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Novel 3D laser-testing approach for evaluating of soil-shrinkage-curve (SSC)

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ABSTRACT: Soil shrinkage is defined as soil volume change associated with water, as well as function of related properties, consistency or plasticity. In the case of soft consistency and/or high plasticity, standardized measurement methods reach their limits for detection of soil shrinkage and innovative non-destructive methods are necessary. In this paper, theoretical insights into the shrinkage of near-surface expansive clays are provided, considering an innovative novel non-destructive testing approach to evaluate the *soil-shrinkage-curve (SSC)*. Volume change was detected using a mobile *HandySCAN-3D-laser* with a volumetric accuracy of 0.02 mm and 480^{k} measurements/s. The 3D laser was first validated on calibrated objects and then tested on different expansive clays with highly swelling and shrinking montmorillonite mineral-fractions during desiccation experiments. The laser showed promising results, specifically for differentiation of the different phases during the shrinking process. The results, especially the slope of the soil-shrinkage-curve (SSC), can be used to evaluate the relation of water content changes with resulting volumetric shrinkage. It is obvious that the accuracy of the 3D laser is higher than standardized soil mechanical measurement methods and that it can provide an alternative method for non-destructive detection and 3D visualization in geotechnical engineering. Furthermore, the detailed three-dimensional acquisition of soil volume with respect to water content opens new evaluation approaches regarding the determination of SCC e.g. considering deeper insight into the main direction of shrinkage and a more detailed evaluation of volumetric shrinkage.

Keywords: non-destructive measurement, soil shrinkage, 3D-laser-technology, clay

1 INTRODUCTION

The soil mechanical behaviour of soft or clayey soils is mainly influenced by the complex multi-phase material behaviour as soils consist of soil particles, water and air. One aspect with practical relevance is soil shrinkage due to reduction in water content activated by temperature changes for example. In recent times, anthropogenic activities like increasing sealing of the subsurface lead to decreasing water supply into the soil. Together with increasing temperatures, soil shrinkage becomes increasingly important as it can induce significant vertical soil movement.

After Bachmann, 1998 soil shrinkage activates the following three mechanisms:

- Interaction between water-dipoles and soil (adsorption),
- intermolecular connection between the water molecules (cohesion),
- Brown's molecular movement as thermodynamic effect.

As result of these mechanisms the water flow inside the soil matrix is determined. Finally, the water flow leads to changes in soil moisture tension which leads to changes in volume and/or consistency. If water is transferred out of the soil matrix due to evapotranspiration for example, this leads to volume reduction.

The water-content related volume changes of soils are subdivided in different phases which are often mathematically described by means of so-called *Soil-Shrinkage-Curves (SSC)*. The four phases of soil shrinkage are described in Machacek, 2020 for example.

1. Quasi-saturated phase
2. Normal / Proportional phase (partially saturated)
3. Residual phase (drained)
4. Null-phase (dried)

Related to these phases the volume changes (e.g. by means of volumetric shrinkage strains or void ratio) can be plotted over water content, see Fig. 1.

A main issue regarding the experimental determination of the SSC is the exact and non-destructive determination of volume changes due to shrinkage with respect to changes in water content.

Therefore, the present paper presents first experimental investigations using a 3D-laserscanner to evaluate the SSC for different clays.

2 3D-LASERSCANNING

3D-laserscanning is based on an optical image capturing method to transfer the surface of scanned objects into the form of a triangulated mesh. Technically, the 3D-laserscanner projects light onto the scanned surface that is reflected and recorded as 2D pictures. All 2D pictures are then transformed into 3D-data which finally leads to a 3D mesh.

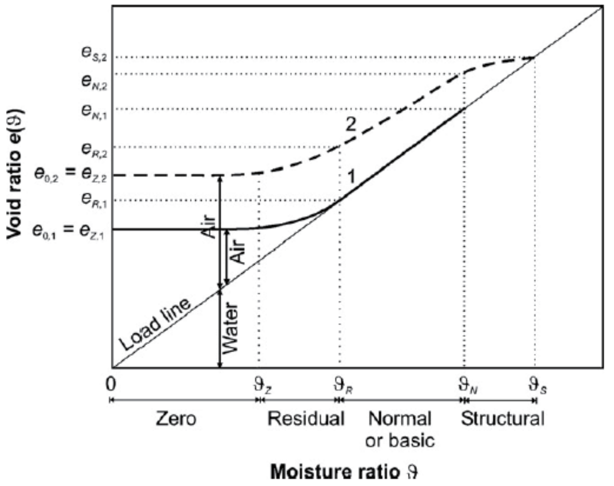

Fig. 1. Schematic presentation of a soil shrinkage characteristic curve of a non-structured soil (line 1) and a well-structured soil (line 2) after Cornelis et al. 2006.

