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Experimental study of the soil structure variable z used in constitutive models such as Neohypoplasticity or Sanisand

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Abstract: The tensorial state variable $\boldsymbol{z}$ stores the current soil structure or *fabric* in constitutive models. This study presents macroscopic monotonic undrained triaxial tests on sand samples subjected to different cyclic preloading. The data demonstrates that a pronounced drained cyclic preloading practically erases $\boldsymbol{z}$ and effects the fabric induced by the preparation method. In contrast, a less pronounced undrained cyclic preloading do not impact the fabric induced by the preparation method. Using the results, evolution equations of corresponding state variables in constitutive models can be adapted.

1. Motivation

The mechanical behavior of soil can be described using constitutive models incorporating different state variables. In soil mechanics, the most commonly used state variables are the effective stress $\boldsymbol{\sigma}$ and the void ratio e. Using these, the experimentally observed soil behavior (for example, *pycnotropy*, *barotropy*, and *critical state concept*) can well be represented. However, despite having the same σ_{ij} and e, samples prepared using different preparation methods exhibit different initial mechanical behavior. For example, undrained monotonic triaxial tests accompanied with different changes in the mean effective pressure depending on the sample preparation method [1, 2]. These differences are often attributed to the vague concepts of sample's structure, or *fabric* which depends on the preparation method of the sample. Additionally, changes in the fabric, possibly due to mechanical preloading, also influence the soil behavior to cyclic loading [3, 4, 5].

An additional state variable accounting for the fabric should be incorporated in constitutive models for soil. Several constitutive models already consider such a variable, e.g. the SaniSand model [6, 7], the hypoplastic model after [8, 9] or the novel neohypoplastic model [10, 11]. However, the constitutive description of a fabric variable and its evolution equation lack of empirical data because they cannot be directly measured in the experiments. For the development or verification of the corresponding evolution equation, the present work investigates how cyclic preloading (CP) affects the subsequent monotonic undrained triaxial compression test of samples prepared with different preparation methods. Both a drained cyclic preloading (DCP) and an undrained cyclic preloading (UCP) are tested. The results are compared with ones without cyclic preloading.

2. Monotonic undrained triaxial tests with cyclic preloading

The monotonic triaxial compression tests are conducted using Karlsruhe Fine Sand (KFS), which is a well-known quartz sand from the literature [2]. Thereby, tests on medium-dense samples ($0.52 < I_D < 0.66$) with an isotropic initial stress state of $p_0 = 200$ kPa as well as tests on loose samples ($0.26 < I_D < 0.35$) with an isotropic initial stress of $p_0 = 300$ kPa have been performed. In each case, two monotonic undrained tests on samples prepared using dry air pluviation (AP) or moist tamping (MT) serve as references, as described in [12]. Different kind of cyclic preloadings have been applied to AP and MT samples. Their effect was observed during a subsequent a monotonic undrained compression. All tests are summarized in Table 1. The compaction caused by the CP is documented using the relative density $I_D = (e_{\max} - e)/(e_{\max} - e_{\min})$ before the CP and before the undrained triaxial compression. The compared tests have all an identical initial stress and an almost identical initial

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Test	I_D [-]	p_0 [kPa]	N [-] /q^{ampl} [kPa]	Preparation	Comment
TMU2	0.64	200	-	AP	from [2]
TMU2-DCP1	0.30 $\xrightarrow{DCP}$ 0.66	200	Hammer blows	AP	-
TMU-MT10	0.56	200	-	MT	
TMU-MT10DCP1	0.30 $\xrightarrow{DCP}$ 0.52	200	Hammer blows	MT	-
TMU-AP2	0.30	300	-	AP	from [2]
TMU-AP2UCP1	0.33 $\xrightarrow{UCP}$ 0.33	300	40/20	AP	-
TMU-AP2UCP2	0.35 $\xrightarrow{UCP}$ 0.35	300	100/20	AP	-
TMU-AP2UCP3	0.25 $\xrightarrow{UCP}$ 0.26	300	100/40	AP	-
TMU-MT5	0.27	300	-	MT	from [2]
TMU-MT5UCP1	0.31 $\xrightarrow{UCP}$ 0.31	300	40/20	MT	-
TMU-MT5UCP2	0.32 $\xrightarrow{UCP}$ 0.32	300	100/20	MT	-
TMU-MT5UCP3	0.30 $\xrightarrow{UCP}$ 0.30	300	100/40	MT	-

