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An experimental data base for the development, calibration and verification of constitutive models for sand with focus to cyclic loading. Part II: tests with strain cycles and combined loading

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Abstract: For numerical studies of geotechnical structures under earthquake loading, aiming to examine a possible failure due to liquefaction, using a sophisticated constitutive model for the soil is indispensable. Such model must adequately describe the material response to a cyclic loading unser constant volume (undrained) conditions, amongst others the relaxation of effective stress (pore pressure accumulation) or the effective stress loops repeatedly passed through after a sufficiently large number of cycles (cyclic mobility, stress attractors). The soil behaviour under undrained cyclic loading is manifold, depending on the initial conditions (e.g. density, fabric, effective mean pressure, stress ratio) and the load characteristics (e.g. amplitude of the cycles, application of stress or strain cycles). In order to develop, calibrate and verify a constitutive model with focus to undrained cyclic loading, the data from high-quality laboratory tests comprising a variety of initial conditions and load characteristics are necessary. It is the purpose of these two companion papers to provide such data base collected for a fine sand. Part II concentrates on the undrained triaxial tests with strain cycles, where a large range of strain amplitudes has been studied. Furthermore, oedometric and isotropic compression tests as well as drained triaxial tests with un- and reloading cycles are discussed. A combined monotonic and cyclic loading has been also studied in undrained triaxial tests. All test data presented herein will be available from the homepage of the first author. As an example of the examination of an existing constitutive model, the experimental data are compared to element test simulations using hypoplasticity with intergranular strain.

Keywords: data base, cyclic triaxial tests, strain cycles, oedometric compression tests, isotropic compression tests, un- and reloading cycles, combined monotonic and cyclic loading, fine sand

1 Introduction

In the companion paper [12] the data from purely monotonic or cyclic tests with stress cycles have been presented. This paper documents undrained cyclic triaxial tests performed with strain cycles. A first test series with relatively small strain amplitudes ($4\cdot10^{-4} \leq \varepsilon_1^{\rm ampl} \leq 8\cdot10^{-4}$) was followed by another one with larger cycles ($5\cdot10^{-3} \leq \varepsilon_1^{\rm ampl} \leq 10^{-2}$). Furthermore, oedometric, isotropic compression or triaxial tests with a combined monotonic and cyclic loading are presented.

In order to give an example for an examination of the prediction of a constitutive model, some of the laboratory experiments have been recalculated using hypoplasticity with intergranular strain [4, 7] as the constitutive model. The model prediction is compared to the experimental results.

2 Undrained tests with strain cycles

2.1 Small strain amplitudes $\varepsilon_1^{\rm ampl} \leq 8\cdot10^{-4}$

Typical data from tests with strain cycles of relatively small amplitude applied under undrained conditions are provided in Figure 1. All three samples were medium dense. In tests TCUE1 and TCUE2 the samples were anisotropically consolidated at $p_0 = 200$ kPa and $\eta_0 = 0.75$ (triaxial compression), while the initial stress was $p_0 = 200$ kPa and $\eta_0 =$ -0.50 (triaxial extension) in test TCUE3. Afterwards the axial strain was oscillated with an amplitude $\varepsilon_1^{\rm ampl} = 6\cdot10^{-4}$, i.e. the axial strain accumulation rate was zero in these tests ($\dot{\varepsilon}_1^{\rm acc} = 0$). Tests TCUE1 and TCUE2 differ from each other with respect to the first cycle. In test TCUE2 a first drained cycle was applied (also with $\varepsilon_1^{\rm ampl} = 6\cdot10^{-4}$) while in test TCUE1 the undrained cyclic loading was started directly after consolidation at p_0, η_0. The strain cycles were applied with a displacement rate of 0.02 mm/min in all tests of this series.

A comparison of the results of tests TCUE1 and TCUE2 in Figure 1 reveals that the first drained cycle has only a marginal effect on the material response during the subsequent undrained cyclic loading. The strain cycles lead to both an accumulation of pore water pressure (relaxation of p) and a decrease (for $\eta_0 > 0$) or an increase (for $\eta_0 < 0$) of axial effective stress with increasing number of cycles. The effective stress path takes the shape of a fir tree. After a sufficiently large number of cycles it finally reaches $p = q = 0$, i.e. it ends in a point. Further strain cycles applied in this fully liquefied state are without any further effect on the effective stress.

Several such tests with different strain amplitudes ($4\cdot10^{-4} \leq \varepsilon_1^{\rm ampl} \leq 8\cdot10^{-4}$), initial stresses (50 kPa $\leq p_0 \leq$ 300 kPa and $-0.75 \leq \eta_0 \leq 1.15$) and initial relative densities ($0.38 \leq I_{D0} \leq 0.82$) have been performed. The testing

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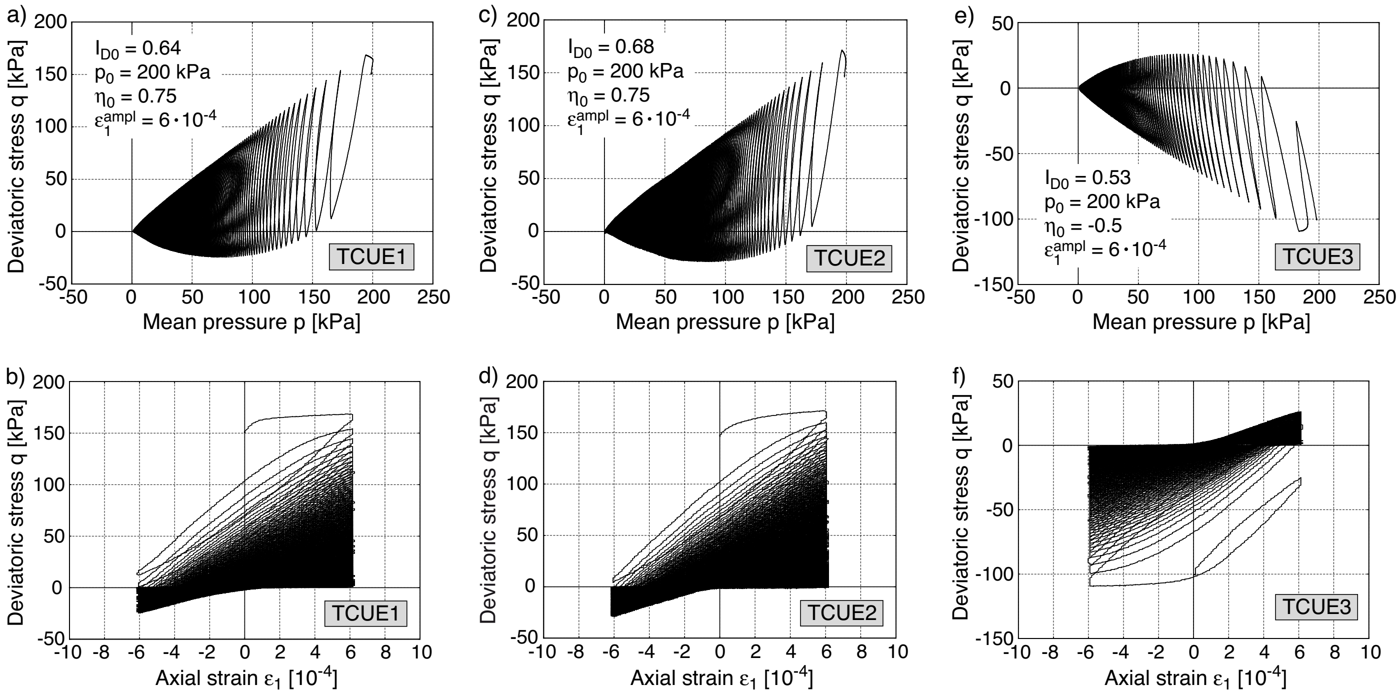

Fig. 1: Effective stress paths and stress-strain relationships in undrained cyclic triaxial tests with anisotropic initial stresses and relatively small strain cycles ($\varepsilon_1^{\rm ampl} = 6 \cdot 10^{-4}$) applied without (TCUE1, TCUE3) or with (TCUE2) a first drained cycle

