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Development of a triaxial test for hydraulic loading of fine-grained soil

Développement d'un essai triaxial pour le chargement hydraulique de sols à grain fin

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ABSTRACT: According to Eurocode 7 (EC7), the strength of soil is not taken into account for hydraulic failure ULS verifications. For hydraulic heave, the established equilibrium of effective soil weight and seepage force considers the loss of effective stress in granular material but neglects the fact that in silt and clay, the failure mechanisms under hydraulic loading are considerably different whereby additional soil parameters play a decisive role.
Insitu and laboratory observations indicate that the hydraulic failure in cohesive material is initiated by fractures in the ground. Hence, this paper presents a modified triaxial test with a hollow needle to locally induce an excess pore pressure in the soil sample in order to ultimately investigate the resistance of these soils against hydraulic fractures and its dependence on specific soil parameters and state variables.

RÉSUMÉ: Conformément à l'Eurocode 7 (EC7), la résistance du sol n'est pas prise en compte quant aux vérifications de la rupture hydraulique de l'état limite ultime. Pour prouver la rupture par annulation des contraintes effectives verticales, l'équilibre établi entre le poids effectif du sol et la force d'écoulement provoque une perte de la contrainte effective des matériaux granulaires. Pour les limons et argiles, il ignore toutefois le fait que les méchanismes de défaillance sont considérablement différents pendant le chargement hydraulique. Dans ce cas, d'autres paramètres de sol jouent un rôle décisif.
Des observations in situ et en laboratoire indiquent que la défaillance hydraulique des matériaux cohésifs est causée par des fissures dans le sol. Alors, cet article propose un essai triaxial modifié à l'aide d'une aiguille creuse afin d'appliquer une pression interstitielle locale dans l'échantillon. Cela sert à examiner la résistance de ces sols à des fissures hydrauliques et sa dépendance de paramètres de sol spécifiques et de variables d'état.

Keywords: fine-grained soil; triaxial test; hydraulic failure; hydraulic fractures

1 INTRODUCTION

Hydraulic heave, uplift, internal erosion and piping are the hydraulic failure mechanisms considered for the ULS verification in the Eurocode 7 (2014). The failure by hydraulic heave is often discussed as it can be decisive for the design of constructions exposed to current load whose sudden occurrence does not leave time for countermeasures.

However, little effort has been made to improve the verification method to take into account the properties of fine-grained soil subjected to hydraulic loads. The currently applied equilibrium of forces

$$S_{\mathrm{dst,d}} \leq G'_{\mathrm{stb,d}}$$

with the driving seepage force S (N) and the resisting buoyant soil weight G' (N) is based on the studies concerning granular material by Terzaghi (1961). This approach is suitable for soil if bonds between particles are absent and boiling or liquefaction occurs when the critical hydraulic gradient is reached. For soil with a certain amount of fines, capillary, electrostatic and chemical forces can lead to cohesion and tensile strength and prevent the loss of the grain-to-grain contact. Hence, with an increasing amount of fines, other hydraulic failure mechanisms are decisive and the verification according to Terzaghi's force equilibrium at a soil column is not necessarily on the safe side. The application of the additional resistance resulting from the cohesion or tensile strength of these soils against hydraulic heave at the boundaries of the soil column to achieve a more economical design is negligent. Firstly, the observed rectangular soil column is not necessarily the reference volume of interest for the occuring failure mechanism in cohesive soil and secondly, the resisiting soil parameters are determined by laboratory or insitu-tests under boundary conditions which do not correspond to those during hydraulic loading.

2 REVIEW OF PREVIOUS INVESTIGATIONS

In the literature few investigations on the hydraulic failure of deep excavation in cohesive ground can be found. Milligan & Lo (1970) document several construction sites in clay and suggest a critical ratio of the excavation depth to the water head. The laboratory set-up of a perspex box with a wall in cohesive soil by Wudtke (2014) enables the detailed observation of the failure sequence during the controlled increase of water level difference. The initiation of the hydraulic failure starts at the bottom of the wall with emerging horizontal fractures. These fractures extend to the surface of the downstream side of the model and a parabolic soil block detaches, held in place by its buoyant weight and the remaining resistance in the sodding shear band.

