Quantifying shrinkage of marine and fluvial clay deposits by means of soil-shrinkage curves

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Abstract

Shrinkage and swelling due to moisture content changes in clay-rich expansive soils are well-known and notorious phenomena, as they cause damage to infrastructure and change the hydrological and mechanical characteristics of the soil. Irreversible soil shrinkage also induces land subsidence. Shrinkage behaviour is often described by a soil-shrinkage curve, which relates the void ratio to the moisture content. The shape of these curves depends on sampling method, sample size and type, and is related to the soil and porewater composition, soil density and its stress history. The aim of this research project is a) to acquire understanding of clay deformation due to drying and chemical changes and b) to quantify the interacting processes in situ such as compaction and shrinkage in a soil column. To do so, an adapted soil-shrinkage curve methodology was devised, combining several types of measurements. With the use of the methodology clear differences in soil-shrinkage curves can be identified. Organic fluviatile clay samples show relatively more shrinkage during the first phase of shrinkage, compared to inorganic marine clay samples. The organic clay samples also show an increasingly dominant vertical deformation during drying.

Introduction

Damage to infrastructure and changing hydrological and mechanical soil properties are notorious phenomena as a result of volume change of expansive soils. When unconsolidated soft deposits are dried irreversible shrinkage can take place, leading to (enhanced) land subsidence. Both reversible and irreversible soil shrinkage have been studied extensively for over 70 years (e.g., Stirk, 1954; Davidson & Page, 1956; Yule & Ritchie, 1980; Cornelis et al., 2006) using diverse methods and sample types. An important tool in understanding shrinkage and swelling is a soil-shrinkage curve, which relates the void ratio to the moisture content of a soil.

Traditionally, four shrinkage phases are defined in a shrinkage curve; (1) structural shrinkage, (2) proportional shrinkage, (3) residual shrinkage and (4) zero shrinkage (e.g., Peng & Horn, 2007). Structural shrinkage can occur during the first phase of drying in which macropores dry, but the volume loss is not equal to the volumetric water loss. After the structural shrinkage, proportional shrinkage occurs when volume loss equals moisture loss. Thereafter, the residual and finally zero shrinkage phases take place, when the loss of moisture yields little to no shrinkage. Not all phases are present in every soil-shrinkage curve: small (aggregate size) or remoulded samples lack the structural shrinkage phase as large macro pores are not present in the samples (Peng & Horn, 2013). However, the structure of a soil also changes during the zero shrinkage-phase, as intraparticle space is transferred to interparticle layers, which does not necessarily cause a change in the bulk density (Bruand and Prost, 1987). A change in the structure of the soil can cause permanent changes in the 2 soils' hydrological and mechanical behaviour. To capture the shrinkage behaviour in phases two to three, Lu & Dong (2017) proposed an alternative soil-shrinkage curve that focusses on the properties of the water that is transferred during drying. Two main regimes were identified: capillary and adsorption, in which the capillary phase encompasses water that can flow freely, and adsorption is the phase in which soil particle surfaces start to dehydrate.

The shrinkage curve and the field shrinkage limit (maximum amount of shrinkage at a suction of -1600 hPa; Bronswijk & Evers-Vermeer, 1990) has been correlated with soil characteristics such as expansive clay content (Crescimanno & Provenzano, 1999; Mishra et al., 2008), organic matter content (Peng & Horn, 2007;), soil density, specific surface area, cation exchange capacity (Gray & Allbrook, 2002) and maximum adsorbed water content (Lu & Dong, 2015). These characteristics can be related to the soil water retention curve (SWRC, or pF-curve), which related the water content to the soil water suction. Greene-Kelly (1974) also found a significant correlation between expansive mineral content and shrinkage for remoulded samples, but not for samples that have been exposed to drying and wetting cycles, indicating the effect of stress history on the shrinkage behaviour. Rasa et al. (2009) studied the effect of land use on shrinkage and found a difference of 4.8% in total shrinkage when a clay soil was managed differently, whereas on average shrinkage was 10% in these soils. These results highlight the importance of studying natural undisturbed samples to identify shrinkage governing soil characteristics.

The aim was to create a non-disturbing continuous volume change measurement set-up while also measuring soil water suction and the weight of the sample, in order to create soil-shrinkage curves during air drying of natural undisturbed samples. The method and preliminary results are described and assessed in the following sections.

Methodology

The first step in the project was measuring the soil-shrinkage curves of marine and fluviatile undisturbed clay-rich samples from the Netherlands, using a basic measurement set-up. These results are summarized in the next section. After confirming the sample size to be suitable to measure all shrinkage phases, a measurement method was devised that measures soil shrinkage, evaporation and soil water suction, continuously in controlled conditions. This set-up is used to measure the shrinkage of clay-rich samples from all over the Netherlands, focusing on differences in organic matter content, clay mineralogy, porewater salinity and stress history, to be able to understand the influence and quantify the effect of soil composition and stress history on soil shrinkage.