Table 1. Undrained monotonic triaxial tests on samples prepared by either moist tamping (MT) or dry air pluviation (AP) with different cyclic preloading

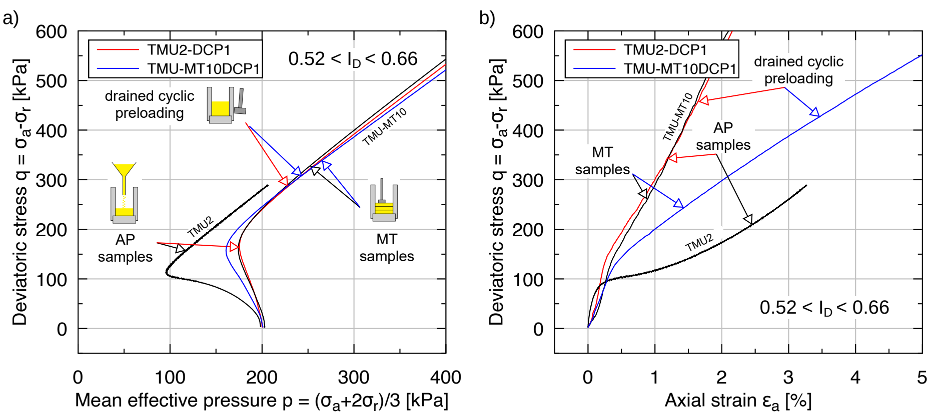

Figure 1. Undrained monotonic triaxial compression tests on medium-dense samples with and without drained cyclic preloading (achieved by rubber hammer blows): a) effective stress path in the pq diagram and b) deviatoric stress q as a function of the axial strain ε_a

density. Observed differences can therefore be attributed to the fabric and their changes due to the CP before the undrained monotonic compression.

The medium-dense samples ($I_D \approx 0.6$) with drained cyclic preloading (DCP) have been initially prepared with $I_D \approx 0.3$ using AP or MT. The DCP was applied by just tapping the mold with a rubber hammer until the desired density was reached. The DCP is therefore accompanied with a densification of the sample. The corresponding experiments without CP show the well-known dependence of the effective stress path on the sample preparation method, see Figure 1. The latter can be attributed to the different fabrics of the samples induced by the sample preparation method [2]. It can be seen that

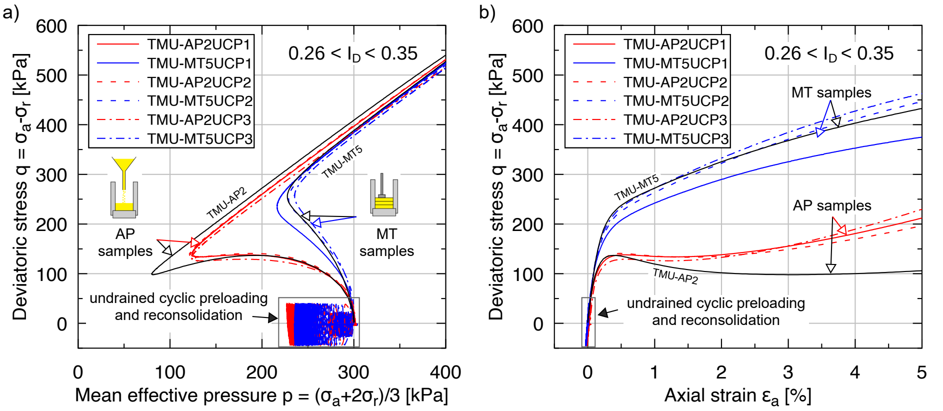

Figure 2. Undrained monotonic triaxial compression tests on loose samples with and without undrained cyclic preloading: a) effective stress path in the pq diagram and b) deviatoric stress q as a function of the axial strain ε_a

the effect of the sample preparation method is pronounced. The DCP leads to almost identical test results independently of the preparation method. In other words, the differences in fabric due to the preparation method have been nearly overwritten by the DCP. In addition, the tests with DCP are very similar to the experiments without CP using MT samples.

