastic material or retarded by 90° for a fully plastic material, while for soil $0° < \delta < 90°$, and d) visualization of the amplitude sweep test with increasing strain γ amplitude over time t.