*Physical Modelling in Geotechnics*


# Investigation of soil clogging mechanisms at the cutting tool-soil interface with miniaturised separation tests and computed tomography

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**ABSTRACT:** Complex interactions between the cutting wheel and the soil exist in mechanised tunnelling with tunnel boring machines. Especially for tunnelling in cohesive soil, many open questions regarding the occurrence of clogging still prevail. Therefore, it is necessary to gain fundamental insights into the stickiness or adhesion of clay. Within the scope of this work, a new miniaturised testing apparatus which has been developed by the authors is presented. It allows performing separation tests on Northern German clay in a computer tomograph. In the experiment, the vertical displacement and the force onto the piston are measured. Adhesion is measured as peak separation resistance. During the test, four different loading and incremental separation steps are applied, each followed by a CT scan, resulting in local 3D data around the emerging separation gap between loading piston and clay. Using image processing, exact failure mechanisms and adhesion patterns are investigated based on the 4D (3D + time) experimental data. The new test apparatus is a promising tool to further investigate adhesion phenomena. It will be further developed.

**Keywords:** adhesion, clogging, computed tomography, clay, separation test

## 1 INTRODUCTION

The stickiness of cohesive soil is a long-known phenomenon that has mostly been studied using interface shear tests and separation tests. Already Atterberg (1911) defined a so-called stickiness limit. Still, the adhesion phenomena of cohesive soil remain not fully understood. There has been extensive research, but results remain partially contradictive. For example, Fountaine (1954) elaborated that the adhesive forces must only be due to interface suction, whereas Littleton (1976) proved that failure in shear tests is mostly cohesive, meaning within the soil specimen. The proof was given by microscopic investigation of the steel surface showing the adhesion of clay particles.

The influencing factors on soil adhesion are numerous. Significant origins of influence are consistency, clay mineralogical composition, loading and separation velocities, temperature and surface roughness of the interface (Thewes, 1999). According to Burbaum (2009) there exist differences in the relevance of these influential factors for adhesion in the normal direction (separation) and tangential direction (shear) (Burbaum, 2009).

In mechanised tunnelling clogging of the cutting-wheel can occur due to the massive adhesion of the soil. This can lead to a decrease of performance of up to 70 per cent and even a possible standstill of the entire machine (Thewes, 1999). Clogging is usually mitigated using foams, polymers and other chemical substances that allow for better soil conditioning (Alberto-Hernandez et al., 2018). However, the use of these substances is to be examined critically with regard to their environmental impact. Moreover, the mined soil material must be carefully deposited at a high cost.

In undergoing investigations at the Institute of Geotechnical Engineering and Construction Management at Hamburg University of Technology (TUHH) adhesion phenomena are investigated using miniaturised separation tests which are performed in a computer tomograph. Computed tomography (CT) allows for in situ 4D data acquisition (3D and time). The research aims at a better understanding of the adhesion mechanisms. Within this contribution, a preliminary test set-up is presented showing the potential of the undergoing investigations.

## 2 MINIATURISED TESTS AND COMPUTED TOMOGRAPHY

The use of miniaturised tests and CT is a long-used research technique at the authors' institute. In the past, it has mostly been applied in research on partially saturated granular media (Milatz et al., 2021). However, within this work, it is shown that the technique is also applicable for cohesive material.

CT uses X-rays to produce 3D scanning data of the investigated specimen. The density variation of the image data is shown by different grey values. Analysis of CT data can allow for exact determination of failure surface, adhesive soil volume and distribution of phases (soil, air and water).

As the resolution of the scan data is crucial, test set-ups are usually scaled-down. The investigated area in the scans is very small.

## 3 CONDUCTED TEST

The presented test is a normal separation test where a loading piston is pushed onto a clay sample by displacement control. Piston and specimen are separated in three different separation steps. One CT scan is performed between every single test step which leads to a total number of four scans (see Fig. 3).

### 3.1 Tested soil

The investigated soil is a typical Northern German clay that is mined in a clay pit close to the city of Lüneburg, Lower Saxony. It is typically used for landfill sealings. The soil has been chosen as it is similar to other cohesive soils in the Hamburg region where numerous tunnel construction projects will be undertaken within the next decade. In most of these projects clogging is likely to occur. The grain-size distribution of the material is depicted in Fig 1.