While these case examples demonstrate that the failure procedure in cohesive ground varies according to the soil properties and state variables, they have in common that the failure mechanism is initiated by hydraulic fracturing.

In other fields of the geotechnical engineering the fracturing of fine-grained soil by the increase of pore pressure is a familiar issue: Since the failure of Teton Dam (Idaho/USA, 1976) (Seed & Duncan 1987) several studies have dealt with fractures in the cohesive core of earth dams causing seepage failure (Jaworski et al. 1981, Sherard 1986, Lo & Kaniaru 1990). Other research activites have been motivated by practical applications in the grouting technology (Mori & Tamura 1987, Soga et al. 2004) and for the insitu-determination of the ground permeability (Bjerrum et al. 1974) or lateral earth pressure (Bjerrum & Andersen 1972, Levebvre et al. 1991).

Based on insitu- or laboratory tests, failure criteria are suggested to either avoid or provoke the hydraulic fractures. The deduced models can be classified into four categories: analytical derivations, empirical relations, application of mechanical fracture models and numerical simulations.

Analytical approaches are practicable to estimate the stress conditions in the area of the borehole or the injection needle, which is simplified to an expanding cavity with an internal pressure according to the fracturing pressure. The closed-form solution of Bishop et al. (1949) for concentric cavities in elastic, non-frictional material has been expanded for cohesive, frictional and elastoplastic soil behaviour (Massarsch 1977, Carter et al. 1986, Panah & Yanagisawa 1989, Ghanbari & Rad 2013). Thus, hydraulic fractures occur if the

minimum stress at the cavity exceeds soil strength.
Empirical correlations between the fracturing pressure P_f (Pa) and the minor principal stress σ_{min} (Pa) can be expressed by a linear equation:

$$P_{\mathrm{f}} = m\sigma_{\min} + n\,.$$

Depending on the material and the boundary conditions of the corresponding investigation, the constants m and n refer to the shear or the tensile strength of the soil while either total or effective stresses are applied (Mori & Tamura 1987, Andersen 2001).
In fracture mechanics the stress intensity factor (LEFM) or the J-Integral (elasto-plasticity) solve the problem of discontinuity at the fracture tip. Hence, these methods are applied for soils in Murdoch (1979).
Increasing computational power enables the implementation of coupled processes during hydraulic fracturing in saturated, porous and permeable media in particle or continuum simulation methods. By applying suitable material and failure models, the interactions between the fracture initiation and propagation due to the fracturing pressure, the flow in the fracture and the exchange with the pore fluid, the deformation of the continuum and the pore fluid flow can be observed (Zielonka et al. 2014, Xu et al. 2018). To verify the numerical methods and validate the soil models, well documented experiments are crucial.

Previous studies on hydraulic fractures in cohesive soil have shown inconsistent results regarding fracturing pressure, failure mechanisms and fracture geometry. This is mainly due to the differing material, sample preparation, laboratory set-up and test procedure.
However, there is large consensus that the fracture propagates perpendicular to the minor prinicipal stress according to mechanical theories (Murdoch 1979, Lo & Kaniaru 1990, Soga et al. 2004). With a decrease of the overconsolidation ratio (*OCR*) or normally consolidated soil, the direction of the fracture is harder to predict, or an area of fine fissures is observed (Alfaro & Wong 2001).
The required fracturing pressure increases with the confining pressure (Panah & Yanagisawa 1989, Lo & Kaniaru 1990, Andersen 1994, Djarwadi et al. 2015) and decreases if the sample is notched to initially insert an inhomogeneity (Mori & Tamura 1987, Alfaro & Wong 2001).
To assess the fracture criterion of cohesive soil by laboratory studies the samples and the boundary conditions must be derived from the insitu conditions.

3 AIM AND PROCEDURE

To improve the verification procedure against hydraulic failure in fine-grained ground, a laboratory study will be conducted to evaluate the resistance of soil with different contents of fines against the initiation of hydraulic induced fractures. As fractures are stated to announce the hydraulic failure mechanism in silt and clay, it seems helpful to apply a fracture criterion to avoid hydraulic failure.
The hydro-mechanical behaviour of soil containing a significant content of fines strongly depends on the composition of minerals, the overconsolidation ratio (*OCR*), the degree of saturation and the loading velocity, just to mention the most important influencing factors.
Hence, a triaxial test suits this purpose best as it enables variable initial states of *OCR*, stress ratio and saturation for the samples to be fractured.