Test	e_{0d} [-]	I_{D0d} [-]	e_0 [-]	I_{D0} [-]	p_0 [kPa]	η_0 [-]	$\varepsilon_1^{\rm ampl}$ [10^{-4}]	1. drained cycle?
TCUE1	-	-	0.812	0.64	200	0.75	6.0	no
TCUE2	0.789	0.70	0.789	0.70	200	0.75	6.0	yes
TCUE3	-	-	0.854	0.53	200	-0.5	6.0	no
TCUE4	0.829	0.60	0.829	0.60	200	0.75	4.0	yes
TCUE5	0.794	0.69	0.793	0.69	200	0.75	8.0	yes
TCUE6	0.910	0.38	0.910	0.38	200	0.75	6.0	yes
TCUE7	0.746	0.82	0.745	0.82	200	0.75	6.0	yes
TCUE8	0.805	0.66	0.805	0.66	200	1.15	6.0	yes
TCUE9	0.802	0.67	0.801	0.67	200	0	6.0	yes
TCUE10	0.844	0.56	0.844	0.56	200	-0.50	6.0	yes
TCUE11	0.836	0.58	0.835	0.58	200	-0.75	6.0	yes
TCUE12	0.834	0.58	0.833	0.59	50	0.75	6.0	yes
TCUE13	0.788	0.71	0.788	0.71	100	0.75	6.0	yes
TCUE14	0.806	0.66	0.806	0.66	300	0.75	6.0	yes

Table 1: Program of undrained cyclic triaxial tests with strain cycles of relatively small amplitude ($\varepsilon_1^{\rm ampl} \leq 8 \cdot 10^{-4}$). Void ratios e_0 and relative densities I_{D0} measured at initial stress p_0, η_0 prior to undrained cyclic shearing. e_{0d} and I_{D0d} are the values at p_0 prior to the first drained cycle (if applied).

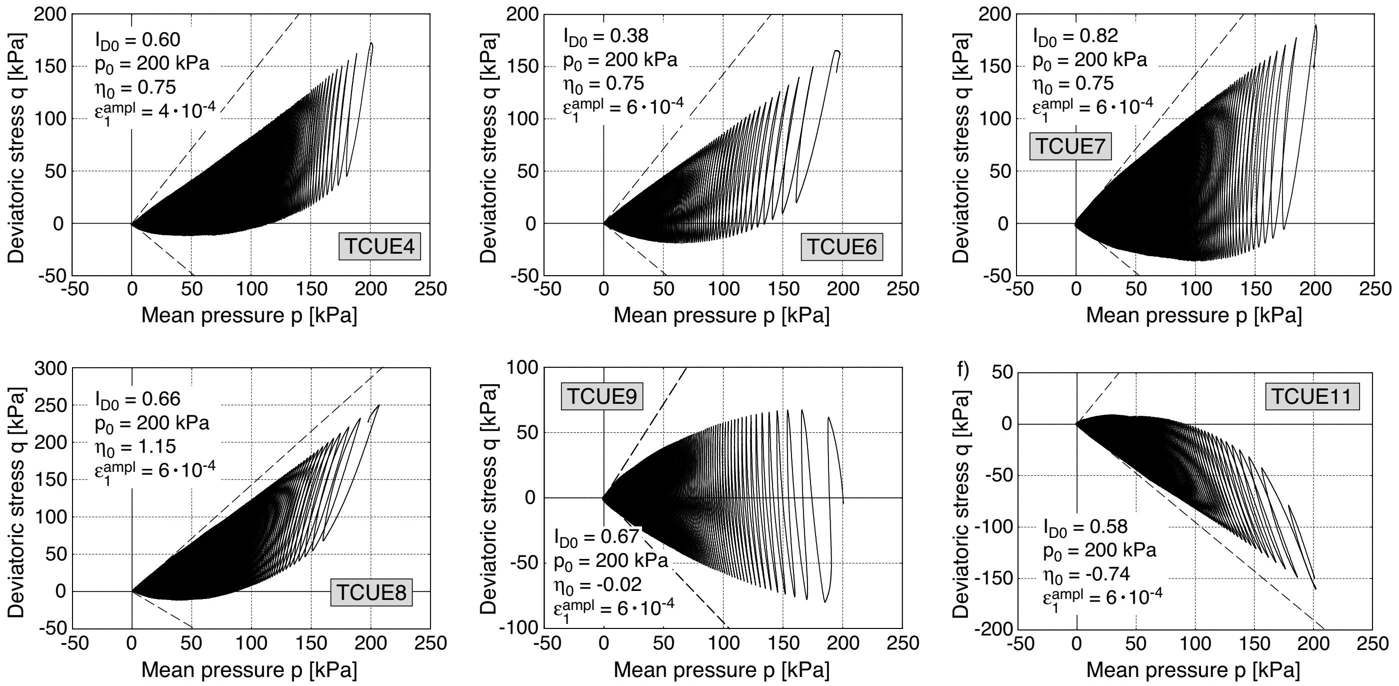

Fig. 2: Effective stress paths in undrained cyclic triaxial tests with relatively small strain cycles ($4 \cdot 10^{-4} \leq \varepsilon_1^{\rm ampl} \leq 6 \cdot 10^{-4}$). The initial density I_{D0}, the initial stress ratio η_0 and the strain amplitude $\varepsilon_1^{\rm ampl}$ have been varied.

program is summarized in Table 1. Since this test series was originally dedicated to a calibration of the high-cycle accumulation (HCA) model of Niemunis et al. [5] (in particular of Poisson's ratio ν used in the elastic stiffness of the HCA model), most of these tests have been performed with a first drained cycle and the strain amplitudes have been chosen relatively low, i.e. in a typical range for a high-cyclic loading. However, the strain amplitudes in these tests are still larger than the threshold strain amplitude below which no accumulation of excess pore pressure occurs (typically $\gamma^{\rm ampl} \approx 10^{-4}$ for sand [1, 8]), considering $\gamma = 1.5\varepsilon_1$ for the undrained triaxial tests.

Some of the measured effective stress paths are collected in Figure 2. Independently of the test conditions the effective stress path finally reaches a state of zero effective stress ($p = q = 0$). Of course, the number of cycles necessary to reach this state depends on the amplitude, initial density and initial stress. Similar data as those shown in Figures 1 and 2 have been documented e.g. in [2, 3, 6].

The development of normalized average mean stress $p^{\rm av}/p_0$ with increasing number of cycles is shown in the first row of diagrams in Figure 3. All curves start from $p^{\rm av}/p_0$ = 1 at $N = 0$. The corresponding average effective stress paths are provided in normalized $q^{\rm av}/q_0$-$p^{\rm av}/p_0$-diagrams in the second row of Figure 3. Stress relaxation occurs faster for larger strain amplitudes $\varepsilon_1^{\rm ampl}$ (Figure 3a), lower initial densities (not shown in Figure 3), lower initial pressures p_0 (Figure 3c) and (with the exception of the test at η_0 = -0.75) lower initial stress ratios η_0 (Figure 3e). The shape of the normalized average effective stress path is rather independent of strain amplitude (Figure 3b) and density and only moderately affected by the initial pressure (Figure 3d). For a given $p^{\rm av}/p_0$ value, the normalized average deviatoric stress $q^{\rm av}/q_0$ is larger for higher amounts of the initial stress ratios $|\eta_0|$ (Figure 3f). For a more detailed analysis of the average effective stress paths it is referred to [11].

A simulation of test TCUE1 with the hypoplastic model with intergranular strain [4, 7] is presented in Figure 4a,b. The stress relaxation to $p = q = 0$ is reproduced by the constitutive model. Both the effective stress path and the stress-strain relationship look similar as measured in the test (compare Figure 1a,b). With the exception of the first two or three cycles, the rate of stress relaxation predicted by the constitutive model is, however, larger than that observed experimentally.

2.2 Large strain amplitudes $5 \cdot 10^{-3} \leq \varepsilon_1^{\rm ampl} \leq 10^{-2}$

Nine tests with larger strain amplitudes of $\varepsilon_1^{\rm ampl} = 5 \cdot 10^{-3}$ or $\varepsilon_1^{\rm ampl} = 10^{-2}$ were performed. These strain amplitudes are closer to typical earthquake conditions than those applied in the previous test series. The testing program is given in Table 2. A displacement rate of 0.05 mm/min was used for these tests. The measured effective stress paths are provided in Figure 5, while the stress-strain relationships are summarized in Figure 6. The diagrams in the first row of Figures 5 and 6 belong to tests TCUE15 - TCUE17 with different densities (I_{D0} = 0.29, 0.66 or 0.94) but identical consolidation stress (p_0 = 200 kPa, $\eta_0 = 0$) and strain amplitude ($\varepsilon_1^{\rm ampl} = 10^{-2}$). The loose sample in test TCUE15 liquefied within a single cycle (Figure 5a), while some more cycles could be applied to the medium dense sample in test TCUE16 until $p = q = 0$ was reached (Figure 5b). Even in the test TCUE17 on the dense sample a liquefaction was observed after a sufficiently large number of cycles (Figure 5c).