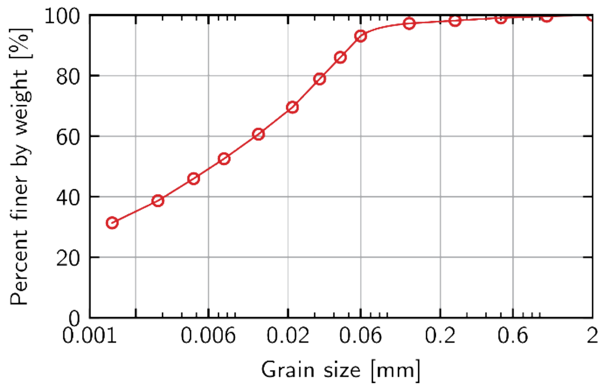


Fig. 1. Grain-size distribution.

The soil is delivered in disturbed condition and subsequently remoulded and homogenised using a commercially available meat grinder. Within this work, the desired consistency is controlled by the added amount of water. The initial water content of the specimen was 54 per cent. The Atterberg limits of the soil are depicted in Tab. 1. The consistency index of the specimen is 0.35 at the beginning of the test. The specimen is prepared by inserting the material into a cylindrical specimen holder and smoothing the surface using a metal spatula.

Table 1. Atterberg limits.

| Liquid limit [-] | Plastic limit [-] | Shrinkage limit [-] |
|---|---|---|
| 0.67 | 0.301 | 0.149 |

According to Schniedermann et al. (2021), clogging is likely to occur as the amount of clay minerals of the smectite group is above 40 per cent and the quartz percentage is comparably low. The entire mineralogical composition is shown in Tab. 2.

Table 2. Mineralogical Composition.

| Mineral | Fraction [-] |
|---|---|
| Quartz | 0.3308 |
| Microcline | 0.0879 |
| Chlorite/Illite/Smectite | 0.4438 |
| Kaolinite | 0.0842 |
| Gypsum | 0.0256 |
| Pyrite | 0.0182 |
| Anatase | 0.0094 |

### 3.2 Test set-up

The test apparatus is based on the work of Milatz (2019). It consists of a modified miniaturised uniaxial compression device which is shown in Fig. 2. A stepper motor is driving the load piston onto the clay sample. The load piston is made of PVC and has an average roughness value of $R_a$ = 0.4669 µm. A load cell below the specimen measures the force. The entire set-up is 161 mm in height and 40 mm in diameter. The soil specimen is 30 mm in diameter and 5 mm in height. The piston has a diameter of 10 mm.

The press is controlled by a single-board computer which also receives the force measurement data from the load cell. In total, the set-up consists of the motor and its driver and a measuring amplifier and subsequent AD converter which processes the analogue load cell data. All control scripts are written using the programming language Python. Further information on the basic functional principles of the set-up can be retrieved from Milatz (2019) and Milatz et. al (2021).

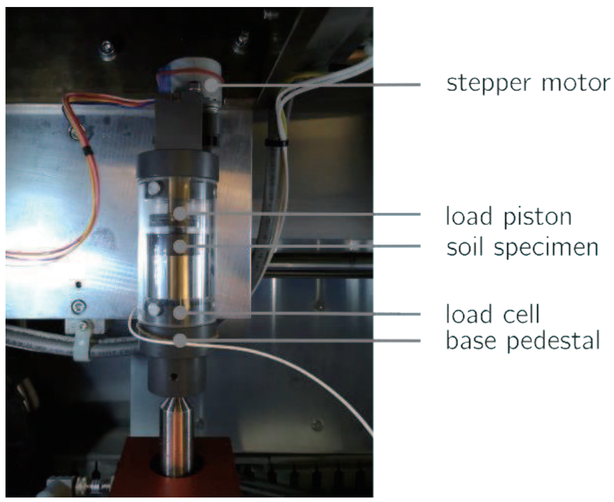


Fig. 2. Miniaturised experimental set-up in the computer tomograph.

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### 3.3 Test procedure

The test procedure is shown in Fig. 3. The first scan a) is performed after pushing the piston 1 mm into the soil. Separation is performed in three steps, each followed by a scan. The scan time for a scan is 75 min with a voxel size of 10 µm (see Tab. 3). The loading and separation speed is 0.2 mm/min. The scans were performed in a SCANCO Medical MicroCT 35 at the Institute of Biomechanics of TUHH.