2.1 Technical details

The present experimental investigations are carried out using a portable laser scanner type *HandySCAN 700* from *Ametek Creaform*, see Fig. 2.

Fig. 2. *HandySCAN 700* from *Creaform* together with measurement range and scanning area.

Using this laser scanner an area of 25 cm x 27.5 cm can be measured. The maximum distance between scanner and object should not exceed 30 cm, see Fig. 2. Regarding the technical details given by the producer, the resolution is about 0.05 mm with a volumetric accuracy of 0.02 +/- 0.06 mm/m, such that the overall accuracy is about 0.03 mm. Therefore, it is possible to measure volumetric changes of the soil specimen with high accuracy much below 1 mm.

2.2 Calibration tests

For evaluation of the scan-accuracy, calibration tests were carried out using cylindrical calibration objects of different height and diameter fabricated by means of CNC cutting, see Fig. 3.

The calibration objects were fabricated in a fine mechanics workshop with diameters *d* ranging from 6 mm to 70 mm and heights *h* of 10 mm respectively 20 mm. As the scanning process showed difficulties dealing with reflections on the shiny surfaces, the objects were covered with anti-reflection-spray before starting the scanning process.

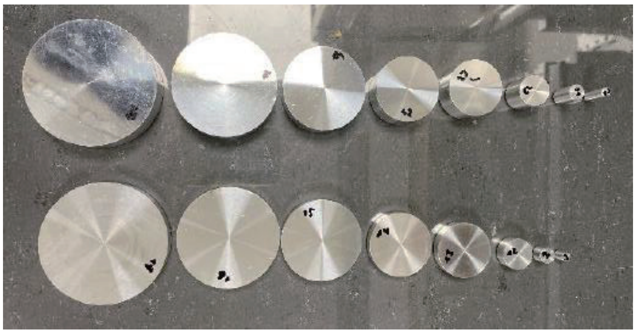

Fig. 3. Cylindrical calibration objects of stainless steel with eight different diameter and two heights.

As the resolution of the scanner mainly influences accuracy as well as the number of data captured and stored, the scanning resolution was varied throughout the calibration tests between 0.2 mm, 0.4 mm, 0.6 mm, 0.8 mm and 1.0 mm.

2.3 Determination of accuracy

For determination of accuracy the theoretical volume of the calibration objects is compared with the volume calculated out of the laserscan results. For this the scanned data can be transferred into programs like Matlab or SolidWorks where the soil volume can automatically be calculated out of the scanned mesh. The comparison of measured and theoretical volume for the investigated calibration cylinders is shown in Fig. 4.

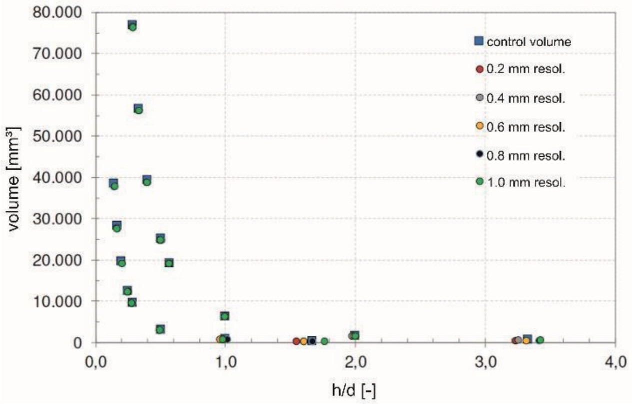

Fig. 4. Comparison of measured ratio *h/d* considering different scan resolution (0.2 mm – 1.0 mm) with theoretical volumes.

In Fig. 4 the measured volume for the different scanned objects is plotted over ratio *h/d* considering different scan resolutions. As control volume, the theoretical volume is plotted. Discussing the results, it is evident that especially for objects with higher control volume (> 10.000 mm³) the differences between theoretical value and measurement is negligible independent from scan resolution. Only regarding smaller objects (< 10.000 mm³) the resolution significantly influences the results.

