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Behavior of a poorly graded medium sand in undrained cyclic direct simple shear tests

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Abstract. In order to estimate accumulated excess pore pressures in the soil around a cyclically loaded (offshore) foundation structure, cyclic laboratory tests are required. In practice, the cyclic direct simple shear (DSS) test is often used. From numerous undrained tests (or alternatively tests under constant-volume condition) under varying stress conditions, contour diagrams can be derived, which characterize the soil's behavior under arbitrary cyclic loading conditions. Such contour diagrams can then be used as input for finite element models predicting the load-bearing behavior of foundation structures under undrained or partially drained cyclic loading. The paper deals with the general behavior of a poorly graded medium sand in cyclic DSS tests under undrained loading conditions. The main objective of the research was to investigate and parametrize the soil's behavior and to identify possible effects of sample preparation. Numerous tests with varying cyclic stress ratios (CSR) and mean stress ratios (MSR) have been conducted. Also the relative density of the sand was varied. A new set of equations for a relatively easy handable mathematical description of the resulting contour plots was developed and parametrized. In the original tests, the sand was poured into the testing frame and carefully compacted to the desired relative density by tamping. In offshore practice, a preconditioning of a soil sample is usually realised by cyclic preshearing with a certain CSR-value or additionally by preconsolidation under drained conditions. By that, a more realistic initial state of the soil shall be achieved. In order to investigate the effect of such a preconditioning on the resulting contour diagrams, additional tests were conducted in which preshearing and preconsolidation was applied and the results were compared to the test results without any preconditioning. The results clearly show a significant effect of preshearing and an even more pronounced effect of preconsolidation for the considered poorly graded medium sand.

Keywords: accumulated excess pore pressures; direct simple shear test; preconsolidation; preshearing; sand

1. Introduction

Many foundation structures, especially under offshore conditions, are subjected to intensive cyclic loading, which leads to cyclic shear stresses in the surrounding soil. Under such cyclic shear stresses, soil compaction generally occurs under drained loading, leading to accumulated plastic deformations of the foundation structure. Under undrained or partially drained loading conditions, accumulation of excess pore water pressures can occur, leading to a temporary reduction in the bearing capacity of the foundation structure. It is therefore important to know the behavior of the soil under cyclic shearing in order to derive predictions of deformation or pore water pressure accumulation.

The complex soil behavior under cyclic load can be investigated in cyclic direct simple shear (DSS) tests. A corresponding test program for a soil comprises numerous tests with variable stress boundary conditions, in which either the development of volume compression or the build-up of excess pore water pressure is measured as a function of the number of load cycles. The results of such tests can be displayed graphically as contour plots and described by parameterized equations.

In this form, the results can then be used as input values in calculation models for predicting deformation or excess pore water pressure accumulations. Examples of such calculation models are the NGI method (e.g., Andersen and Hoeg 1992) or the EPPE method (Saathoff and Achmus 2024a). This paper deals with the behavior of sandy soil in DSS tests under cyclic undrained loading. The results of an extensive series of tests with a poorly graded medium sand are presented, from which parameterized contour plots were developed. The samples were not preconditioned, i.e., preconsolidated or presheared, before the cyclic test phase. In geotechnical practice, however, it is common practice to first apply a certain number of load cycles with a shear stress of a specified magnitude under constant-normal stress. In addition, preloading and subsequent unloading with a normal stress, here termed preconsolidation, can also be carried out in advance. This should take into account the formation conditions of the soil and any pre-loads in situ. For example, the test results reported by Andersen *et al.* (2015), which are often used as a reference, apply to a preloading of the sample with 400 cycles of a shear stress amounting to 4% of the initial vertical stress. It is to be expected that preconditioning leads to a lower accumulation

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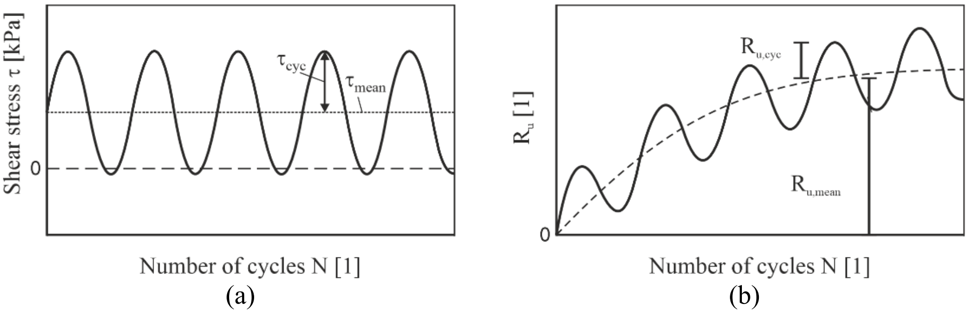


(a) (b)

Fig. 1 Results of a cyclic DSS test (schematic) with shear stress τ (a) and normalized excess pore pressure R_u, (b) over the number of cycles

of excess pore water pressures than without. However, the effect of a certain type of drained preconsolidation and preshearing on the results of subsequent undrained shear tests is largely unclear. In order to gain indications on this effect, this paper compares the results of cyclic undrained DSS tests of medium dense and dense samples with different preconditioning procedures. By this systematic comparison, the effect of preconditioning measures shall be generally clarified, paving the way for the development of general recommendations regarding sample preparation in practice.