In tests TCUE18 and TCUE19 lower (p_0 = 100 kPa) or higher (p_0 = 700 kPa) initial pressures were tested on medium dense samples (Figures 5d,e and 6d,e). The initial

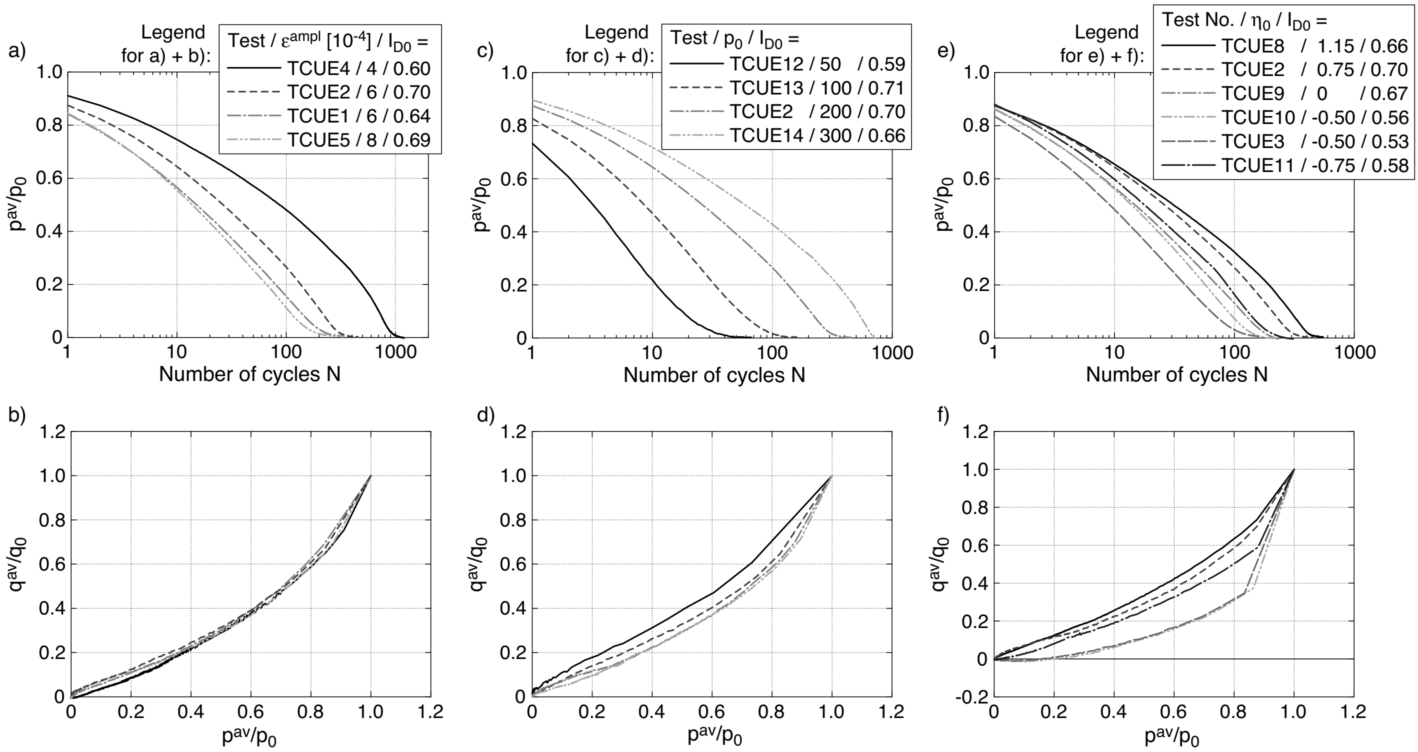

Fig. 3: Relaxation of normalized average mean stress p^{av}/p_0 with increasing number of cycles (upper row of diagrams) and effective stress path in q^{av}/q_0-p^{av}/p_0-diagrams (lower row). Data from undrained cyclic triaxial tests with relatively small strain cycles $4 \cdot 10^{-4} \leq \varepsilon_1^{\text{ampl}} \leq 8 \cdot 10^{-4}$.

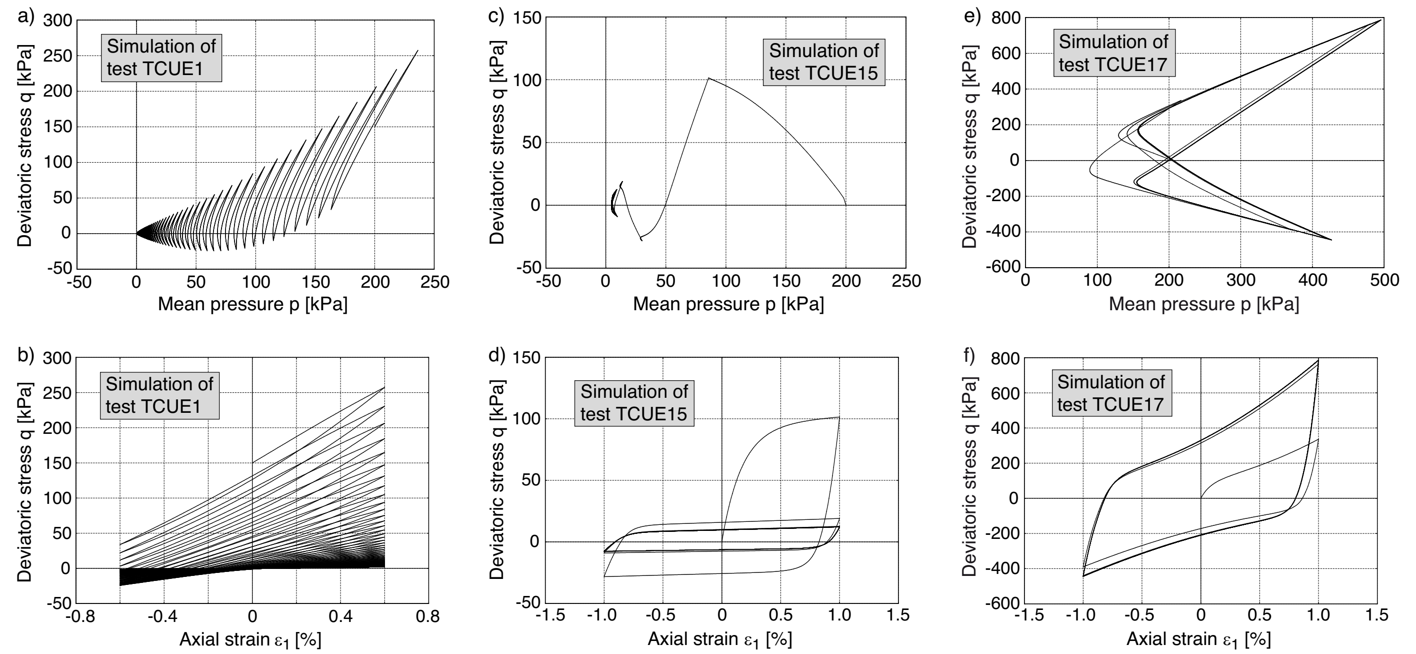

Fig. 4: Simulations with hypoplasticity and intergranular strain of undrained cyclic triaxial tests with strain cycles: a,b) test TCUE1 ($I_{D0} = 0.64$, $p_0 = 200$ kPa, $\eta_0 = 0.75$, $\varepsilon_1^{\text{ampl}} = 6 \cdot 10^{-4}$), c,d) test TCUA15 ($I_{D0} = 0.29$, $p_0 = 200$ kPa, $\eta_0 = 0$, $\varepsilon_1^{\text{ampl}} = 1 \cdot 10^{-2}$), e,f) test TCUA17 ($I_{D0} = 0.94$, $p_0 = 200$ kPa, $\eta_0 = 0$, $\varepsilon_1^{\text{ampl}} = 1 \cdot 10^{-2}$)