All test data is statistically evaluated regarding the mean deviation between control volume and measured volume leading to a mean deviation of about 1.19%.

3 INVESTIGATED CLAYS AND EXPERIMENTAL PROCEDURE

3.1 Investigated clays

In the presented test series, three different clays with highly swelling and shrinking montmorillonite mineral-fractions and different plasticity are investigated:

- Medium to highly plastic clay (Frankfurt)
- Highly plastic clay (Offenbach)
- Extreme plastic tarras-clay (Northern Germany)

3.2 Experimental procedure

After determination of index parameters like liquid limit and plasticity index the shrinkage tests are carried out. The following test procedure is followed for every test:

1. Homogenization of the clay material.
2. Preparation of the test plate with scan targets that are necessary for localization of the scanned object, see Fig. 5, left.
3. Preparation of the internal wall of the test ring with Vaseline to avoid sticking of the clay sample during the shrinkage process.
4. Installation of the clay sample with a water content of 1.1 times the liquid limit into the test ring to provide a test specimen with known volume.
5. Removal of the ring to allow scanning of the specimen.
6. First scan process to receive the initial geometry.
7. Evaluation of specimen's weight for water content determination.
8. Shrinking by means of drying the specimen in an oven with 35° and medium air humidity of 30%.
9. Scanning, weighing and further drying of the specimen at different times to evaluate the SSC.

The 3D-scan of each specimen is then checked and postprocessed to exclude obvious artefacts in the scan and to close parts of the scan which are not fully closed, see Fig. 6.

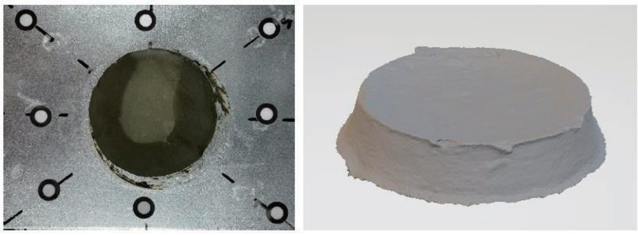

Fig. 5. Left: clay sample with scan targets for localization of the specimen during laser-scanning; right: Scan of the tarras-clay specimen after 47.8 h

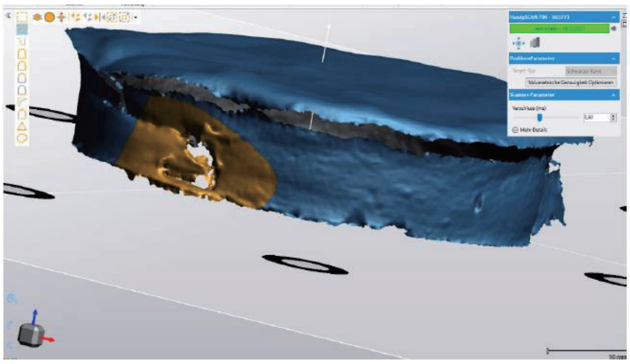

Fig. 6. Scanned specimen with non-closed surface (brown)

4 RESULTS

In the following section exemplary results are presented and discussed mainly regarding the applicability of 3D-laserscanning for evaluation of the SSC.

In Fig. 7 the measured surfaces of a tarras-clay with successively decreasing water content are shown.

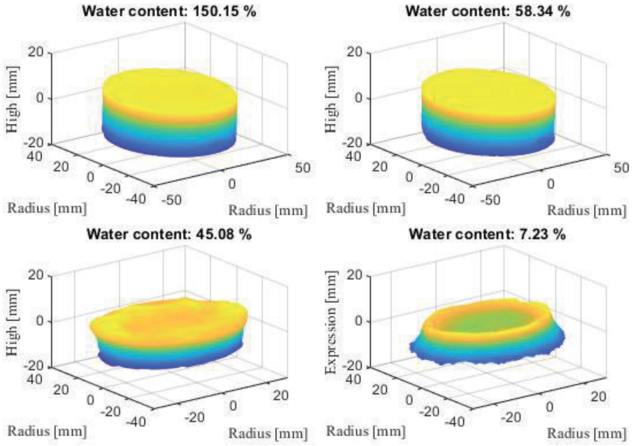

Fig. 7. Meshes received by laser-scanning of a tarras-clay specimen at different shrinkage phases (water content 150.15% (start), 58.34%, 45.08% and 7.23%)

Regarding the results in Fig. 7, it can be concluded that the volumetric shrinkage process can be visualized in much higher detail compared to classical measurements during shrinkage tests. For the investigated highly plastic tarras-clay for example, it can be seen that especially reaching a water content < 50% further shrinking leads to highly irregular volume changes. Considering these results and the possibilities of the laser-scanning technique, in further test series the degree of shrinkage can be evaluated with respect to specimen's geometry as well as direction in much more detail.

