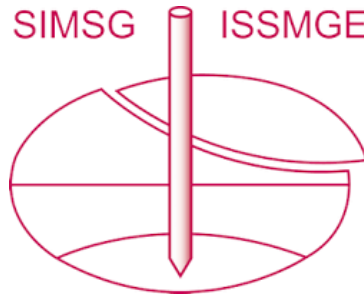


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Development of a laboratory testing device for soil-structure-interaction characterization

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ABSTRACT: Investigation of special geotechnical phenomena related to the interaction between soil and structure requires innovative experimental testing setup. In this relation, a laboratory testing device, called *GEOTribometer* is presented in this paper. The *GEOTribometer* is able to investigate the soil-structure-interaction in various ways and combine the features of *standard incremental loading test* and *ring shear apparatus*. A rotational pressure plate with variable interface roughness is connected with a highly sensitive multi-component sensor that measures moments and forces in x, y and z direction. By interpretation of forces, moments and additional rotations, the laboratory testing device enables insights to be found about three different directions of shear strength and their volumetric distribution at the interface. Prototype tests were made with clay to confirm the functionality of the *GEOTribometer*. The device is intended to provide a further step towards understanding the relationship between shear strength and radial stresses in terms of relative movement between soil and structure.

Keywords: Tribology, shear behaviour, interface friction, laboratory testing

1 INTRODUCTION

In geotechnical engineering soil-structure-interaction (SSI) is of high importance to describe the behaviour of various geotechnical systems. The SSI is various and its characterization requires an explicit understanding of the influences and properties both of soil and structure. The interface between soil and structure depends on several factors and its investigation needs innovative and as comprehensive as possible experimental set up. A frequent example for an SSI problem in practice is the relative movement between pile and soil during and after installation. Affected by the stress level and grain size distribution and particle geometry of the soil, the type and velocity of installation method, as well as the roughness of the structure, the result is a complex system with a high interaction of all these influencing factors (Brumund and Leonards 1972), (Henke 2013), (Han et al. 2018). Therefore, only an experimental device considering as many of the above-mentioned influencing factors under redundant conditions as possible allows for a realistic representation of the soil-structure-interaction in laboratory scale. Based on findings from (Kelly 2003), the *GEOTribometer* was developed for soil-structure investigation on element scale and is presented in this study. First, a short introduction into the principals regarding the *GEOTribometer* is given. Finally, the results of prototype tests are presented.

2 GEOTRIBOMETER

The word tribometer is a derivation of *tribology*. The

GEOTribometer developed by the *Professorship for Geotechnics at Helmut Schmidt University (HSU)* bases on the experimental testing setup of a standard incremental loading test (standard oedometer test) according to European standard DIN EN ISO 17982-5. The apparatus and measurement specifications are based on “*a ring shear torsion apparatus*” by (Yoshimi and Kishida 1981), (Ramsey et al. 1998) according to DIN EN ISO 17892-10. The name tribology was first mentioned in a research document in 1966, written by Peter Jost. The science of tribology describes the contact mechanics, friction, lubrication and wear between materials. However, first experiments on contact mechanics date back to Leonardo da Vinci, such as his *Codex-Madrid I of 1495* on the proportionality of normal and shear stress, and 200 years later by the rediscovery of Guillaume Amontons in 1699 as *Amonton's Law*, see (Popova and Popov 2015). Based on these findings, Leonard Euler 1750 and 30 years later the French Engineer Coulomb introduced the friction coefficient as well as static and kinetic friction, which contains all essential parts of tribology, see (Popov 2016). The *GEOTribometer* unifies these findings by friction referring to soil mechanics and geotechnical specifications. The principle experimental setup of the *GEOTribometer* consists of 6 basic elements (Fig. 1).