Two sampling sites were selected based on depositional environment (marine and fluvial), texture, organic matter content and practical considerations with regard to land use and accessibility. Both the sampling sites are located in the western Netherlands: near the villages Abbenes (marine deposit) and Montfoort (fluvial deposit) (Figure 1). Samples were extracted by using a ring sampler to minimize disturbance. In the laboratory the samples were transferred from the stainless-steel sample rings to latex pouches, to be able to measure both height and diameter changes. Water samples were collected from the same sampling depth in nearby (50 cm) boreholes to determine the local groundwater composition at both sampling sites.

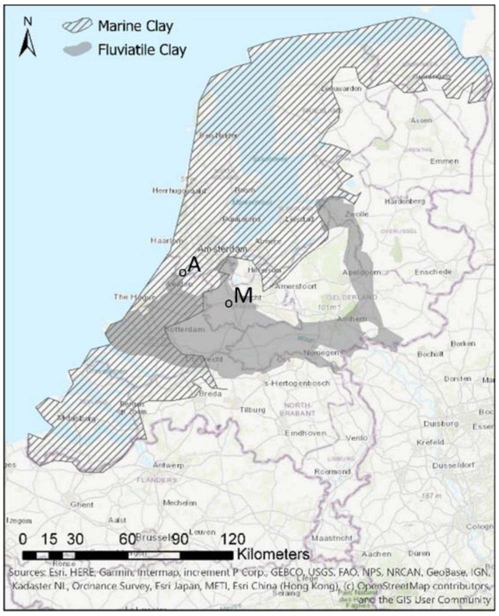

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Figure 1 Sample locations Montfoort (M) and Abbenes (A) and an indication of the marine and fluviatile Holocene clay deposits in the Netherlands.

Sample preparation and characteristics

The soil samples were left to dry in a climate-controlled room for up to 20 days, while the height and diameter of the samples were measured with the use of a digital caliper twice a day (9:30 and 16:30), with exception of weekends. The top of the samples was not covered by the latex cover, creating an evaporative surface. The measurements were terminated when no volume loss was detected for at least two days. After the measurements samples were analyzed on textural composition (pipette method; Gee & Bauder, 1986), organic matter content (loss on ignition; Heiri et al., 2001) and CaCO3 content (Schleiber method; Eijkelkamp). The sample characteristics are shown in table 1.

Table 1 Composition of the organic fluvial (Montfoort) and inorganic marine (Abbenes) clay soils in terms of calcium carbonate content, organic matter content, and grain size distribution. All values are given in weight percentages.

Soil ID	**Sample depth**	**$CaCO_3$**	**Organic matter**	**<2 µm**	**2-8 µm**	**8-16 µm**	**16-32 µm**	**32-63 µm**	**>63 µm**
Organic clay 1	95 cm	0.19	26.81	47.74	18.76	3.72	0.51	2.12	0.07
Organic clay 2	95 cm	0.19	29.63	41.12	21.4	3.93	2.66	0.91	0.21
Inorganic clay 1	185 cm	2.40	6.65	44.85	29.43	13.56	4.09	0.91	0.0
Inorganic clay 2	185 cm	0.56	7.37	39.77	32.22	10.31	9.39	0.46	0.0

Measured and fit shrinkage curves

The measurement method is suitable to measure differences in the soil-shrinkage curves of the different samples, with a measurement interval of twice a day (Figure 2). The fluviatile samples (Organic clay 1 and 2) have significantly higher initial moisture contents and void ratios than the marine samples (Inorganic clay 1 and 2). The different shrinkage phases were identified on the representative inflection points and are shown in Figure 2. The fluvial samples also show a more extensive structural shrinkage phase than the marine samples, responsible for 14-18% of the total shrinkage (Table 2).