3.1 Pre-trials

A feasibility study was conducted at the Materialforschungs- und Prüfanstalt Weimar (MFPA) using samples of silt (h/d=120/100 mm) compacted to 97% of the Proctor density

on the dry side and a conventional triaxial apparatus. For the fracturing of the samples a special top plate was designed (Figure 1) with a needle (d=4,5mm), which was inserted into a pre-drilled hole in the sample. To regulate the fracturing pressure at the porous tip of the needle, an external volume-pressure controller was used. In the course of these pre-trials, six samples were charged by internal fracturing pressure to failure in this set-up.
The preliminary study confirmed that the set-up is generally suitable for hydraulic fracturing of cohesive soil. Sample installation or leakage along the needle were not an issue. The initiation of a fracture at the tip of the needle was indicated by a sudden pressure drop at the needle and an increase in the flow rate. To observe the formation of the fracture with non-destructive methods, two trial-samples were observed with 3D-scans by nanotomography (Figure 4).

However, the pre-trials showed structural and procedural shortcomings. Firstly, the microstructure of the compacted samples did not represent the insitu state of soil at construction sites which is naturally sedimented. The incidence of aggregates which lead to various pore sizes within the sample caused inhomogeneity and was therefore not suited to determine the resistance of natural soil against hydraulic pressure.
Secondly, neither the hardware nor the applied software were suitable to carry out the test procedure reasonably. Prior to the fracture initiation, the excess pore pressure at the needle caused local dilatancy which resulted in an increase of permeability and a significant change of the resistance for the volume-pressure controller at the fracturing needle. This led to an oscillation of the regulatory circuit as the PID controller could not be adjusted and caused a premature damage in the sample. Furthermore, the pressure at the needle was manually operated and there was no possiblity to view the recorded data during the the test.

3.2 Experimental setup

With the experiences from the trial tests in Weimar, an optimised triaxial set-up for hydraulic fracturing could be designed for the laboratory study at the Federal Waterways Engineering and Research Institute in Karlsruhe: Two cells are equipped with a modified top plate (**Error! Reference source not found.**). While saturation and consolidation are in progress in one of the devices, the other one is attached to four independent high-precision volume-pressure-controllers to determine the hydraulic conductivity of the sample and perform the final pressure increase to failure.

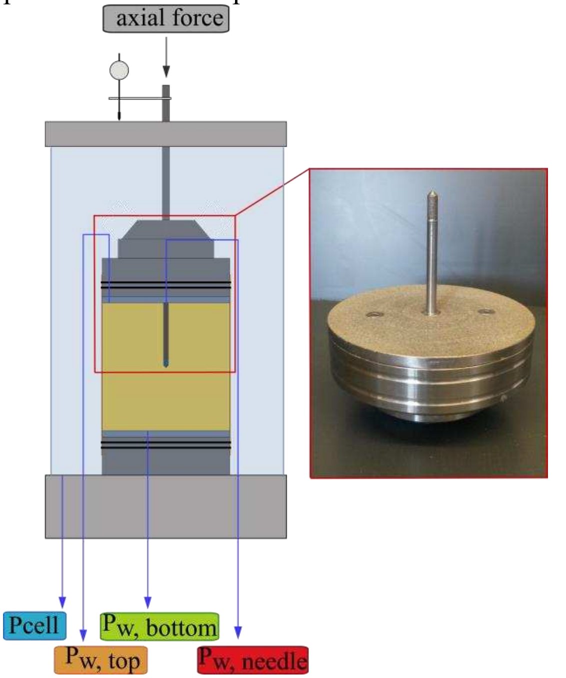

Figure 1. Sketch of the triaxial cell with four independent volume-pressure-controllers (left) and modified top plate for hydraulic fracturing (right).

A freely progammable control enables flexible test procedure and data recording. Thus the PID-controller can be adjusted during the testing and measured data is plotted throughout. With this software, a flexible response to changes of the sample properties is possible and termination criteria, which are required when the fracture initiates, can be determined.

