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Method for triaxial experiments for unconventional strain paths and back-calculation using Neohypoplasticity

Méthode d'essais triaxiaux pour des trajectoires de déformation non conventionnelles et calcul rétrospectif avec Neohypoplasticity

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ABSTRACT: Triaxial tests are commonly used in soil mechanics to determine the shear strength of soils. In standard tests, either the development of volumetric strain is restricted (undrained), or the development of pore water pressure is inhibited (drained). In this work, a new approach to triaxial testing is proposed that couples the evolution of pore water pressure with the development of volumetric strain. The resulting unconventional strain and stress path is referred as a partially drained path. The experiments can be interpreted as true partially drained since time dependence due to pore water flow does not occur. This new approach offers a third possibility for conducting triaxial tests as element tests, besides fully drained or undrained tests. A series of monotonic tests were conducted on Karlsruhe fine sand. The obtained unconventional strain paths were simulated using Neohypoplasticity, a novel constitutive model for sand. The simulation results were evaluated concerning the experimental data. A good agreement between the experimental results and numerical calculations can be shown.

RÉSUMÉ: Les essais triaxiaux sont couramment utilisés en mécanique des sols pour déterminer la résistance au cisaillement des sols. Dans les essais standard, soit le développement de la déformation volumétrique est restreint (non drainé), soit le développement de la pression de l'eau interstitielle est inhibé (drainé). Ce travail propose une nouvelle approche des essais triaxiaux qui associe l'évolution de la pression de l'eau interstitielle au développement de la déformation volumétrique. La trajectoire de déformation et de contrainte non conventionnelle qui en résulte est appelée trajectoire partiellement drainée. Les expériences peuvent être interprétées comme de véritables essais partiellement drainés puisque la dépendance temporelle due à l'écoulement de l'eau interstitielle ne se produit pas. Cette nouvelle approche offre une troisième possibilité de réaliser des essais triaxiaux en tant qu'essais d'éléments, en plus des essais entièrement drainés ou non drainés. Une série d'essais monotones a été réalisée sur du sable fin de Karlsruhe. Les trajectoires de déformation non conventionnelles obtenues ont été simulées à l'aide de la Neohypoplasticity, un nouveau modèle constitutif pour le sable. Les résultats de la simulation ont été évalués par rapport aux données expérimentales. Une bonne concordance entre les résultats expérimentaux et les calculs numériques peut être démontrée.

Keywords: Partial drainage; triaxial; experiments; Neohypoplasticity.

1 MOTIVATION

In the realm of classical triaxial experiments performed mostly on fully saturated soils, a popular distinction emerges between two testing paradigms: (1) drained and (2) undrained conditions. In drained testing, the primary objective is to have a constant pore fluid pressure and to measure the volumetric deformations, while undrained testing seeks to have a constant volume of the sample. Due to some insufficiencies, it is important to note that undrained tests should not be considered isochoric because of membrane penetration and the compressibility of the substance consisting of grains, water, and gas (Niemunis and Knittel, 2020). Nevertheless, the in situ conditions in saturated soils often pose a challenge, where both pore water pressure changes and volumetric deformations occur simultaneously.

This phenomenon is commonly known as partially drained conditions, and frequently arises in geotechnics such as the foundation of offshore piles or structures in saturated soils.

This paper presents a novel experimental approach that couples the volumetric strain rate and pore water pressure rate within a specimen during a globally undrained triaxial test. This coupling is achieved by using the compressibility of a precisely defined gas bubble enclosed within the experimental setup. In such an experiment, strains, pore water pressure, and stresses within the specimen can be considered as uniform fields. Methods presented in the literature for partially drained tests typically manipulate drainage resistance (Suzuki et al., 2020, Umehara et al., 1985) and are therefore not time-independent. In contrast, the presented novel approach can be assumed as a triaxial element test (Zürn et al., 2023). Consequently, this approach allows for unconventional stress and strain paths that bridge the gap between well-established drained and undrained conditions.

In this paper, the novel approach is introduced. Experimental data were obtained from a series of 8 monotonic triaxial tests. The novel constitutive model of Neohypoplasticity was used to recalculate the experimental results.