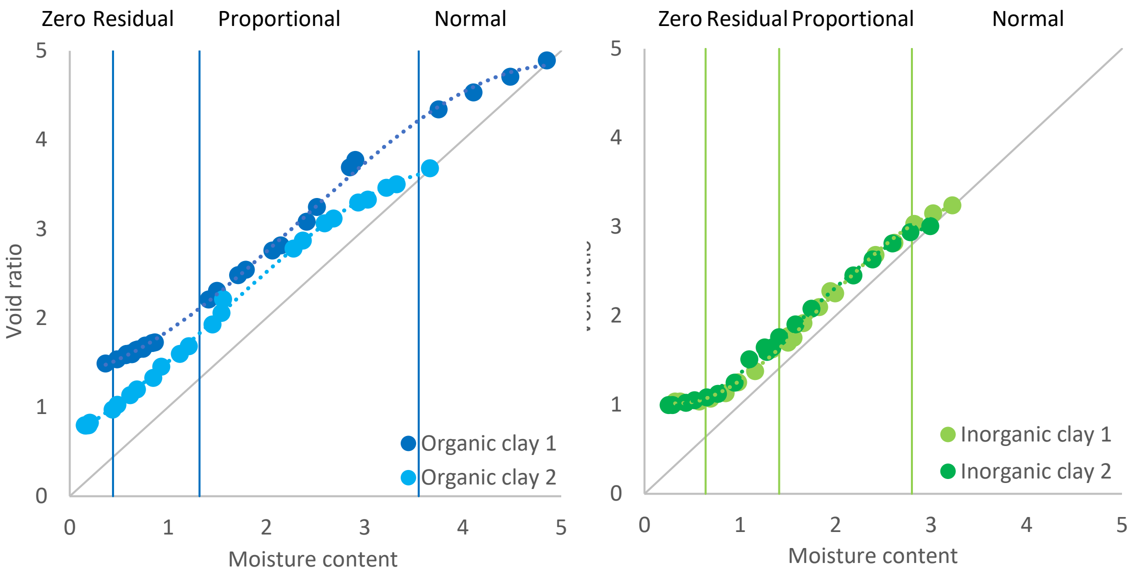

Figure 2. Soil shrinkage curves of organic fluviatile and inorganic marine samples, measured during air drying. Including indications of the transition between shrinkage phases for organic clay 1 and inorganic clay 1.

Table 2. The moisture content loss (ϑ) and decrease in void ratio (e) as per sample during the structural (s), proportional (p), residual (r) and zero (z) shrinkage phases.

Sample	ϑ_s**(%)**	ϑ_p**(%)**	ϑ_r**(%)**	ϑ_z**(%)**	e_s**(%)**	e_p**(%)**	e_r**(%)**
Organic clay 1	27.40	45.60	18.00	9.00	14.11	43.15	11.45
Organic clay 2	27.99	50.82	18.75	2.45	17.94	47.01	14.67
Inorganic clay 1	13.58	42.90	23.77	19.75	7.92	43.54	14.31
Inorganic clay 2	13.62	44.52	25.91	15.95	8.21	43.14	16.43

Shrinkage can be measured volumetrically and is often assumed to be isotropic. The measured shrinkage is not completely isotropic in these samples. Relatively, the marine inorganic clay samples show a larger height decrease during the first phase of shrinkage, followed by a more dominant decrease of radius in a later stage of the shrinkage (Figure 3). The organic fluviatile samples show a relatively larger height decrease during all phases of the shrinkage.

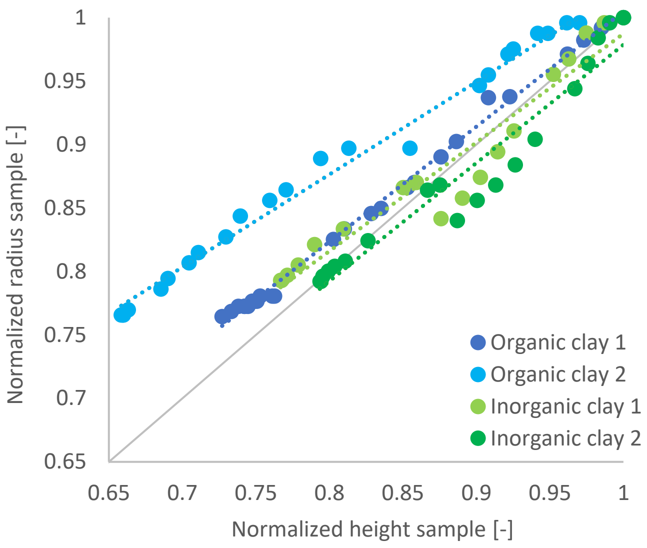

Figure 3. The normalized radius over the normalized height of the sample during shrinkage.

Conclusion and outlook

The base set-up that was devised for measuring the shrinkage of undisturbed natural clay samples is sufficient to capture the four shrinkage phases occurring during air-drying clay rich samples. The methodology would benefit when volume measurements are carried out more frequently, with regard to identifying the different shrinkage phases in the soil-shrinkage curves.

The differences in shrinkage behaviour that are identified for the four analyzed samples are a combined effect of differences in the composition, structure and density of the samples. However, the relatively larger decrease in the height of the fluviatile organic rich clay samples can be explained by the structure of the clay as a result of the depositional environment. The clay particles are deposited mostly horizontal in plate form in fluviatile low-energy deposits, whereas the high ion content in salt or brackish water causes the clay particles to flocculate and deposit in a card-house structure in marine depositional environments (Gibbs, 1983). The laminar platelets can create a denser structure than the card-house structured platelets, especially in the vertical direction.

To be able to understand and quantify the shrinkage behaviour of Holocene clay deposits in the Netherlands a larger database is needed. The aim of this research project is to create that dataset and to incorporate the results in soil shrinkage simulations. Both horizontal and vertical shrinkage can add to land subsidence, either via exposing buried organic-rich deposits to oxygen via cracks, or because of irreversible shrinkage in unripe clay layers.

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