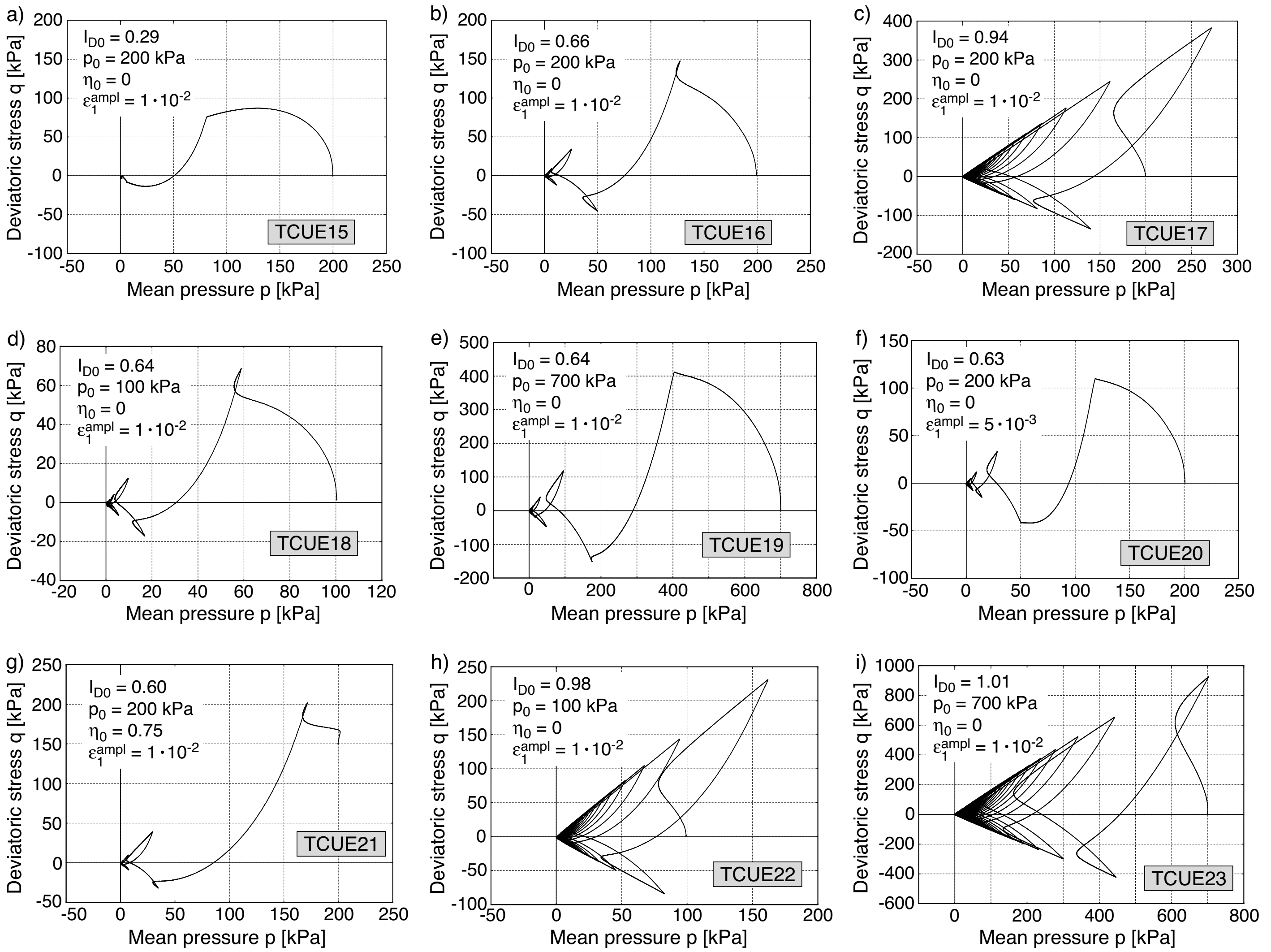

Fig. 5: Effective stress paths measured in undrained cyclic triaxial tests with strain cycles of large amplitude

Test	e_0 [-]	I_{D0} [-]	p_0 [kPa]	η_0 [-]	$\varepsilon_1^{\text{ampl}}$ [10^{-2}]	1. drained cycle?
TCUE15	0.944	0.29	200	0	1.0	no
TCUE16	0.804	0.66	200	0	1.0	no
TCUE17	0.698	0.94	200	0	1.0	no
TCUE18	0.812	0.64	100	0	1.0	no
TCUE19	0.814	0.64	700	0	1.0	no
TCUE20	0.816	0.63	200	0	0.5	no
TCUE21	0.827	0.60	200	0.75	1.0	no
TCUE22	0.686	0.98	100	0	1.0	no
TCUE23	0.674	1.01	700	0	1.0	no

Table 2: Program of undrained cyclic triaxial tests with strain cycles of large amplitude ($\varepsilon_1^{\text{ampl}} \geq 5 \cdot 10^{-3}$). Void ratios e_0 and relative densities I_{D0} measured at initial stress p_0, η_0 prior to undrained cyclic shearing

stress ratio $\eta_0 = 0$ and the strain amplitude $\varepsilon_1^{\text{ampl}} = 10^{-2}$ were chosen identical to the tests TCUE15 - TCUE17. Test TCUE20 (Figures 5f and 6f) was performed with a lower strain amplitude ($\varepsilon_1^{\text{ampl}} = 5 \cdot 10^{-3}$) and test TCUE21 (Figures 5g and 6g) with an anisotropic consolidation ($\eta_0 = 0.75$). Finally, very dense samples were tested at $p_0 = 100$ or 700 kPa, respectively, in the two tests TCUE22 and TCUE23 (Figures 5h,i and 6h,i). For all tested combinations of I_{D0}, p_0, η_0 and $\varepsilon_1^{\text{ampl}}$, a zero effective stress ($p = q = 0$) was reached after a certain number of cycles. This was observed even for the test TCUE23 with an initial density of $I_{D0} = 1.01$. Note, that for the calculation of I_{D0} the void ratio e_0 at p_0 is referred to the limit void ratios $e_{\min}$ and $e_{\max}$ determined from standard tests at $p = 0$. The I_{D0} value would be somewhat lower if pressure-dependent limits $e_{\min}(p)$ and $e_{\max}(p)$ had been applied.

Simulations of tests TCUA15 and TCUA17 performed with $\varepsilon_1^{\text{ampl}} = 1 \cdot 10^{-2}$ on loose or dense fine sand are presented in Figure 4c-f. In these simulations an eight-shaped effective stress path is repeatedly passed through after a certain number of cycles. The higher the density, the larger is its distance to the origin of the p-q-plane. A liquefaction

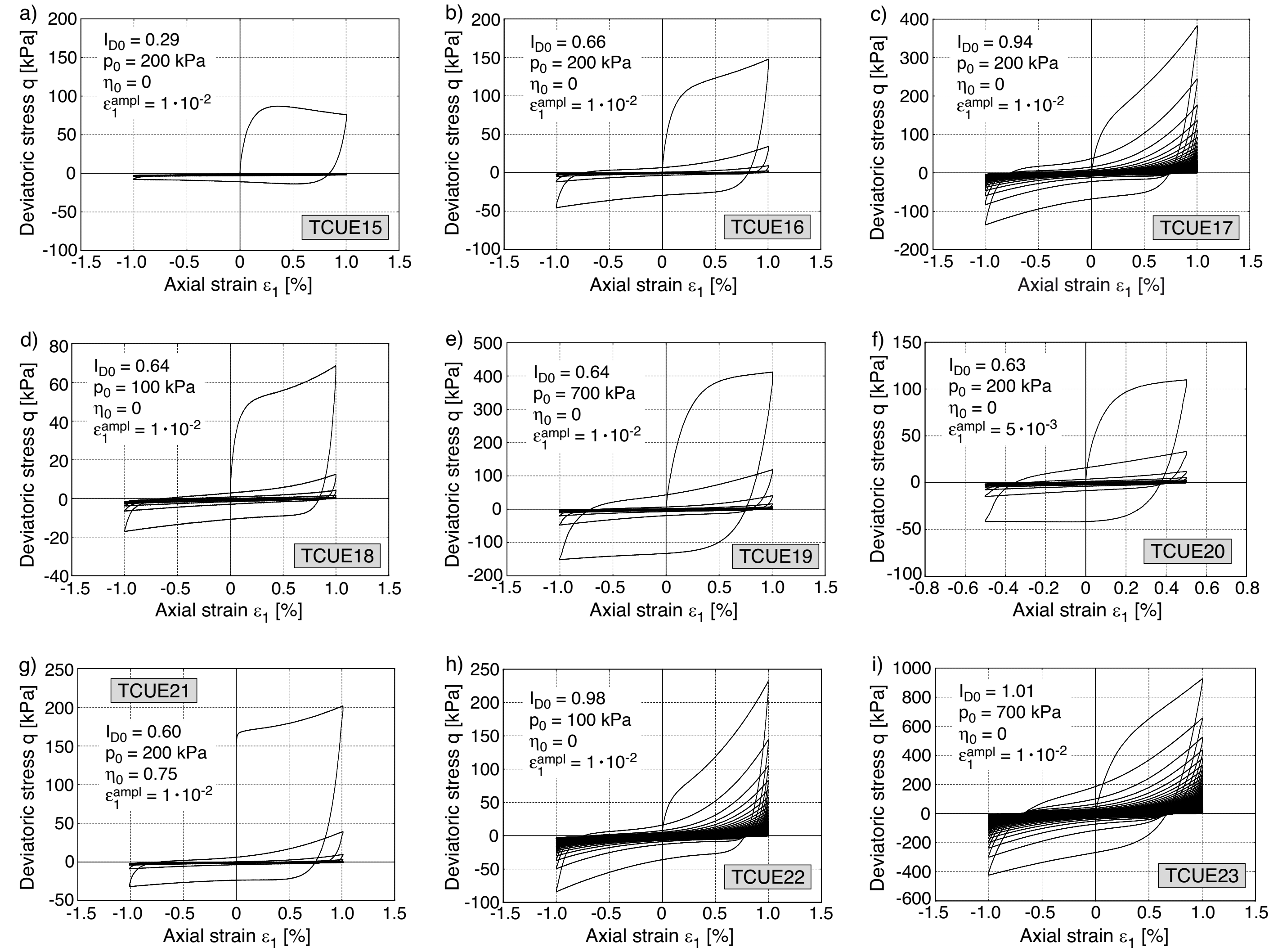

Fig. 6: Stress-strain relationships measured in undrained cyclic triaxial tests with strain cycles of large amplitude