Further, void ratio with respect to water content is determined. In Fig. 8 the relation between water content w and void ratio e for four different clay samples is depicted.

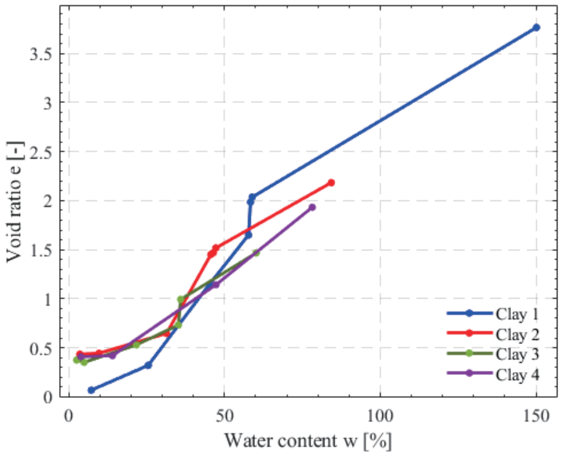

Fig. 8. Void ratio e over water content w for four test series of different clay samples.

In Fig. 8, it can be seen that the typical characteristics of the SSC are well captured. Especially, the transitions between normal, residual and null phase can be well identified. In further test series this will be investigated in more detail considering more tests especially during the start of shrinkage.

Finally, the volumetric strains over water content are evaluated for the medium to highly plastic clay in Frankfurt, see Fig. 9. The volumetric strains ε_v are evaluated by summation of radial $\Delta\varepsilon_r$ and axial strains $\Delta\varepsilon_{ax}$ which are received directly out of the digital scan data. In Fig. 9 the normal shrinkage phase of the tested specimen is marked. It becomes evident that during normal shrinkage a reduction in water content of 1% leads to a volume reduction of approx. 1.07%.

CONCLUSIONS AND OUTLOOK

The present research shows that the 3D-laserscanning approach is well-suited to evaluate the SSC of clay with higher accuracy compared to classical approaches.

Using the digital measurement data, the options for data-postprocessing are high such that many opportunities to interpret the test data arise.

E.g. it is possible to visualize the volumetric changes of soils during shrinkage with high accuracy such that the shrinkage process can be investigated with respect of direction and sample geometry for example. This may be of high interest for evaluation of shrinkage induced cracking of the top clay layer of dikes for example.

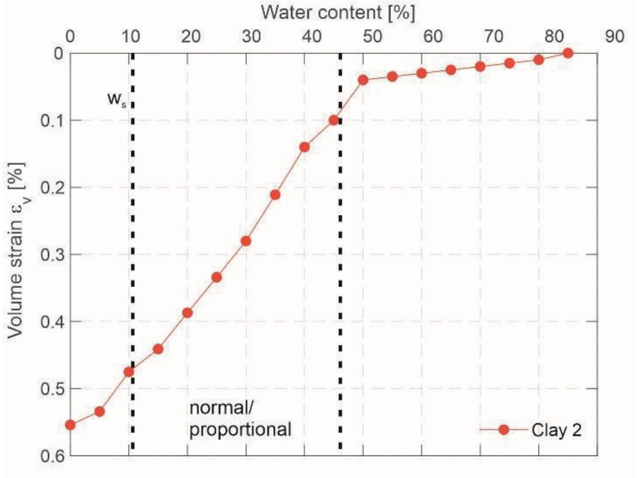

Fig. 9. Volumetric strain ε_v over water content w for a clay sample (medium to highly plastic clay / Frankfurt).

In further test series the possibilities of 3D-laserscanning in context with soil shrinkage will be investigated in more detail for example considering the variation of sample size as well as sample geometry to better understand the volumetric shrinkage process of clay materials.

Using the test data, it is aspired to develop formal relationships to characterize the shrinkage process of clay materials. These relationship will then be used in numerical simulations for numerical prediction of shrinkage induced settlements for example.

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