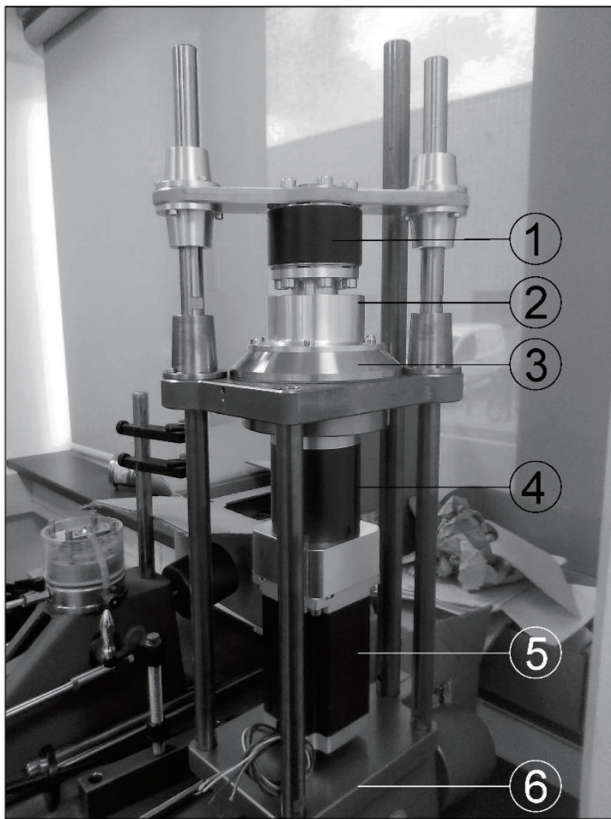


Fig. 1. Principle experimental setup of GEOTribometer.

The main element for friction measurement is the highly sensitive multi-component sensor (1), which detects both forces and moments in the three directions of a cartesian coordinate system. The sensor is connected via 24 pol cable with a measuring amplifier which passes the data to a smart computer, called *Raspberry Pi*. The multi-component sensor is mounted and centred with six female thread M8 x 1.25 screws. The screws attached the load beam above according to the principles of standard oedometer test. The attachment requires defined locking torque; thus damages, deformations and strains are avoided. The bottom of the sensor is linked with a rotational pressure plate with variable interface roughness for measuring friction between soil sample and other materials. The soil sample is filled in a pressure cell (2) with a diameter of 75 mm. This is larger compared to standard oedometer test. The larger dimension allows the installation of additional internal tubes for measuring shaft friction between soil sample and the pressure cell. However, this will be developed in further research. The pressure plate is placed on a rotation frame (3). The rotation frame is connected to a *precision planetary gearbox* (4), which reduces the incremental steps of rotation velocity, as small deformation-rates are necessary. The planetary gear is powered by an electric *stepper motor* (5). The motor and the additional experimental setup are placed on a steel frame, which is linked to the centre area (6) of a standard oedometer test.

3 MULTI-COMPONENT SENSOR

The sensor of *ME-Meßsysteme Ltd.* measures forces and moments in three orthogonal directions, x, y and z direction. The system of the sensor consists of six single-axis force sensors, which are connected to strain gauges. The signal of the strain gauges is processed via cable to a measuring amplifier. The measurements are then transformed to forces and moments using a calibration matrix. The calibration matrix is responsible for optimization of accuracy and to minimize crosstalk's, providing valid and reliable values for specific load cases. After transforming signals to forces and moments, USB 3.0 port supply data to PC, which can export as ASCII code. The multi-component sensor is made of high-strength, ferritic stainless steel. The transmission of forces and moments is guaranteed via 1 mm high trapezoidal circular segments, between inner cantering and outer diameter. The area in the centre of the sensor and the slots between the circular segments are not loaded (Fig. 2).

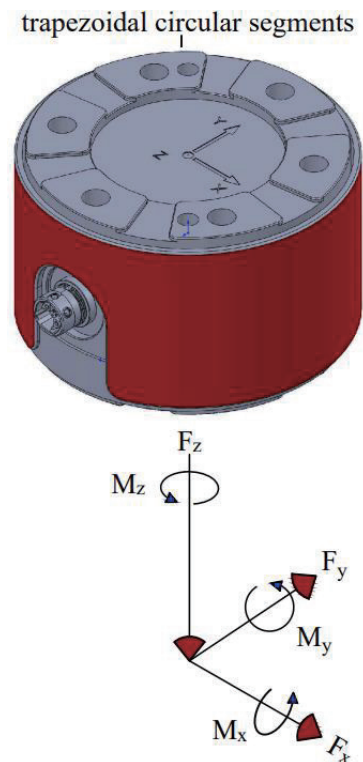


Fig. 2. Multi-component sensor (1).