as observed in the experiments, independently of density, is not reached in the simulations. Figure 4 reveals that the prediction of hypoplasticity with intergranular strain for undrained tests with large strain cycles is not satisfying, especially when high initial densities are involved.

3 Tests with a combination of monotonic and cyclic loading

3.1 Oedometric compression tests

Four stress-controlled oedometric compression tests were performed on dry samples (d = 150 mm, h = 30 mm) with different initial relative densities $0.15 \leq I_{D0} \leq 0.79$. The loading to the maximum axial stress of σ_1 = 400 kPa was interrupted by four un- and reloading cycles each with a minimum stress of σ_1 = 1 kPa. The testing program is given in Table 3. The σ_1-ε_1-curves from three of these tests are shown in black color in the σ_1-ε_1-diagrams in Figure 7. For comparison purpose the data from tests with similar initial density but only one un- and reloading cycle performed at the end of the test (see Table 1 in [12]) have been added as the gray curves in Figure 7.

A simulation of test OEC1 with I_{D0} = 0.15 is presented in Figure 8a. The simulation starts at σ_1 = 1 kPa with intergranular strain fully mobilized in the vertical direction ($h_{11} = -R$). Beside a slightly too large predicted initial stiffness, an "overshooting" of the numerical $e(\sigma_1)$ curve in the first un- and reloading cycle and a "ratcheting", i.e. a too large accumulation of strain in the last two cycles is obvious in Figure 8a. The predictions for the tests with higher initial density look very similar to that given in Figure 8a.

Test No.	e_0 [-]	I_{D0} [-]
OEC1	0.998	0.15
OEC2	0.890	0.44
OEC3	0.792	0.70
OEC4	0.756	0.79

Table 3: Program of oedometric compression tests with four un- and reloading cycles. Void ratios and relative densities measured at axial stress $\sigma_1 = 0$

3.2 Drained isotropic compression tests

A drained isotropic compression was tested on six samples with different initial densities ($0.21 \leq I_{D0} \leq 0.99$). In three

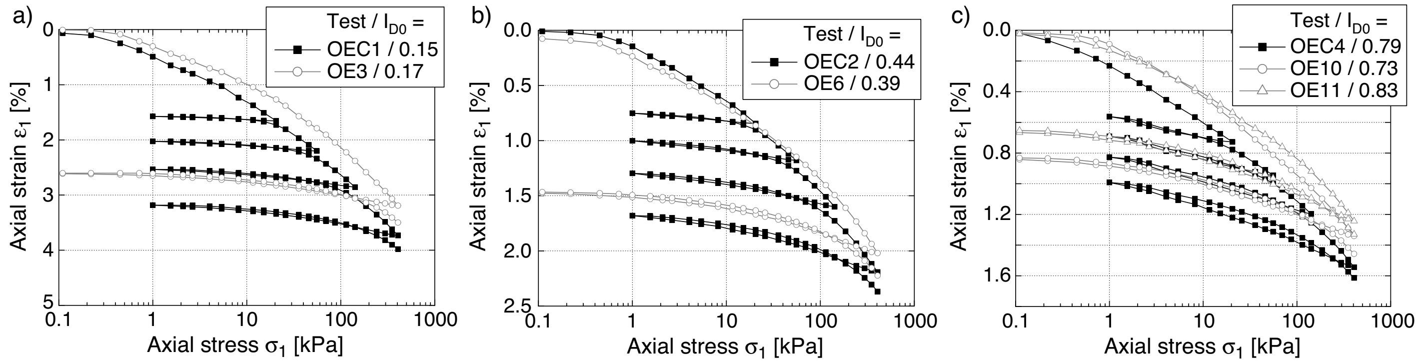

Fig. 7: Axial strain ε_1 versus axial stress σ_1 measured in oedometric compression tests with un- and reloading cycles performed on samples with different initial relative densities

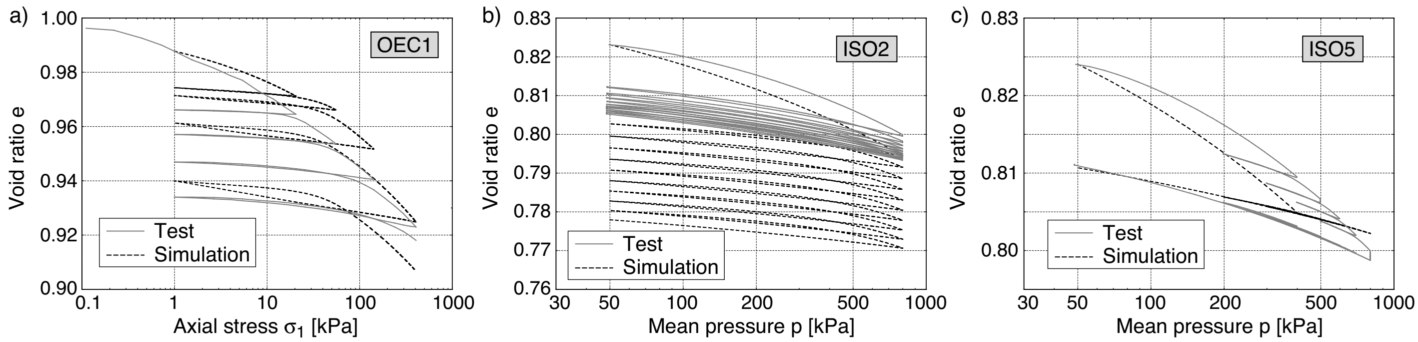

Fig. 8: Simulations of a) oedometric and b,c) isotropic compression tests with un- and reloading cycles

Test No.	e_0 [-]	I_{D0} [-]	Cycles	p^{ampl} [kPa]
ISO1	0.974	0.21	large	750
ISO2	0.823	0.61	large	750
ISO3	0.690	0.97	large	750
ISO4	0.963	0.24	small	200
ISO5	0.824	0.61	small	200
ISO6	0.680	0.99	small	200

Table 4: Program of isotropic compression tests with un- and reloading cycles. Void ratios e_0 and relative densities I_{D0} measured prior to isotropic compression at p_0 = 50 kPa and η_0 = 0. p^{ampl} = amplitude of the cycles.

tests (ISO1 - ISO3 in Table 4) 10 cycles between $p^{\min} = p_0$ = 50 kPa and $p^{\max}$ = 800 kPa were applied. The resulting curves of volumetric strain ε_v versus effective mean pressure p are provided in Figure 9 (black solid curves). In three other tests the loading from p_0 = 50 kPa to p = 800 kPa and back was interrupted by four smaller un- and reloading cycles with $p^{\max} - p^{\min}$ = 200 kPa (ISO4 - ISO6 in Table 4). The measured data $\varepsilon_v(p)$ from these tests are given as dashed gray curves in Figure 9.

Simulations of tests ISO2 and ISO5 performed on medium dense samples are presented in Figure 8b,c. For the test ISO2 with large un- and reloading cycles the predicted initial stiffness is somewhat too low and the rate of strain accumulation is significantly too large compared to the experimental results (ratcheting, Figure 8b). Similar to the recalculations of the oedometric tests, the simulation of test ISO5 reveals an overshooting of the $e(p)$ curve (Figure 8c).