2. State of the art on excess pore pressure contour plots

The accumulation of excess pore water pressures in sandy soils plays an important role not only in the design of offshore foundations for cyclic loads, but also in earthquake engineering with regard to potential soil liquefaction. Soil behavior under cyclic loads has been studied by Seed and Lee (1966), Lee and Seed (1967), Seed *et al.* (1975), Silver *et al.* (1976), Dobry *et al.* (1982), Vucetic and Dobry (1986), Polito (1999) and more recently by Do *et al.* (2023), Cui *et al.* (2023) and Moreno-Torres *et al.* (2023), among others. Both cyclic triaxial tests and cyclic direct simple shear (DSS) tests were carried out. Lee and Seed (1967) conducted load-controlled cyclic triaxial tests. Seed et al. (1975) later presented normalized excess pore water pressures as a function of the number of cycles, based on an approach by DeAlba *et al.* (1975), and observed that the normalized curves had similar shapes for different shear stress amplitudes. A detailed description of the knowledge regarding cyclic behavior of sand soils can be found in Saathoff (2023).

In practice, the cyclic DSS test is often used to investigate soil behavior. Undrained tests normally require a saturated soil sample in which pore water is prevented from flowing out and the resulting excess pore water pressure is measured. Alternatively, tests can also be carried out with unsaturated or dry sand under constant-volume (CV) conditions. In this case, the vertical load stress is controlled in such a way that no significant settlement of the load plate occurs. The decrease in vertical stress that then occurs can be approximately equated to the increase in excess pore water pressure in an actual undrained test (Airey and Wood 1986, Finn and Vaid 1977, Feda 1971). The ASTM regulation D8296-19 (2019) also assumes that the soil reaction under CV conditions is equal to undrained conditions.

Fig. 1 shows the result of an undrained DSS test schematically. The stress boundary conditions are given by the effective vertical stress at the start of the test $\sigma'_{v,0}$, the mean shear stress τ_{mean}, which is applied drained, and the undrained applied cyclic shear stress amplitude τ_{cyc}. The cyclic stress ratio (CSR) and the mean stress ratio (MSR) describe the stress boundary conditions in dimensionless form

$$CSR = \frac{\tau_{cyc}}{\sigma'_{v,0}} \tag{1}$$

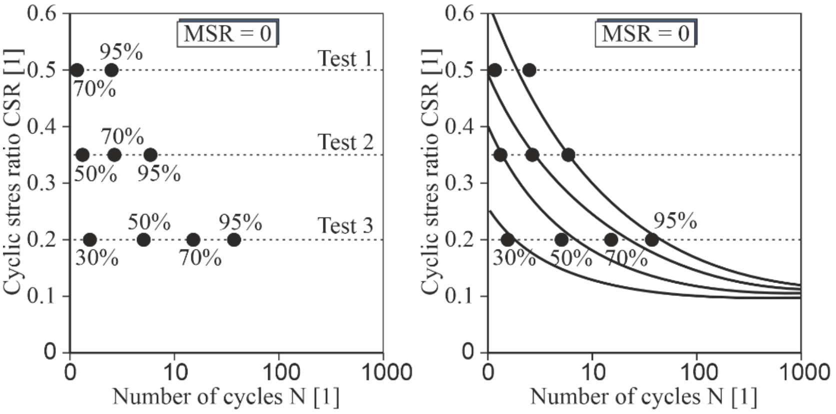
$$MSR = \frac{\tau_{mean}}{\sigma'_{v,0}} \tag{2}$$

As the number of cycles increases, the excess pore water pressure Δu in the sample increases. The excess pore water pressure ratio R_u indicates the ratio of the excess pore pressure to the effective vertical stress at the start of the test $\sigma'_{v,0}$