The total time of the test was about 7 hours including sample preparation, test initialisation and execution.

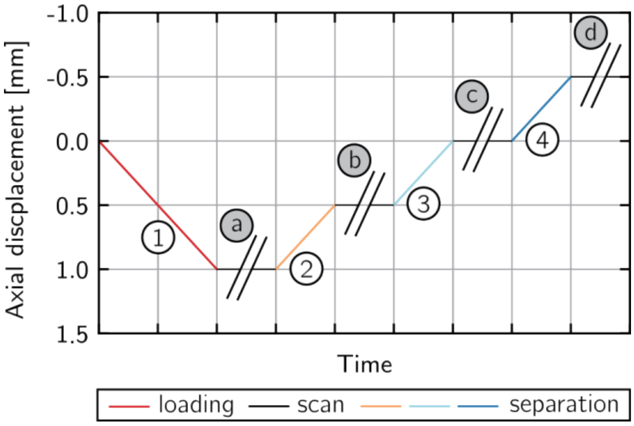


Fig. 3. Test procedure.

Table 3. CT settings.

| | |
|---|---|
| Energy/Intensity | 70 kVp, 114 µA, 8 W |
| Field of view | 20.5 mm |
| Voxel size | 10 µm |
| Number of slices | 464 |
| Integration time | 800 ms |
| Averaging | 2 |
| Measuring time | 75 min |

## 4 RESULTS AND DISCUSSION

The stress-displacement curve of the test is depicted in Fig. 4. The maximum pressure is 37 kN/m² at the end of the loading phase. Due to the relaxation of the material, the pressure drops to about 18 kN/m² at the start of the first separation step. The maximum tensile stress is 19 kN/m². Since the failure occurs slowly and partially between scans (compare Fig. 5), the maximum separation stress cannot be determined. After full cohesive failure within the specimen, the measured stress drops to zero. All stresses are calculated by dividing the measured force by the piston surface area.

Fig. 5 shows vertical 2D cross-sections of the CT data in the middle of the specimen at the different separation steps. The surrounding air is depicted in darker grey values. Silt and sand particles in the soil are visible with low grey values. The investigated soil area is homogenous and without visible air inclusions.

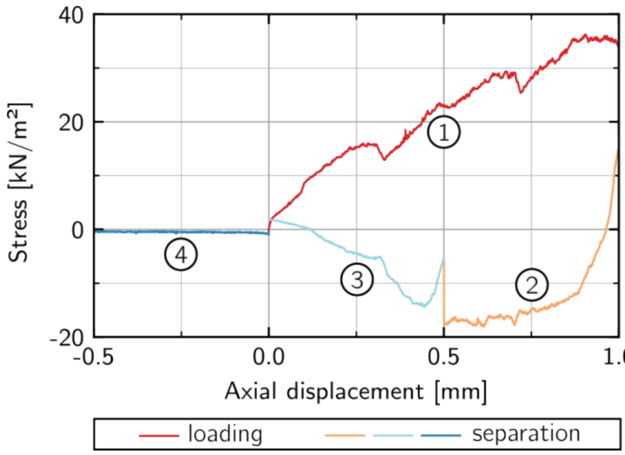


Fig. 4. Exemplary stress-displacement curve during a separation test with CT imaging (tensile stresses are negative).