2 EXPERIMENTAL METHOD

To achieve the partial drainage conditions, a modification of a common triaxial set-up is sufficient. The experimental setup is shown in Figure 1. An enclosed gas bubble with adjustable initial volume $V_{\mathrm{a},0}$ and gas bubble pressure $p_{\mathrm{a},0}$ is connected to the pore water of the sample via the burette and drainage system.

A change in the sample volume ΔV leads to an outflow or inflow of water from the sample and a change of V_a. According to the law of Boyle-Mariotte $p_\mathrm{a} \cdot V_\mathrm{a} = \mathrm{const.}$, such a change of V_a leads to a change of p_a. With the known initial variables $p_{\mathrm{a},0}$ and $V_{\mathrm{a},0}$ and the measurement of p_a using the pore pressure transducer, the actual gas bubble volume V_a can be calculated. Assuming that the change in volume of the sample is equal to the change in gas bubble volume $\Delta V \approx \Delta V_\mathrm{a}$, we can calculate the volumetric deformation of the sample ε_vol.

3 EXPERIMENTAL RESULTS AND BACK-CALCULATION

3.1 Experiments

A series of monotonic tests was carried out with Karlsruhe fine sand (KFS), a uniformly graded fine sand. The grading curve and characteristic values of KFS can be found in the literature (Wichtmann , 2016). The tests which were conducted are given in Table 1. All medium-dense tests were prepared by moist tamping, the dense tests were prepared by air pluviation. For comparison, two additional tests (TMU6 and TMD23) from the literature were used (Wichtmann and Triantafyllidis, 2016).

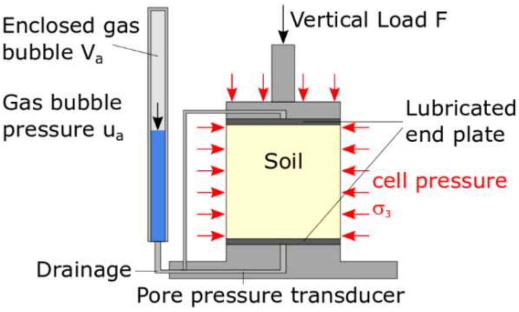

Figure 1. Experimental setup for the testing of partially drained conditions.

First, Figure 2 shows the evolution of the bulk moduli in the experiments calculated using

$$K_m = \dot{p}_f / \dot{\varepsilon}_\mathrm{vol} \tag{1}$$

whereby, the pore fluid pressure p_f and the volumetric strain ε_vol are measured directly. First of all, it should be mentioned that the initial values of K_m can be reproduced well. However, the bulk modulus changes significantly during the test.

The well-known initial contractancy of the sample leads to a compression of the gas bubble. The bubble becomes smaller and stiffer, which increases the bulk modulus. In a subsequent dilatancy, the gas bubble becomes larger and softer, resulting in a decreased bulk modulus. The observed differences in the maximum strains are the result of test termination due to large stresses.

The stress path in the p - q diagram and the strain path in the ε_1 - ε_vol diagram are shown together with the corresponding simulations in Figure 3-6. It can be seen that all the test results are between the limits of the drained and undrained test and both volumetric deformations and pore water pressure changes occur simultaneously.

As the size of the gas bubble increases, the behavior of the tests changes from more undrained to drained conditions.

Table 1. Overview of the experiments on KFS.

Test	**e_0 [-]**	**I_{D0} [-]**	**p_0 [kPa]**	**Gas bubble size**
V1	0.896	0.42	200	large
V2	0.910	0.38	200	medium
V3	0.901	0.39	200	small
V4	0.698	0.95	200	large
V5	0.702	0.93	200	medium
V6	0.694	0.96	200	small
U1	0.901	0.41	200	zero (undrained)
D1	0.898	0.41	200	infinite (drained)
TMU6	0.728	0.87	200	zero (undrained)
TMD23	0.706	0.92	200	infinite (drained)

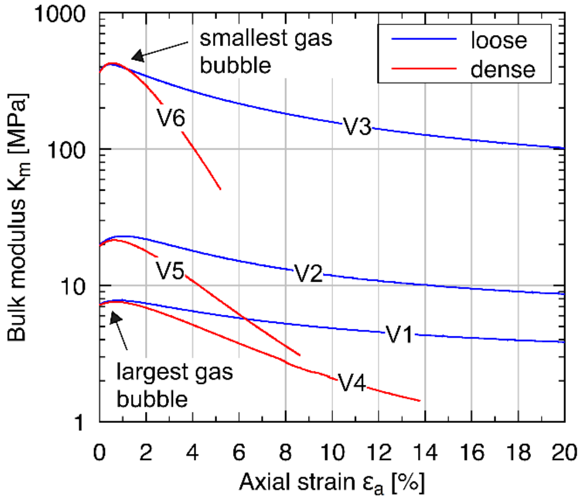

Figure 2. Evolution of the bulk modulus K_m for the different tests.