$$R_u = \frac{\Delta u}{\sigma'_{v,0}} \tag{3}$$

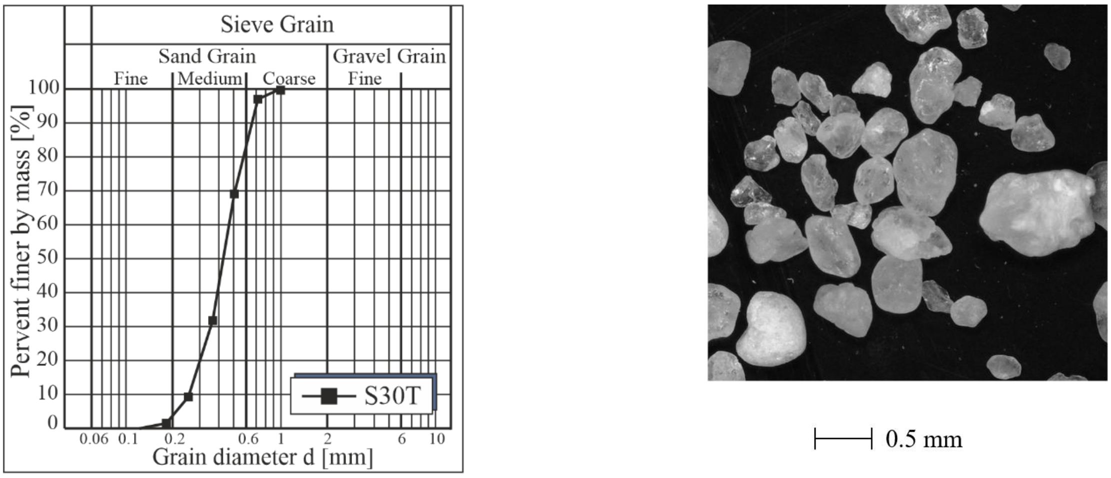
A contour plot for a certain soil can be derived from a number of discrete cyclic DSS tests with varying loading conditions (i.e., τ_{cyc}, τ_{mean}, $\sigma'_{v,0}$ or CSR, MSR). In order to reduce the high effort required for a complete test program, some authors suggest using existing test data or experience regarding the course of the contour plots in order to determine complete contour plots by means of calibration with relatively few tests (scaling approach, see e.g., Andersen 2015). Andersen *et al.* (2023) have also proposed how preliminary contour plots can be derived based on experience, taking into account common soil parameters. For sandy soils, the key parameters are the relative density D_r, the fines content and the over consolidation ratio (OCR).

Fig. 2 shows schematically how a contour plot for Δu or R_u, respectively, is derived. For each cyclic test conducted, the results for R_u values after distinct cycle numbers are recorded in a CSR-N diagram (Fig. 2(a)). From that,



(a) (b)

Fig. 2 Derivation of a contour plot for excess pore pressure ratio from a series of cyclic laboratory tests (following Andersen 2015): (a) test results and (b) derivation of regression curves



(a) (b)

Fig. 3 Grain size distribution of the investigated sand S30T (a) and microscopic images of particles (b)

isocurves (R_u = const) are derived by graphical or analytical regression (Fig. 2(b)). From several contour plots for different MSR values, a three-dimensional representation can finally be derived. As schematically depicted in Fig. 2, the excess pore pressure ratio increases with increasing cyclic stress ratio and number of cycles. Example contour plots for sand soils can also be found in Blaker and Andersen (2019) and Andersen (2015).

3. Contour plots of a sand without preconditioning

In Saathoff and Achmus (2024b), the results of extensive DSS tests under undrained conditions for a poorly graded medium sand were reported. The results of these tests are summarized below because they form the basis for assessing the influence of sample preconditioning.

Liquefaction of the soil sample is given when either the excess pore water pressure ratio becomes $R_u = 0.95$ or when the shear strain amplitude exceeds a value of 5%. The number of cycles at which this is fulfilled for the first time is referred to as N_{liq}.

3.1 Sand material and testing conditions

The tests shown here were carried out with a poorly graded quartz sand with the designation S30T. The grain size distribution of this material is shown in Fig. 3(a). It is a medium sand with a coarse sand content of approx. 15%. The uniformity index is $C_U = 1.8$. The microscopic image of particles (Fig. 3(b)) shows that the particles have predominately subangular shape. The index parameters of the material are summarized in Table 1.

The sand was poured into the test apparatus and compacted to the desired relative density by careful tamping.

A load plate was then placed on the sample and a vertical stress $\sigma'_{v,0}$ was applied for a consolidation time of 5 minutes. In the tests presented here, the initial vertical stress was not varied. The effective vertical stress at the start of the test was $\sigma'_{v,0}$ = 100 kN/m^2. All DSS tests were conducted at a frequency of 0.1 Hz. This low frequency was chosen to ensure adherence to the constant-volume boundary conditions. The CSR-values were chosen between 0.06 and 0.25.