Experiments on loose samples ($I_D \approx 0.3$) have been preloaded by undrained cycles (UCP) quantified by the number of cycles N and the stress amplitude q^{ampl}. After the UCP, a reconsolidation recovers the desired effective stress for the monotonic compression test. The applied UCP leads to small strain cycles and the changes of the void ratio due to the reconsolidation are negligible. Three different intensities of UCP have been tested. The greatest considered UCP consists of $N = 100$ cycles with an amplitude of $q^{\text{ampl}} = 40$ kPa.

It can be observed in Figure 2, that the influence of the sample preparation method does not disappear after the considered UCP. The reduction in the mean effective pressure that accompanies shearing of the AP samples are slightly weaker in the case of an UCP (regardless of the intensity of the UCP). However, the AP samples show generally a much stronger decrease in the mean effective pressure than the MT samples in all considered UCP tests.

3. Fabric in constitutive models for soil

From the above-mentioned experiments and the literature, five qualitative requirements can be concluded for a constitutive consideration of the fabric effects. The fabric state variable $\boldsymbol{z}$ should (1) primarily change due to shearing and be therefore a tensorial quantity, (2) be differently initialized for different sample preparation, (3) lead to a change in the contractive soil behavior, (4) approach an asymptotic value due to a monotonic shearing to be consistent with the critical state concept, and (5) reduce its value during cyclic loading even if the the evolution of the fabric due to cyclic loading may to be slow in the case of UCP with small intensity. In particular, point (5) is a remarkable observation.

In Neohypoplasticity [10, 11], an additional contractancy term is introduced in the stress rate - strain rate equation

$$\dot{\boldsymbol{\sigma}} = \bar{\mathsf{E}} : \left(\dot{\boldsymbol{\varepsilon}} - \boldsymbol{m}Y\|\dot{\boldsymbol{\varepsilon}}\| - \omega\boldsymbol{m}^{z}\langle -\boldsymbol{z} : \dot{\boldsymbol{\varepsilon}}\rangle - \boldsymbol{m}^{d}Y_d\|\dot{\boldsymbol{\varepsilon}}\|\right) \tag{1}$$

to consider the fabric effects using the state variable $\boldsymbol{z}$. A general evolution equation of the fabric tensor $\boldsymbol{z}$

$$\dot{\boldsymbol{z}} = F(\boldsymbol{z}, \boldsymbol{\sigma}, \dot{\boldsymbol{\varepsilon}}^{*}, \ldots) \tag{2}$$

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should be formulated taking into account the above-mentioned points, in particular point (5). However, it must be mentioned that the presented experimental data only contains two specific cyclic preloading paths (UCP and DCP) under axisymmetric conditions with two specific initial states of fabric (due to the preparation methods). A holistic calibration of the evolution equation of the fabric tensor should incorporate additional preloading paths and states with different initial fabric.

4. Conclusion and outlook

This work describes experiments aimed to detect and investigate micromechanical processes which may affect the macromechanical material response due to both monotonic and cyclic loading. The change of the soil structure (or fabric) due to different sample preparation methods and different cyclic preloading have been tested. The results show that drained cyclic preloading can erase differences in fabric much faster then undrained cyclic preloading. This was tested using samples prepared with different sample preparation methods. The presented experimental results can be used in the future to develop advanced constitutive models accounting for the micromecanical effects of the fabric of soil.

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