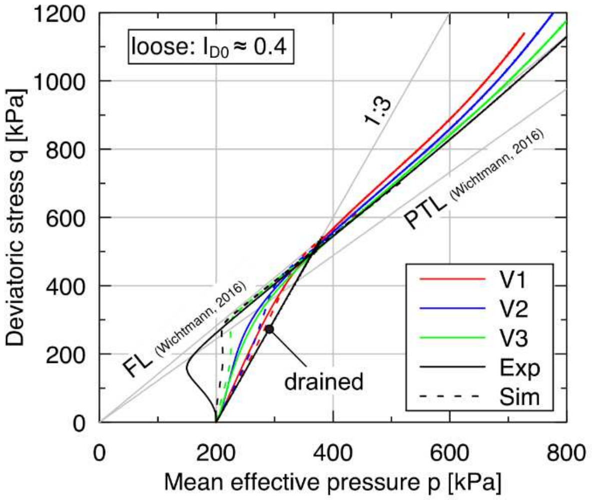

Figure 3. Stress paths for triaxial tests under different drainage conditions of loose KFS: experiments (solid lines) versus simulations with NHP (dashed lines).

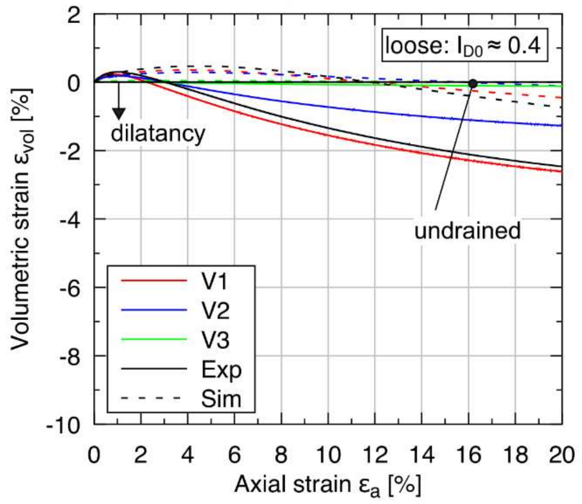

Figure 4. Strain paths for triaxial tests under different drainage conditions of loose KFS: experiments (solid lines) versus simulations with NHP (dashed lines).

The volumetric deformations increase, while the change in pore water pressure decreases. The tests can therefore be considered as partially drained.

The low initial contractancy of the medium-dense samples compared to the dense ones is due to the different preparation methods of the tests, as shown in the literature for KFS (Wichtmann, 2016).

3.2 Simulations using Neohypoplasticity

The Neohypoplasticity (NHP), which is a novel hypoplastic constitutive model for sand was used to recalculate the experimental results for partially drained conditions. For the main rate equation applies

$$\overset{\circ}{\boldsymbol{\sigma}} = k\,\bar{\mathrm{E}} : (\dot{\boldsymbol{\varepsilon}} - \boldsymbol{m}Y \parallel \dot{\boldsymbol{\varepsilon}} \parallel - \omega \boldsymbol{m}^z \langle -\boldsymbol{z} : \dot{\boldsymbol{\varepsilon}} \rangle - \boldsymbol{m}^d Y_d \parallel \dot{\boldsymbol{\varepsilon}} \parallel) \qquad (2)$$

were $\overset{\circ}{\boldsymbol{\sigma}}$ is the objective Jaumann-Zerema stress rate and $\dot{\boldsymbol{\varepsilon}}$ is the strain rate. More details about NHP can be found in the literature (Mugele et al. 2023).