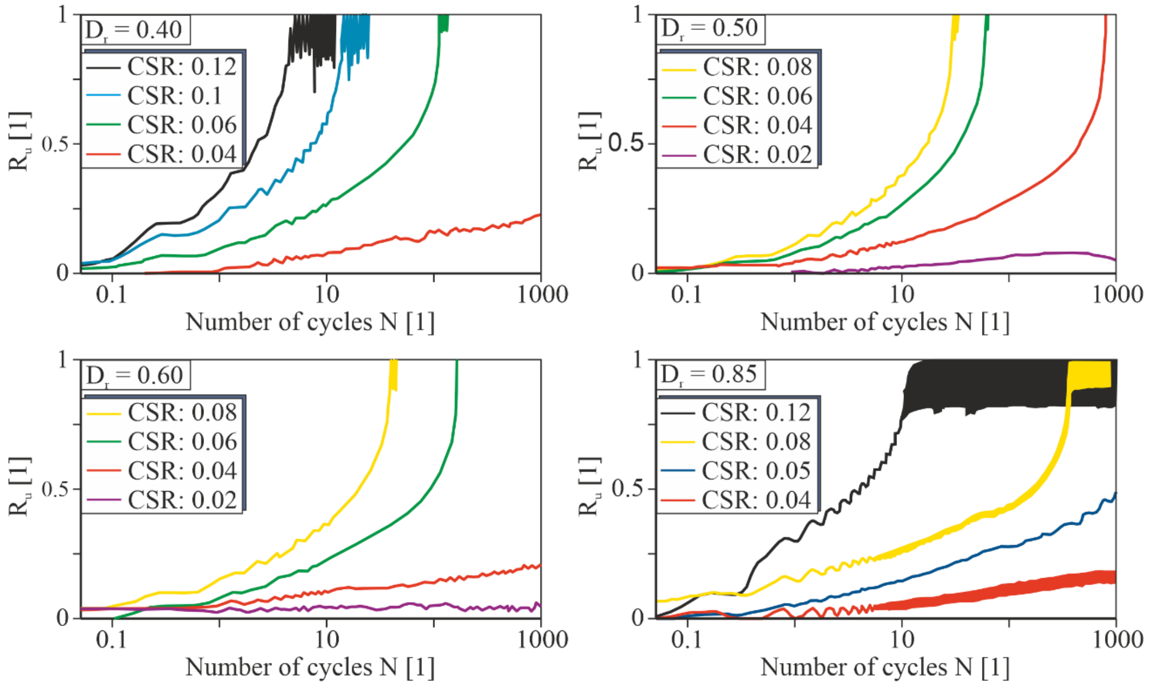


Fig. 4 Measured excess pore pressure ratios over number of cycles for S30T sand with variable relative densities, with a mean stress ratio MSR = 0 and without preconditioning

Table 1 Parameters of the investigated S30T sand

Name [-]	C_u [1]	C_c [1]	e_{max} [1]	e_{min} [1]	ρ_s [g/cm^3]
S30T	1.8	1.0	0.789	0.493	2.65

3.2 Results and contour plot approach

Only the results for MSR = 0 are presented in this paper because the tests with preconditioning were also only carried out with MSR = 0. Results for MSR > 0 can be taken from Saathoff and Achmus (2024b). Fig. 4 shows the results of test series with variable CSR values for MSR = 0 and relative densities of D_r = 0.4, 0.5, 0.6 and 0.85.

From these test results, a contour plot, i.e. a relationship between the excess pore water pressure ratio, the number of cycles N and the cyclic stress ratio CSR, can be derived for each relative density. Fig. 5 shows an example of such a plot for the relative density D_r = 0.85. The symbols are the results of the cyclic DSS tests. The plotted lines result from regression calculations using the equation given in the graph. The parameters a and b in this equation are functions of the pore water pressure ratio R_u. Details on this can be found in Saathoff and Achmus (2024b).

3.3 Scaling approach

Naturally, different contour plots result for different sands and relative densities. However, the basic curves of the contour plots for different sands are generally similar. It therefore makes sense to define a representative variable that can be used to approximately construct the contour plots for a particular sand. Andersen (2015) suggested using the value $CSR_{Nliq=10}$ as a characteristic value for sandy soils, i.e., the CSR value at which liquefaction occurs after exactly 10 cycles. The test results presented in Saathoff and Achmus (2024b) have also confirmed that the normalized representation of $CSR/CSR_{Nliq=10}$ over N_{liq} for different sands and relative densities produces approximately the same curve. Fig. 6(a) shows the curve proposed by Andersen *et al.* (2015). Fig. 6(b) shows the characteristic value $CSR_{Nliq=10}$ as a function of the relative density according to the results of Andersen (2015) and the results presented here and in Saathoff and Achmus (2024b). A strong effect of the sand's relative density on the liquefaction resistance is evident from Fig. 6. This has also been confirmed in triaxial compression tests by Seo and Kim (2024).