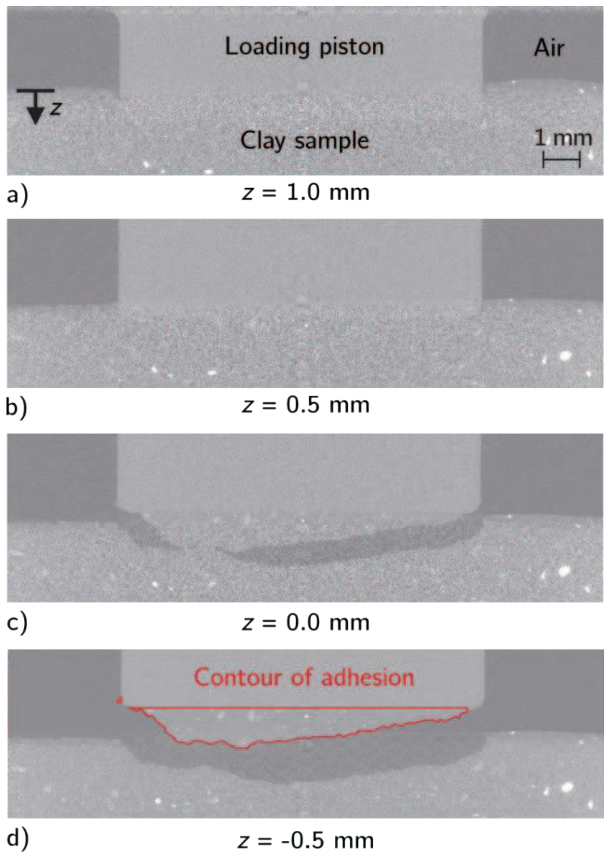


Fig. 5. 2D images from CT scans at different steps of displacement.

After the initial loading phase, soil bulging can be seen which is related to ground failure. After the first separation step, a first separating gap can be observed on the right side of the piston. After the subsequent second separation step, only a small remaining area with soil contact can be observed. The failure mechanism can be further understood and investigated in the 3D visualisation as shown in Fig. 6.

The failure zone is of irregular shape and the adhering soil body is the thickest close to the centre of the piston. The total weight of the adhering soil body was 0.051 g at the end of the test. The contour of the adhering soil body is labelled with a red line in Fig. 5. The volume of the adhering soil body, determined from CT data, is 35.26 mm³. The failure surface is 105.32 mm². In Fig. 6 the surface is shown in blue colour.

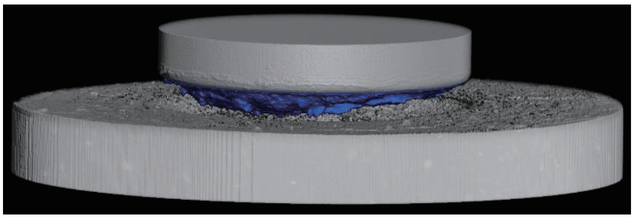

Fig. 6. 3D visualisation of the specimen and load piston after separation step d). Adhering soil body depicted in blue.

The water content of the remaining soil in the specimen holder was 47.22 per cent *($I_c$ = 0.54)* at the end of the conducted test.

## 5 LIMITATIONS

The presented test has several limitations that need to be considered in future work. First, the stress state of the sample is unknown. This is due to the sample preparation technique and because the current set-up can only be operated in displacement-controlled mode.

Secondly, the scan times in the used computer tomograph are very long. This causes dehydration of the sample and allows only for a limited number of scans or rather separation steps. To analyse the separation failure in-depth, it will be necessary to increase the number of scans and shorten scan times without losing scan resolution. Also, continuous scanning without interruptions is desirable.

Finally, the material of the piston needs to be changed to steel to investigate the problem more closely related to mechanised tunnelling.

## 6 OUTLOOK

Currently, a more advanced miniaturised set-up is being developed and tested. It will feature two load cells, one above the piston and one below the sample. The load cell above the piston will allow for a force-controlled sample loading. This will be achieved by implementing a closed-loop proportional–integral–derivative (PID) controller that is included in the Python script that is operating the motor.

Moreover, the sample preparation is going to be changed. Own investigations have shown that reproducibility of sample homogeneity, stress state and sample surface can only be reached by creating reconstituted samples using a consolidation technique. Therefore, samples are going to be pre-consolidated outside the experimental set-up from slurry with water content above twice the liquid limit of the material and subsequently consolidated to the wished-for state within the experimental set-up. This way an optimal interface between piston and sample is assured.

Future tests will also include the development of a miniaturised interface shear box test set-up. CT scans will be performed at the Université Grenoble-Alpes, where a more powerful and efficient computer tomograph is in use.

Advanced analysis of the 4D data will provide further quantitative information about exact failure surfaces, exact failure stresses, exact volumes of the adhering soil body and qualitative assessment of failure modes related to the consistency of the soil and surface roughness of the loading piston.

## 7 CONCLUSIONS

The newly developed test set-up has shown that the use of computed tomography will allow for an in-depth investigation of adhesion phenomena. After further development of the apparatus, new insights will be gained, and existing research can be assessed together with the use of an environmental scanning electron microscope which will allow for investigation of clay particle orientation.

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