3.3 Drained triaxial tests with large un- and reloading cycles

In seven drained triaxial tests the monotonic shearing with a displacement rate 0.1 mm/min was interrupted several times by an unloading to $q = 0$ followed by a reloading. The strain increment between the subsequent un- and reloading cycles ($\Delta\varepsilon_1$ = 2, 6 and 12 %) has been varied as well as the initial density of the samples ($0.24 \leq I_{D0} \leq 0.94$) and the effective confining pressure ($\sigma_3' = p_0$ = 50, 100 and 200 kPa). The testing program is summarized in Table 5. The q-ε_1- and ε_v-ε_1-diagrams for some of these tests are given in Figure 10. The data of the tests with a combined monotonic and cyclic loading (black curves in Figure 10) are compared to the results of purely monotonic tests (gray curves) with similar initial density (Table 3 in [12]). The un- and reloading cycles cause compaction leading to a less pronounced overall dilatancy in the combined tests compared to the purely monotonic loading. The slight "overshooting" of the deviatoric stress during the reloading process may also be attributed to the compaction caused by the cycles, since the density at the end of reloading has increased compared to the state directly before unloading. Furthermore, the peak deviatoric stresses are larger in the combined tests. In [9] the data from this test series has been used to calibrate engineering models for the prediction of long-term deformations of offshore wind power plant foundations. Similar results from tests on medium coarse Karlsruhe sand have been presented by Wu [13].

Simulations of three of these tests are shown in Figure 11. The comparison with the experimental results demon-

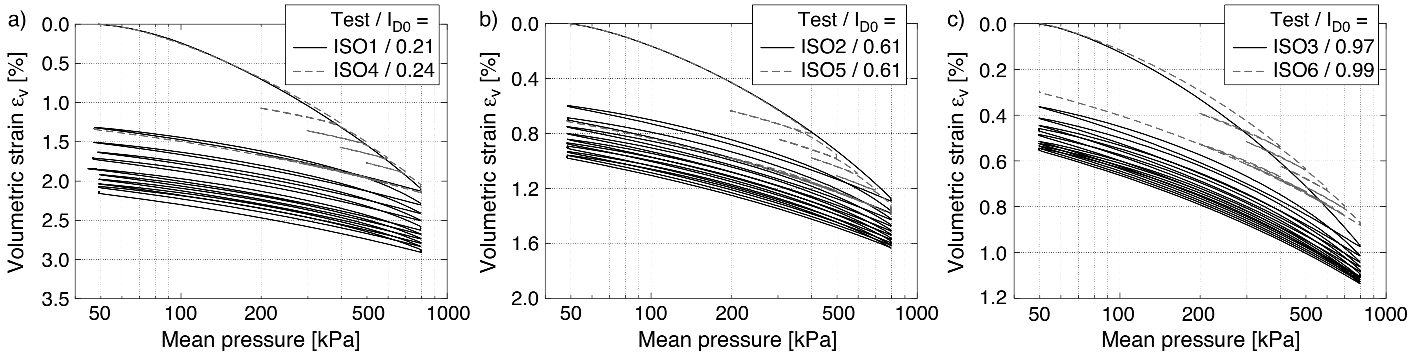

Fig. 9: Volumetric strain ε_v versus effective mean pressure p measured in isotropic compression tests with un- and reloading cycles performed on samples with different initial relative densities

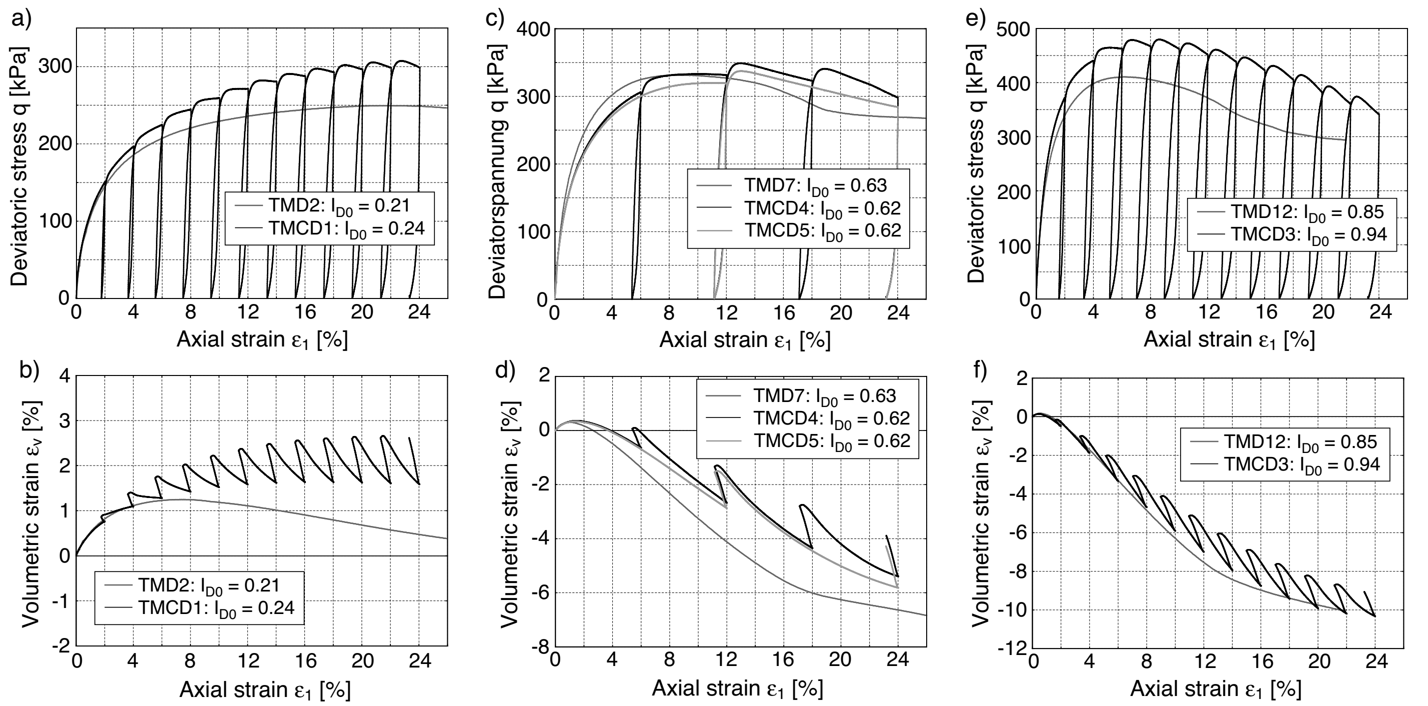

Fig. 10: Stress-strain and dilatancy relationships measured in drained triaxial tests with large un- and reloading cycles

Test	e_0 [-]	I_{D0} [-]	p_0 [kPa]	$\Delta\varepsilon_1$ [%]
TMCD1	0.962	0.24	100	2
TMCD2	0.829	0.60	100	2
TMCD3	0.701	0.94	100	2
TMCD4	0.820	0.62	100	6
TMCD5	0.821	0.62	100	12
TMCD6	0.810	0.65	200	2
TMCD7	0.814	0.64	50	2

Table 5: Program of drained triaxial tests with large un- and reloading cycles. Void ratios e_0 and relative densities I_{D0} measured at isotropic initial stress p_0 prior to shearing. $\Delta\varepsilon_1$ = strain increment between subsequent un- and reloading cycles.

strates a too stiff prediction of the material response during the first loading prior to the first un- and reloading cycle, while the stiffness decrease during the final stage of the reloading phases is too large. The latter observation agrees with the ratcheting in the simulations of oedometric and isotropic compression tests.