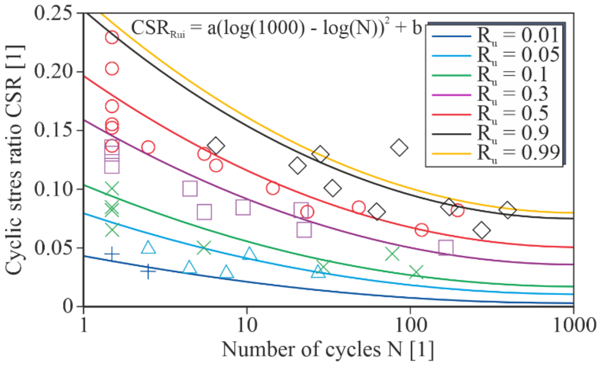
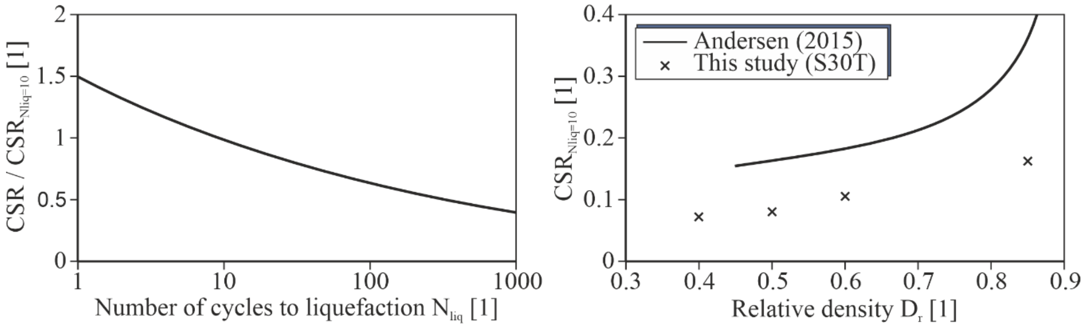


Fig. 5 Contour plot of the soil S30T sand with D_r = 0.85 (MSR = 0)

Andersen's tests were carried out with a sand with angular grains and less than 5% fines (Baskarp sand), whereas the present tests were carried out with a pure sand



(a) (b)

Fig. 6 Normalized liquefaction curved proposed from Andersen (2015) (a) and comparison of $CSR_{Nliq=10}$ from Andersen (2015) and from the present study (b)

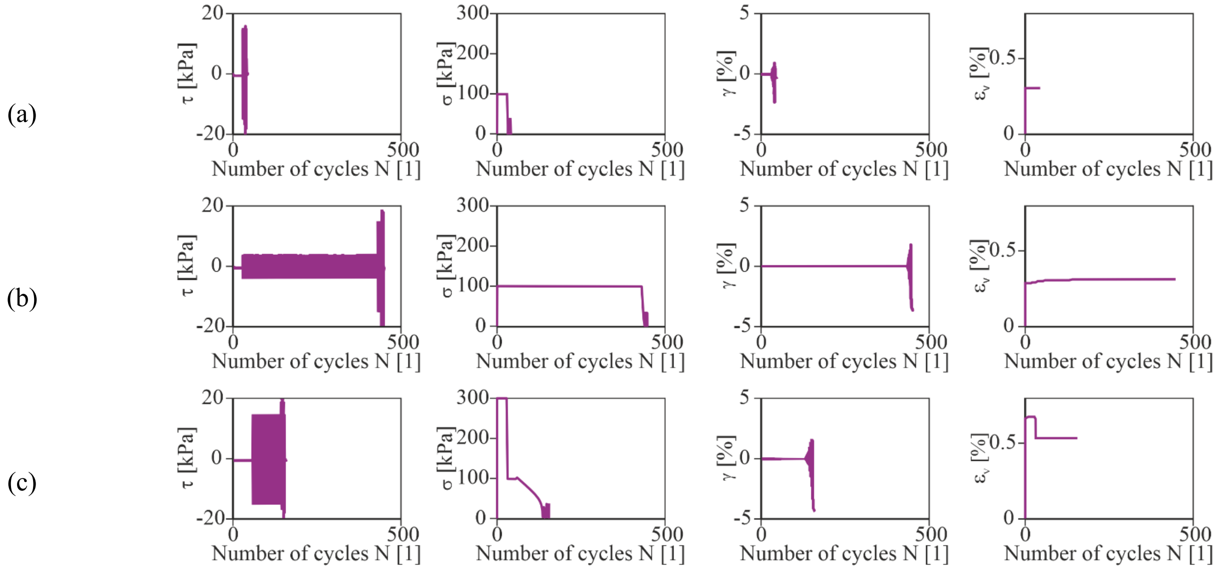


Fig. 7 Shear stresses τ, normal stresses σ, shear strains γ and volume strains ε_v at different stages during a cyclic test without preshearing (a), with preshearing (b) and with preloading (c)

with rounded (subangular) grains. Differences in soil behavior are therefore to be expected. The influence of grain shape on liquefaction resistance is also confirmed by Goldau *et al.* (2024). The sand investigated here has significantly lower bearable CSR values and thus a much greater tendency to liquefy. However, the tests by Andersen (2015) were carried out with cyclic preshearing (CSR = 0.04, N = 400). It is reasonable to assume that at least some of the differences observed are also due to this. The results of tests with different preshearing and preconsolidation procedures are therefore presented and compared below.