3.3 Test material and sample preparation

To examine the influence of different fine-grained soils on the hydraulic fracturing process, three different test materials are chosen: a silt (from Apolda, Germany), kaolin and bentonit, to consider the influence of fine-grained material without clay minerals, with non-swelling and with highly swelling mineral characteristic (Figure 2).

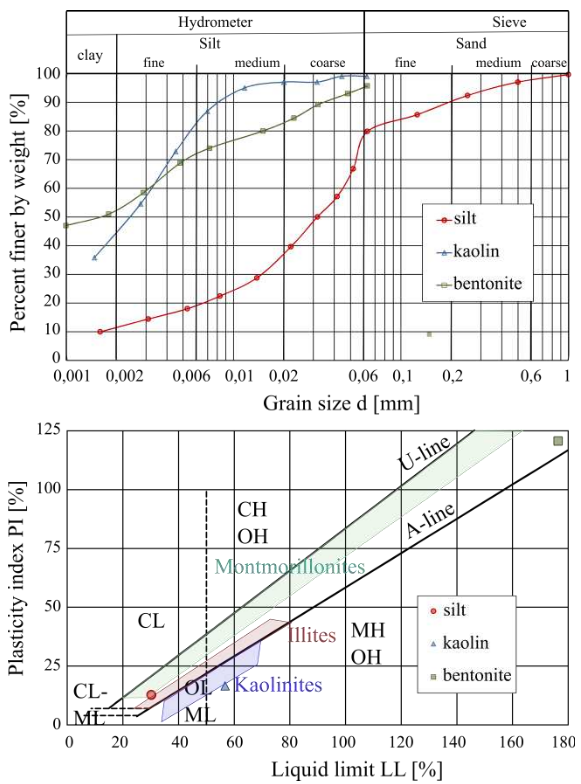

Figure 2. Grain size distribution (top) and Casagrande plasticity chart (bottom) of the test materials.

To achieve the best possible homogeneity, a slurry with a water content of 2-3 times the liquid limit was mixed under vacuum for at least 24 hours to remove trapped air and destroy particle clusters. Subsequently, the slurry was poured into a porous filtertube of a special consolidation apparatus as shown in **Error! Reference source not found.**. To enable drainage to all sides, the sintered filtertube is surrounded by water and porous discs are attached to the top and the bottom. The sample is gradually consolidated to 200 kPa. Once surface friction is high enough, the retaining ring at the bottom of the tube is removed to ensure a uniform compression from both sides. After pre-consolidation, the sample with a diameter of 100 mm and a height of 100 to 140 mm is slowly pressed out of the tube and predilled at the top to insert the injection needle of the top plate for the triaxial test.

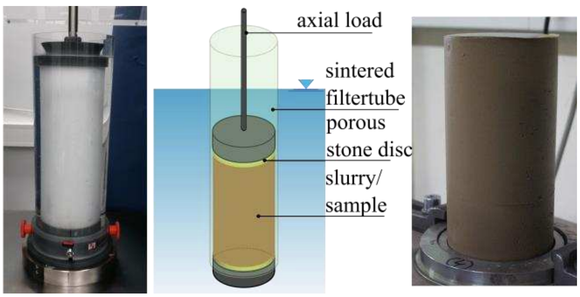

Figure 3. Sketch of the consolidation apparatus (left) and a silt sample consolidated from a slurry (right).

3.4 Test procedure

The test procedure is divided into:

- Saturation (and B-Test)
- Consolidation (and stress relief)
- Permeability test (with constant head)
- Hydraulic loading to failure by stepwise increase of the pore water pressure at the needletip

The degree of saturation is determined in the B-test by evaluating the change of pore water pressure measured at the top, bottom and at the needle in the middle of the sample due to the increase of cell pressure. Potentially, this could provide new insights into the homogeneity of saturation achieved in laboraty tests or the assessment of the B-value.

For higher consolidation pressures than those in the pre-consolidation and defined lateral pressures, a second consolidation phase is conducted. Depending on the intended *OCR*, the sample is unloaded.

The loading phase is presumed to be under drained or undrained conditions if the fracturing pressure at the needle is increased slowly or quickly with regards to the sample‘s permeability. Consequently, a permeability test is prepended by applying a constant pressure difference between the top and the bottom plate while the filter at the needle remains closed.