3.4 Undrained triaxial tests with a combination of small strain cycles and monotonic loading

In four tests strain cycles with an amplitude $\varepsilon_1^{\text{ampl}} = 6 \cdot 10^{-4}$ were superposed by a monotonic loading performed with rates between $\dot{\varepsilon}_1^{\text{acc}} = 2 \cdot 10^{-5}$ and $\dot{\varepsilon}_1^{\text{acc}} = 3 \cdot 10^{-4}$ ($\dot{\varepsilon}_1^{\text{acc}}$ = prescribed monotonic strain per cycle). A schematic drawing of the test control is given in Figure 12e. The displacement rate was 0.05 mm/min in all tests of this series. The effective stress paths and stress-strain-relationships obtained from the tests with $\dot{\varepsilon}_1^{\text{acc}} = 5 \cdot 10^{-5}$, $1 \cdot 10^{-4}$ and $3 \cdot 10^{-4}$ are shown in the p-q-plane in Figure 12. In the tests with the lower $\dot{\varepsilon}_1^{\text{acc}}$ values, similar to the tests with $\dot{\varepsilon}_1^{\text{acc}} = 0$ (Section 2.1), the effective stress path finally reached $p = q = 0$, i.e. the contractive cumulative behaviour due to the strain cycles prevailed over the dilatancy induced by the monotonic shearing (Figure 12a-d). This is also obvious from the average effective stress paths provided in Figure 13. The data

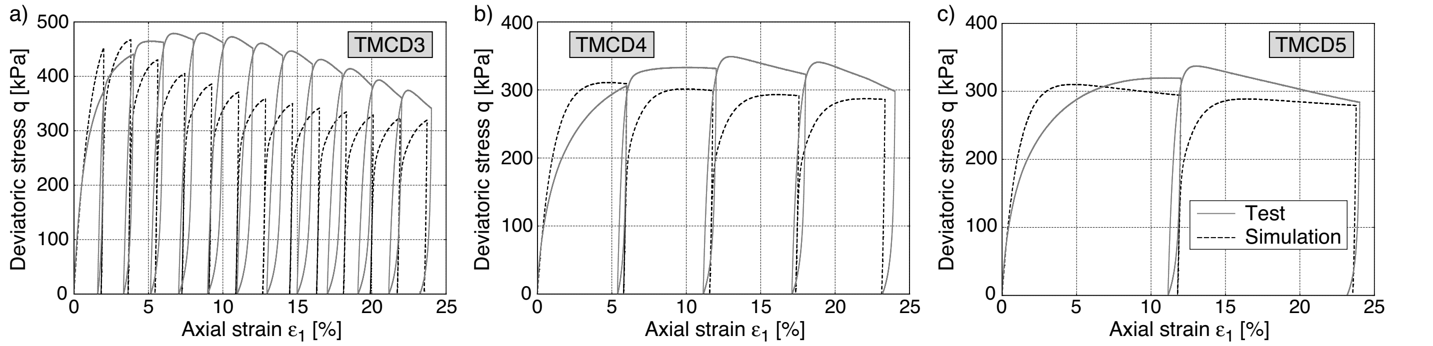

Fig. 11: Simulations of drained triaxial tests with large un- and reloading cycles

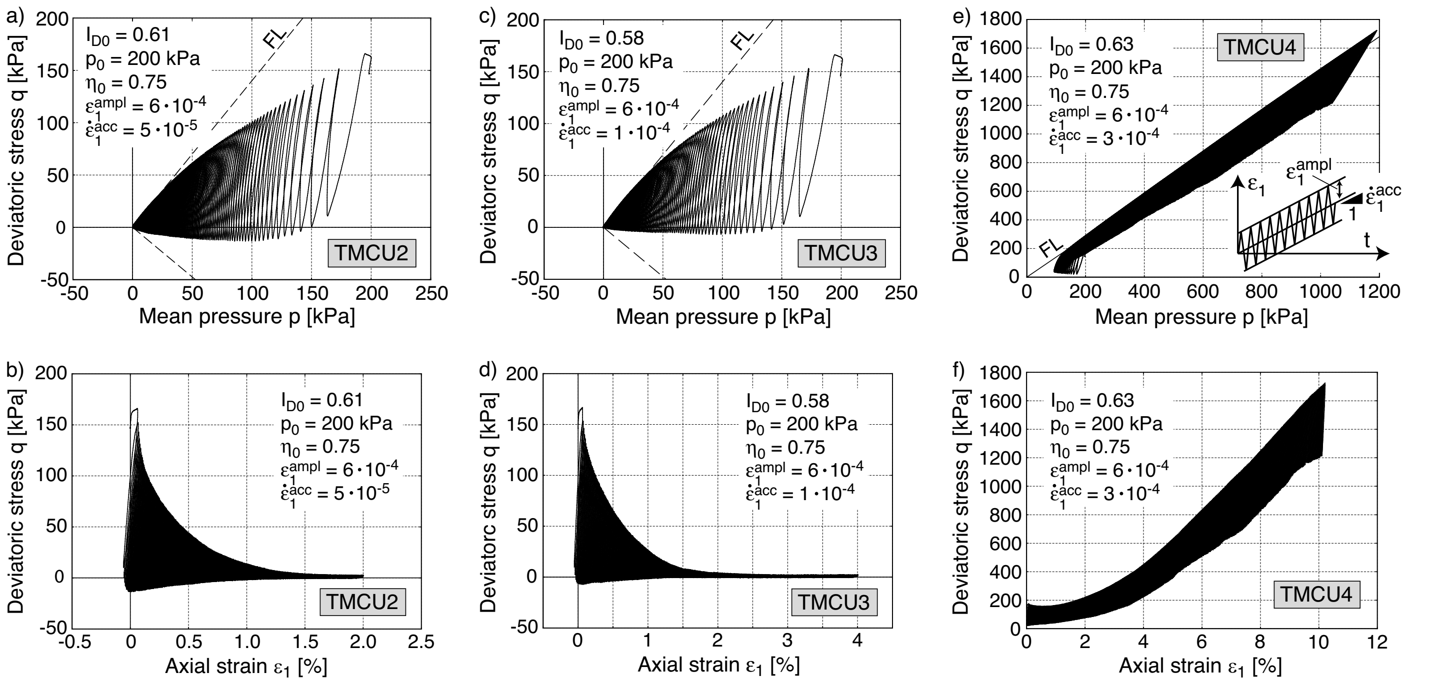

Fig. 12: Effective stress paths and stress-strain relationships measured in undrained cyclic triaxial tests with a combination of monotonic loading (rate $\dot{\varepsilon}_1^{\rm acc}$ per cycle) and small strain cycles (amplitude $\varepsilon_1^{\rm ampl} = 6 \cdot 10^{-4}$). The three tests have been performed with different values of $\dot{\varepsilon}_1^{\rm acc}$.

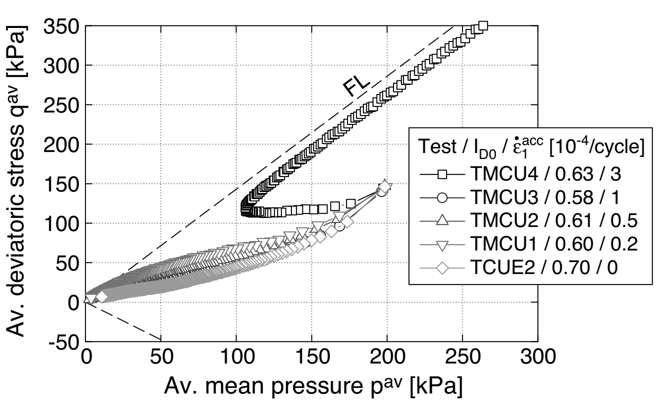

Fig. 13: Average effective stress paths (i.e. p and q values measured at the end of each cycle) in undrained triaxial tests with monotonic compression at a rate $\dot{\varepsilon}_1^{\rm acc}$ superposed by strain cycles with an amplitude $\varepsilon_1^{\rm ampl} = 6 \cdot 10^{-4}$

in Figure 13 corresponds to the p and q values measured at the end of each cycle. In contrast, the dilatancy due to the monotonic loading component prevailed in the case of the largest tested accumulation rate $\dot{\varepsilon}_1^{\rm acc} = 3 \cdot 10^{-4}$ (Figures 12e,f and 13). The resulting effective stress path in that test looked similar to that measured in a monotonic test (see e.g. Fig. 6a,c in [12]), superposed by a cyclic component.

The results of simulations of tests TMCU3 and TMCU4 are provided in Figure 14a,b. In accordance with the experimental results the predicted effective stress path ends up at $p = q = 0$ for test TMCU3 with $\dot{\varepsilon}_1^{\rm acc} = 1 \cdot 10^{-4}$ (Figure 14a), while the stress paths climbs along the failure line for TMCU4 with $\dot{\varepsilon}_1^{\rm acc} = 3 \cdot 10^{-4}$. However, the deviatoric stress q reached in the numerical simulations after approx. 330 cycles is much larger than that observed in the test (Figure 14b), i.e. the dilatancy predicted by the constitutive model is too large.