As mentioned, a rigid connection to the sensor on both flanges has to be flat to be conform to appropriate locking torque influencing accuracy of the sensor. The sensor accuracy depends on so called crosstalk's and reproducibility (standard uncertainty). The effect of crosstalk's describes the introduction of signals in one direction, which also induce interferences in orthogonal directions. The reduction of crosstalk's and the temperature-induced reproducibility lead to so called

accuracy class of about $\pm 0.2\%$. The maximum recordable forces, in x and y direction are 5 kN and in z direction 15 kN. These values include pressure as well as tension loading. The maximum moments to be measured are 250 Nm in every direction. As mentioned, the trapezoidal circular segments at outer diameter allow measurements of the maximum moments and forces.

4 STEPPER MOTOR AND PLANETARY PRECISION GEARBOX

The stepper motor as well as the precision planetary gearbox are made from *Nanotec Electronic Ltd.* The stepper motor is a so-called *NEMA-34 synchronous motor* (Fig. 1, (4)) which rotates synchronously with small rotating steps induced by an electromagnetic field. The motor is powered by 9 V with two phases. The rotation depends on 200 Steps for one revolution, thus results in a step angle resolution of 1.8° ($360^\circ/200$ steps). The motor has holding torque of 11 Nm according to regulations of US-inter trade organization *National Electrical Manufacturers Association* (NEMA). The holding torque depends on steps per second, which has maximum of 6000 steps per second. However, to identify and determine contact behaviour, it's necessary to measure small shear strains in the interface zone between soil and materials. Therefore, a precision planetary gearbox is additionally used in the GEOTribometer, (Fig. 1, (5)). The gearbox is responsible to reduce the step angle from stepper motor. The *GPLE-80* gearbox of *Nanotec Electronic Ltd.* can be easily connected to the stepper motor with the overhead pin and screws. The number 80 indicates the factor of step angle reduction.

5 TESTING SET-UP

A pressure cell (2) with diameter of 75 mm and inner effective high of 45 mm is used for all tests. The soil samples investigated in the current study consist of cohesive clay. The averages of the water related parameters for the clay yield in middle plastic clay with 55% liquid limit and 29% plastic limit. The rotational pressure plate consists of steel with an approximate surface roughness of $R(z) \approx 10 \mu\text{m}$, see (Uesugi and Kishida 1986). The initial water content of the tested clay is 30%. After filling the soil samples into the pressure cell, consolidation starts. The consolidation is applied by means of a vertical normal stress of 226 kPa. Related to the diameter of the pressure cell, this corresponds to an applied load of 1.000 N. Regarding the lever arm of the standard oedometer test of 1:10 after (DIN EN ISO 17982-5), this load is received by application of 10 kg mass. The tribology investigations start after the consolidation process. First, the angular velocity ω of rotational motion is adjusted. The angular

velocity for the following test setup is $10^\circ/\text{min} \approx 0.0029 \text{ rad/sec}$. Shear displacements s as function of time $s(t)$ can then be expressed by means of integration of velocity over time:

$$s(t) = \int v(t) dt \quad (1)$$

For rotational motion, velocity v is calculated using following equation:

$$v = \omega r_{\perp} \quad (2)$$

with the radius $r_{\perp}$ of the pressure plate and the angular velocity ω . It has to be considered that the forces and moments are detected over the entire cross-sectional area of the pressure plate. As described in eq. (2), the radius is a multiplying factor such that the largest shear displacements of the pressure plate develop at the edge of the pressure plate. The following shear displacements therefore refer to half of the diameter of the pressure cell (37.5 mm).

6 RESULTS

The results of force and moment measurements as function of shear displacements are presented in the following Fig. 3 and 4.