During hydraulic loading, the cell pressure and the pore pressures at the top and bottom of the sample are kept constant while the pore pressure in the center is increased step by step. The fracture initiation is indicated by a sudden pressure drop and an increase of the flow rate at the needletip which propagate to the top and bottom. Hence, if the volume-pressure-control of the needle tip is not switched to volume control in time, the damage propagates to the boundary and the membrane surrounding the sample inflates, as the fracturing pressure is higher than the cell pressure.

For the analysis of fracture toughness of the sample, both initiation and propagation of the fracture are of interest. But with an increasing extent of damage caused by the excess pore pressure spreading through the sample, the crack formation is destroyed. Choosing suitable termination criteria in the applied test control the fracture propagation can be stopped automatically.

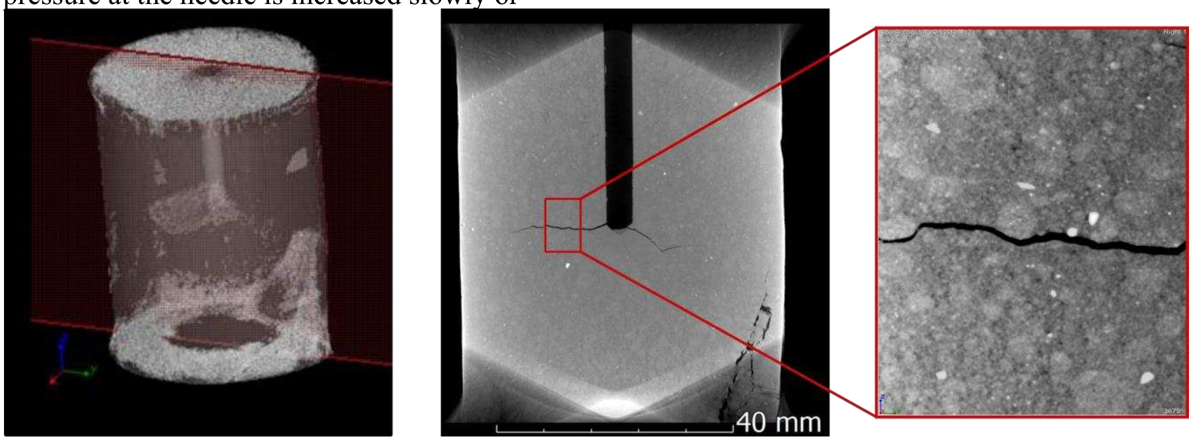

Figure 4. Fracture analysis with nano-CT-scans: 3D-image (left) and a 2D-cut through the main fracture plane (middle). The close-up view (right) shows the fracture propagation along the aggregates in the soil sample (Günther, 2018)

3.5 Variations

Not all parameters influencing the resistance against hydraulic fractures in fine-grained material can be observed in the study as the preparation of the specimen, the saturation and consolidation make the test procedure fairly time-consuming. Referring to the insitu condition of a deep excavation pit in cohesive ground, *OCR* and the actual stress state (K_0=σ‘$_h$/σ‘$_v$) during the hydraulic loading as well as the rate of the fracturing pressure $\partial P_f/dt$ are determined to be the most important influencing variables. Thus, in the context of the study various combinations of *OCR* values of 1.0, 2.0 and 10.0, K_0 values of 0.5, 1.0, 2.0 and fracturing rates - essential for drained or undrained loading - will be chosen for the three testing materials.

4 CONCLUSIONS AND PREVIEW

With the knowledge from simplified pre-trials, a modified triaxial cell for hydraulic fracture experiments on fine-grained soil samples has been designed. In the laboratory study, the resistance of silt, kaolin and bentonite against hydraulically induced fractures will be observed and its dependence on overconsolidation ratio, actual stress state and drainage condition will be determined.

Based on the experimental results the verification against hydraulic failure in cohesive ground can be redefined assuming that the failure is initiated locally by fractures at high gradients. To transfer the laboratory measurements to insitu conditions at a construction site, a practicable model for the fracture criterium must be developed which can be based on soil mechanical laws to relate the fracture resistance to drained or undrained shear parameters of the soil depending on the progress of the excavation. For further investigations of the fracturing process, these models can be implemented in numerical fracture simulations.

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