4. Effect of preconditioning on the test results

4.1 Test program

For the test program presented here, tests were carried out with the S30T sand in medium dense state ($D_r = 0.60$) and in dense state ($D_r = 0.85$). As preconditioning measures, preshearing was investigated using CSR values of $0.04 * \sigma'_{v,0}$ and $0.07 * \sigma'_{v,0}$ with N_{pre} = 400 cycles each and preconsolidation with an overconsolidation ratio of OCR = 3.

Fig. 7 illustrates the test phases for tests without preconditioning (Fig. 7(a)), with preshearing (Fig. 7(b)) and with preconsolidation. In all tests, the initial vertical stress (here 100 kPa) is applied and kept constant for some time (5 minutes), resulting in a consolidation settlement (volume strain ε_v, Fig. 7 right). In the test without preshearing, the cyclic load is then immediately applied with a specified CSR under constant-volume (CV) conditions, resulting in a decrease in vertical stress until liquefaction is reached.

In the test with preshearing (Fig. 7 (b)), a cyclic shear phase is carried out under constant normal load (CNL) conditions after the vertical stress has been applied. Under the - in this case 400 - load cycles, the applied load stress remains constant and further settlement or compaction of the sample occurs. Only after completion of the preshearing phase the cyclic load is applied under CV conditions and the decrease in vertical stress with the number of cycles recorded.

In the tests with preconsolidation (Fig. 7(c)), first a vertical stress of 300 kPa is applied to the sample and kept constant for 5 minutes. Then the vertical stress is lowered to100 kPa, inducing a slight heave of the sample (Fig. 7(c)

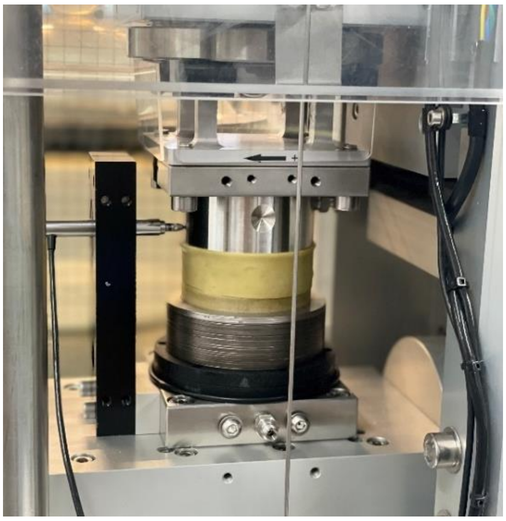


Fig. 8 Photo of the EMDCSS simple shear device used

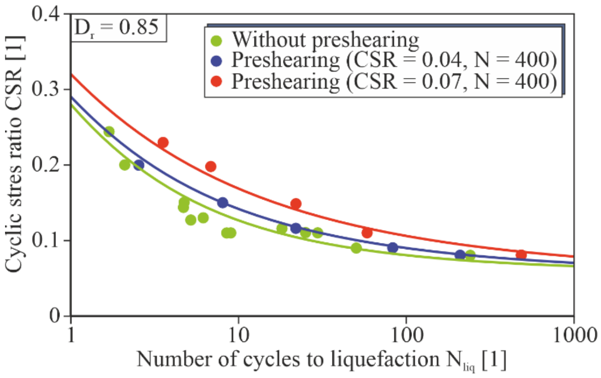


Fig. 9 Liquefaction curves CSR-N_{liq} with and without preshearing for a relative density of 0.85

right), and again kept constant for 5 minutes. By that, an overconsolidation ratio of OCR = 300/100 = 3 is applied to the sample. Eventually, the cyclic load with a specified CSR value is applied under CV conditions.

For this supplementary study, a total of 48 cyclic DSS tests were carried out. The CSR values of the CV phase were varied between CSR = 0.06 and 0.25. Two identical simple shear devices (EMDCSS) from the British company GDS were used to carry out the tests (Fig. 8). In the following figures, results obtained with the two (identical) devices DSS1 and DSS2 are shown separately. The filled symbols belong to tests with the DSS1 device, the unfilled symbols to tests with the DSS2 device. The results from the two devices for identical test conditions were quite similar, although not completely identical. This may also have been caused by slightly different installation conditions. Overall, however, the reproducibility of the results was quite good.

4.2 Results

Effect of preshearing

Fig. 9 shows the results of tests conducted with dense sand (D_r = 0.85) in terms of the recorded number of cycles to liquefaction N_{liq}.