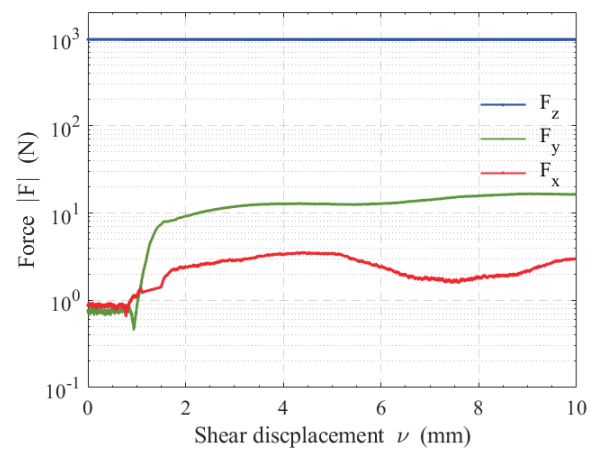


Fig. 3. Amount of measured forces $|F|$ in x, y and z direction vs. shear displacements v .

The test results regarding the forces (Fig. 3) show significant difference between vertical applied load in z direction and forces in x and y direction, thus it's plotted in logarithmic scale. The curve of $|F_z|$ immediately starts with consolidation whereas the forces in x- and y-direction successively develop with increasing rotational motion. The vertical force $|F_z|$, detected by the sensor, is approx. 990 N. This is quite equal to the applied load of 1.000 N with a difference of approx. 10 N. The difference can be attributed to the mentioned accuracy of the device as well as stiffness and connections of the components. Comparing the forces with moments, it is

evident that the applied load in z direction leads to an increase of moment in same direction and decrease in other directions (Fig. 4).

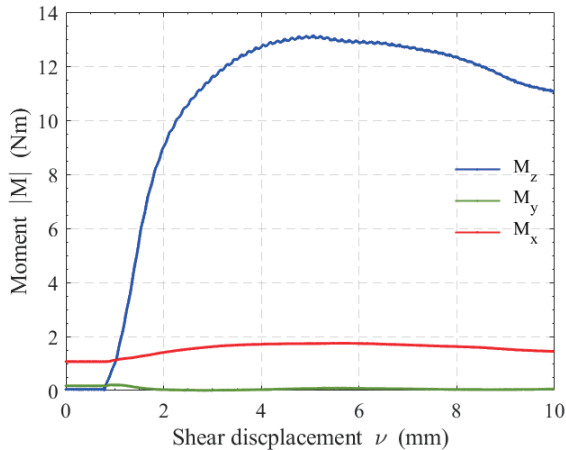


Fig. 4. Amount of measured moments $|M|$ in x , y and z direction vs. shear displacements ν .

The values for $|M_x|$ and $|M_y|$ are inverted, compared to its correspondent forces, which is indicated from rotational moving. The measured curve progression of torque $|M_z|$ is significant for interface shearing compared to simplified Mohr-coulomb frictional model (Coulomb 1821) as well as hyperbolic approaches like described in (Clough and Duncan 1971) and (Lashkari 2013). Summarizing, the *GEOTribometer* shows auspicious results and offers new possibilities for evaluating and modelling interface behavior considering three-dimensional load-bearing behavior. Contrary, the device exhibits some limitations such as soil sampling and the high sensitivity of the sensor. Hence, further development and tests are necessary at this point.

CONCLUSIONS

In this study, the development and first application of a new laboratory testing device the so called *GEOTribometer*- for soil-structure-interaction is presented. The *GEOTribometer* has a highly sensitive multi-component sensor, which detects forces and moments in x , y and z direction. The sensor is connected to a precision planetary gearbox with a suitable stepper motor, powered by electricity. The combination of gearbox and stepper motor enables very small shear strains, regarding interface behaviour in soil mechanics. First tests were made on clay samples to show the capabilities of the testing apparatus. Concluding, the applied vertical loads are well captured by the measured forces in z direction. The torques show characteristic interface behaviour for clay. The forces as well as moments in x and y direction are rather small, but typical shear behaviour can be identified that follows the applied

vertical load in xz and yz shearing. In further research, the *GEOTribometer* will be developed aiming to establish an evaluation approach for SSI characterization based on model scale laboratory tests. Parallely, it is necessary to better understand the complex shear behaviour during the tests which will be investigated by means of numerical simulations.

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