In NHP, the mechanical behavior of non-cohesive soil is described using four state variables: (1) stress $\boldsymbol{\sigma}$, (2) void ratio e, (3) structure variable $\boldsymbol{z}$ and (4) last strain reversal $\boldsymbol{h}^r$. However, for the presented simulations the structure variable is initialized in such a way that their influence on the mechanical response vanishes. The small strain stiffness (increase due to $\boldsymbol{h}^r$) at the beginning of the monotonic deformation is fully considered. The constitutive parameters for KFS were taken from the literature (Mugele et al., 2023) and the test results presented in this work were not considered in the parameter calibration.

The element test simulations were conducted using the program code IncrementalDriver. A challenge for the recalculation of the partially drained tests of the experimental method presented is the bulk moduli, which varies significantly over the test (Figure 2). This corresponds to a non-linear restriction between the effective stress rates and the strain rates.

However, using the incremental driver, only linear restrictions between stress and strain rates can be specified. For simplicity, we have chosen the bulk modulus as a constant. The used value of K_{m} was calculated as the average value over the total strain of the test. For example, a value of K_m = 4.99 MPa was obtained for test V1. A restriction between the effective stress and strain rates can be calculated. This restriction depends on the chosen bulk modulus and is therefore different for the different tests.

The comparison of the simulations with the experiments indicates that the soil behavior can be qualitatively reproduced with the coarse estimation of the bulk modulus.

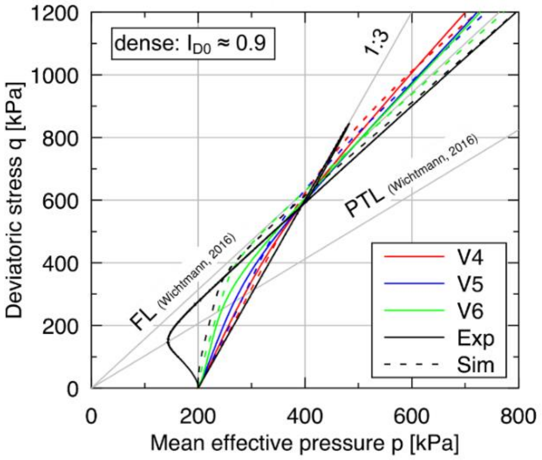

Figure 5. Stress paths for triaxial tests under different drainage conditions on dense KFS: experiments (solid lines) versus simulations with NHP (dashed lines).

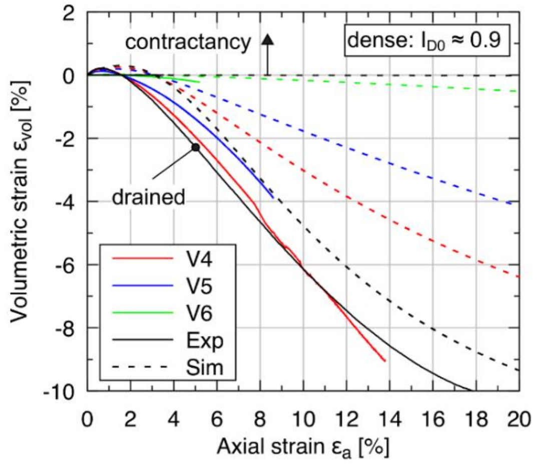

Figure 6. Strain paths for triaxial tests under different drainage conditions on dense KFS: experiments (solid lines) versus simulations with NHP (dashed lines).

The more drained the test is, i.e. the larger the gas bubble and the smaller the bulk modulus, the smaller the deviations of the stress path in the p-q diagram from the 1:3 line (corresponds to the drained test). Simultaneously, these tests and the simulations showed a larger volumetric deformation.

The opposite can be observed for a smaller gas bubble that results in a larger bulk modulus. Smaller volumetric deformations occur but deviations from the 1:3 line become larger.

4 CONCLUSION

The present study presents a method for conducting triaxial tests under partially drained conditions. It was found that:

- The experimental method presented was verified using a series of monotonic tests.
- Partially drained experimental element tests result in stress and strain paths lying between the two well-known extreme cases of undrained and drained tests.
- Simulations of the unconventional test results demonstrate that Neohypoplasticity can qualitatively reproduce the results.
- The quantitative discrepancies between the simulations and the experimental results could probably be improved by considering the nonlinear bulk modulus more accurately, calibrating the parameters, and initializing the structure variable.

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