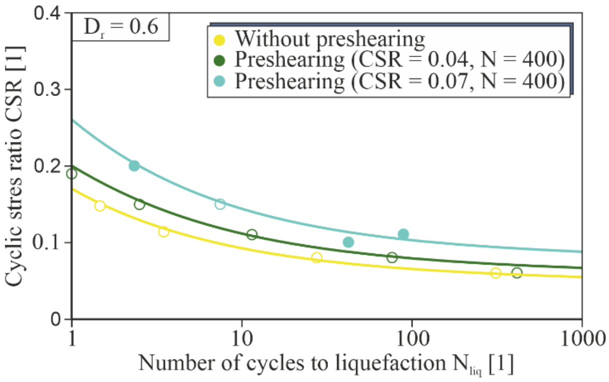


Fig. 10 Liquefaction curves CSR-N_{liq} with and without preshearing for a relative density of 0.6

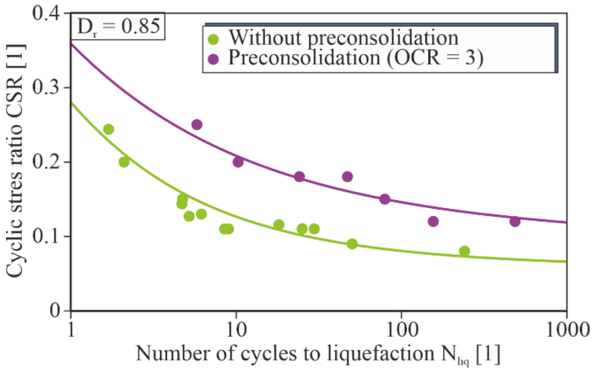


Fig. 11 Liquefaction curves CSR-N_{liq} with and without preloading (OCR = 3) for a relative density of 0.85

As expected, there is a clear trend towards increased liquefaction resistance with preshearing. For the same CSR value, the number of load cycles that lead to liquefaction increases with preshearing. If the mean values of the curves for the DSS1 and DSS2 devices are taken as a basis, the resulting values for CSR = 0.1 are N_{liq} = 28 (without preshearing), N_{liq} = 50 (preshearing with CSR_{pre} = 0.04) and N_{liq} = 120 (preshearing with CSR_{pre} = 0.07). The characteristic value $CSR_{Nliq=10}$ is without preshearing $CSR_{Nliq=10}$ = 0.127 and with preshearing $CSR_{Nliq=10}$ = 0.144 (CSR_{pre} = 0.04) and 0.168 (CSR_{pre} = 0.07), respectively. Hence, the value characteristic for liquefaction resistance increases by 13% and 32%.

In Fig. 10, results for medium dense sand (D_r = 0.6) are depicted. A very similar trend of the effect of preshearing as in the case of dense sand is evident. The increase of $CSR_{Nliq=10}$ is even more pronounced. Without preshearing, the value is $CSR_{Nliq=10}$ = 0.093. Preshearing with CSR_{pre} = 0.04 leads to $CSR_{Nliq=10}$ = 0.112 (increase of 20%) and preshearing with CSR_{pre} = 0.07 to $CSR_{Nliq=10}$ = 0.146 (increase of 57%).

Effect of preconsolidation

The results of tests with OCR = 3 are compared in Fig. 11 (dense sand, D_r = 0.85) and Fig. 12 (medium-dense sand, D_r = 0.6) with the respective test results without any preloading (i.e. also without preshearing).

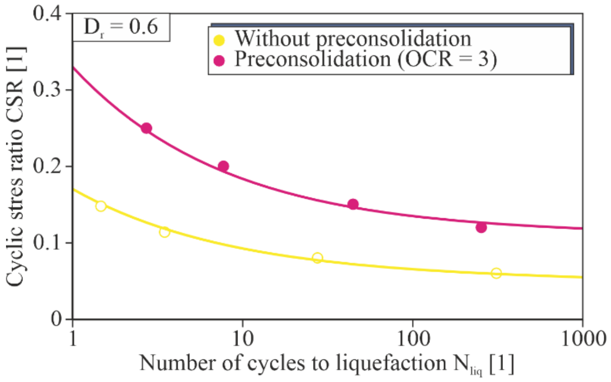


Fig. 12 Liquefaction curves CSR-N_{liq} with and without preloading (OCR = 3) for a relative density of 0.6

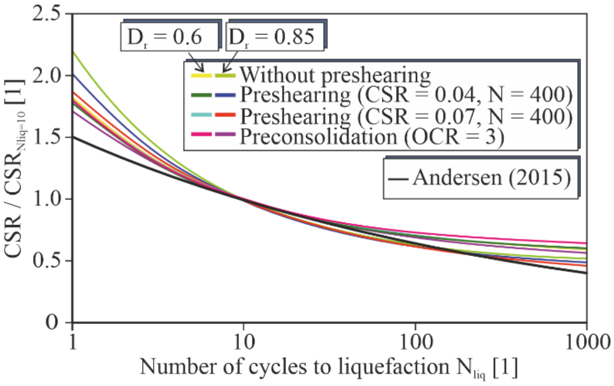


Fig. 13 Normalised liquefaction curves for all conducted tests

For both relative densities, a considerable influence of the preconsolidation is evident. For the dense sand, the number of cycles leading to liquefaction at a CSR value of 0.15 increases from 5 (without preloading) to 80 (with preloading) (Fig. 10). The characteristic value $CSR_{Nliq=10}$ increases from $CSR_{Nliq=10} = 0.127$ to $CSR_{Nliq=10} = 0.210$ and thus by 65%. With medium dense sand (Fig. 12), the effect is again even more pronounced, as with preshearing. The characteristic value $CSR_{Nliq=10}$ increases from $CSR_{Nliq=10} = 0.093$ to $CSR_{Nliq=10} = 0.183$ and thus by 96%.