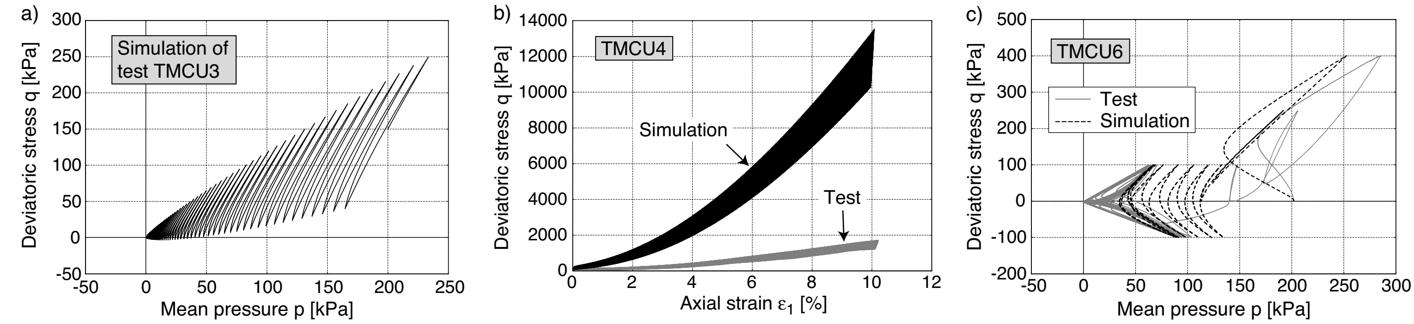

Fig. 14: Simulations of undrained triaxial tests with a,b) monotonic compression at different rates $\dot{\varepsilon}_1^{\rm acc}$ superposed by strain cycles with an amplitude $\varepsilon_1^{\rm ampl} = 6 \cdot 10^{-4}$ and c) a combination of stress cycles and monotonic loading

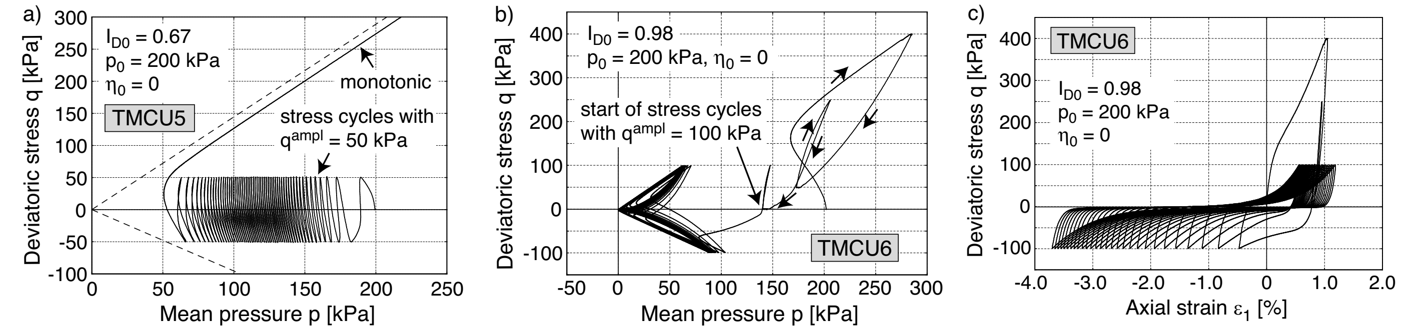

Fig. 15: Effective stress paths or stress-strain relationship measured in undrained cyclic triaxial tests with a combination of stress cycles and monotonic loading

Test	e_0 [-]	I_{D0} [-]	$\varepsilon_1^{\rm ampl}$ [10^{-4}]	$\dot{\varepsilon}_1^{\rm acc}$ [10^{-4}]
TMCU1	0.827	0.60	6.0	0.2
TMCU2	0.825	0.61	6.0	0.5
TMCU3	0.834	0.58	6.0	1.0
TMCU4	0.816	0.63	6.0	3.0

Table 6: Program of undrained triaxial tests with a combination of small strain cycles (amplitude $\varepsilon_1^{\rm ampl}$) and monotonic loading (rate per cycle $\dot{\varepsilon}_1^{\rm acc}$). Void ratios e_0 and relative densities I_{D0} measured at initial stress p_0 prior to undrained cyclic loading

3.5 Undrained tests with a combination of stress cycles and monotonic loading

In an undrained test on a medium dense sample (I_{D0} = 0.67, p_0 = 200 kPa, η_0 = 0, see test TMCU5 in Table 7) the stress cycles ($q^{\rm ampl}$ = 50 kPa, displacement rate 0.05 mm/min) were stopped shortly before the cyclic mobility phase would have started. The sample was then subjected to an undrained monotonic compression. The measured effective stress path during the monotonic test phase slowly adapts to the failure line known from the purely monotonic undrained tests (Figure 15a).

The effective stress path and stress-strain relationship provided in Figure 15b,c were obtained from an undrained test on a very dense sample (I_{D0} = 0.98, p_0 = 200 kPa, η_0 = 0, displacement rate 0.05 mm/min, see test TMCU6 in Table 7) where the deviatoric stress was first increased to q = 400 kPa, followed by an unloading to q = 50 kPa, a reloading to q = 250 kPa and another unloading to q = 0.

Test	e_0 [-]	I_{D0} [-]	p_0 [kPa]	$q^{\rm ampl}$ [kPa]
TMCU5	0.803	0.67	200	50
TMCU6	0.684	0.98	$\approx$ 140	100

Table 7: Program of undrained triaxial tests with a combination of monotonic loading and stress cycles. Void ratios e_0 and relative densities I_{D0} measured at initial stress p_0 prior to undrained cyclic loading

Finally, starting from the isotropic stress state, cycles with a stress amplitude $q^{\rm ampl} = 100$ kPa were applied. Obviously, during the first cycle a large increase of the pore pressure took place on the extension side ($q < 0$), where the effective stress path follows an elongation of the path measured at $q > 0$ during the preceding unloading phases (Figure 15b).

The effective stress path obtained from a simulation of test TMCU6 is depicted in Figure 14c. In particular the prediction of the material response during the un- and reloading cycle performed between $q^{\rm min}$ = 50 kPa and $q^{\rm max}$ = 250 kPa and that during the first cycle with $q^{\rm ampl}$ = 100 kPa starting from q = 0 is unsatisfying, i.e. far away from the experimental curves.

4 Summary and conclusions

The results of cyclic triaxial tests with strain cycles performed on a fine sand have been presented. In all tests a zero effective stress state ($p = q = 0$) was reached after a sufficiently large number of cycles, irrespective of the applied amplitude (a large range $4 \cdot 10^{-4} \leq \varepsilon_1^{\rm ampl} \leq 10^{-2}$ was tested) and the initial values of relative density I_{D0}, mean pressure p_0 or stress ratio $\eta_0 = q_0/p_0$. Even very dense sand ($I_{D0} = 1.01$) finally reached a state of full liquefaction.

Some tests with a combined monotonic and cyclic loading were also performed. Beside oedometric and isotropic compression tests with several un- and reloading cycles, some drained triaxial compression tests were repeatedly interrupted by an unloading to $q = 0$ followed by a reloading. Each un- and reloading cycle causes compaction and thus a less pronounced overall dilatancy compared to the purely monotonic tests. Furthermore, the maximum deviatoric stresses reached in the tests with the un- and reloading cycles are larger than in the case of a purely monotonic loading.

In undrained tests where small strain cycles ($\varepsilon_1^{\text{ampl}} = 6 \cdot 10^{-4}$) were superposed by a monotonic loading component the resulting effective stress path depends on the rate $\dot{\varepsilon}_1^{\text{acc}}$ of monotonic loading (i.e. the prescribed strain per cycle). In case of low rates the stress relaxation due to the cycles prevails over the dilatancy caused by the undrained monotonic shearing and $p = q = 0$ is finally reached. Larger rates $\dot{\varepsilon}_1^{\text{acc}}$ lead to an effective stress path similar to that observed in the undrained monotonic tests but superposed by some cyclic component.

Together with the results from monotonic tests and triaxial tests with stress cycles documented in the companion paper [12], this experimental database may serve for the development, calibration and verification of constitutive models with focus to cyclic loading. All test data presented in this paper will be available from [10].

As an example for the examination of an existing constitutive model based on the presented experimental data, selected tests have been recalculated using hypoplasticity with intergranular strain. The simulations demonstrate that some parts of the material response can be reproduced well (e.g. relaxation to $p \approx q \approx 0$ in tests with small strain cycles $\varepsilon_1^{\text{ampl}} \leq 10^{-3}$) while some other experimental observations are not captured sufficiently (e.g. eight-shaped final effective stress loops far away from $p = 0$ in simulations with large strain cycles $\varepsilon_1^{\text{ampl}} = 10^{-2}$, ratcheting or over-shooting in the oedometric or isotropic compression tests with un- and reloading cycles). The simulations presented herein and in the companion paper [12] demonstrate the difficulty of reproducing all different kinds of test conditions by a single constitutive model with a limited number of parameters. They highlight the need for further improvements of the existing models or for novel models that deliver a better description of the experimental results. Each reader is encouraged to check his own constitutive model against the data base published herein.

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