The investigated relative densities of 0.85 and 0.6 apply in each case to the initial state after specimen installation, i.e., before application of the load and before any preconsolidation or preshearing. Because preloading induces settlement of the specimen, the relative densities at the start of cyclic loading under CV conditions are not exactly identical. However, the differences are relatively small, i.e. only minor settlements occurred under load application and preconditioning measures. The evaluation of axial strain shows that after load application or preconditioning, an increase in relative density of 4% to 7% occurs at an initial relative density of $D_r = 0.6$, while an increase of 2% to 4% is observed at an initial relative density of $D_r = 0.85$. The considerable increases in the liquefaction resistances must therefore be caused by structural changes in the samples or by changes in the stress state in the sample. The preloading of the soil sample by overconsolidation stress presumably not only leads to a small permanent settlement and thus possibly to an improved interlocking of individual grains, but also to an increase in the horizontal stresses in the sample. In sand soils, an increase of the coefficient of earth pressure at rest with approximately $OCR^{0.5}$ can be assumed (Mesri and Hayat 1993). Therefore, with OCR = 3, the horizontal stress in the sample can be estimated to be 73% higher than in the case without preconsolidation. This is the plausible explanation for the considerable increase in liquefaction resistance.

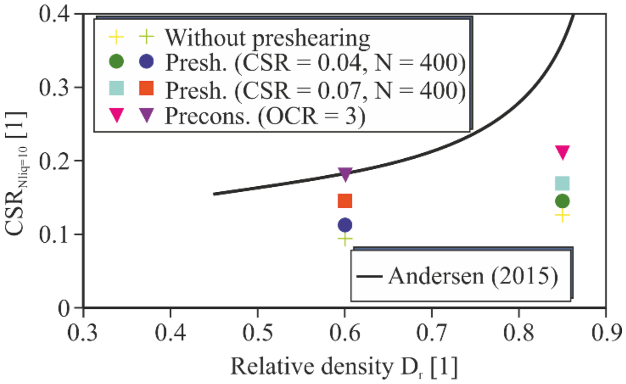


Fig. 14 Normalised liquefaction curves for all conducted tests

Normalized representation

Fig. 13 shows the trend curves from Figs. 9 to 12 in the normalized representation (see Fig. 6(a)), i.e., the CSR values are related to the characteristic reference value $CSR_{Nliq=10}$. It is obvious from this figure that preshearing and preconsolidation have little effect in this representation. All the curves determined with the test results presented here fall in a relatively narrow range. This shows that the same scaling approach with use of $CSR_{Nliq=10}$ as representative parameter can be used independent of any preconditioning measures. However, for the most parts the curves determined for the S30T sand lie slightly higher than the curve proposed by Andersen (2015).

Evidently, much smaller differences of the results for S30T sand and Baskarp sand (as investigated by Andersen) can arise when preconditiong measures are carried out.

Preshearing with CSR = 0.04 and N = 400, as also done by Andersen, has only a relatively small effect, but a preconsolidated S30T sample with OCR = 3 has for medium dense state ($D_r = 0.6$) almost the same liquefaction resistance as the Baskarp sand sample (Fig. 14). This indicates that the overconsolidation state of a sand in situ should be carefully investigated and reproduced in DSS tests in order to gain meaningful test results.

5. Conclusions

The paper presents the results of extensive DSS tests on the behavior of a poorly graded medium quartz sand under undrained cyclic shear. Contour plots were derived and parameterized from the test results. In addition, a scaling approach was presented, which enables the estimation of complete contour plots based on a characteristic parameter that can be determined with just a few tests.

The test results were carried out with non-preloaded samples. In geotechnical practice, however, it is common practice to precede the undrained shear phase with a drained cyclic preshearing phase. Also, a preconsolidation of the sample under increased vertical stress is possible in order to create an overconsolidation state in the sample. In order to quantify the effect of such a preloading on the test results, cyclic DSS tests were carried out on medium dense and dense samples with and without preshearing or preconsolidation phases.

The results show a clear influence of a preshearing phase. As the intensity of preshearing increases, i.e. with the applied shear stress amplitude, the liquefaction resistance (expressed by the number of load cycles leading to liquefaction) increases significantly. The characteristic parameter for the scaling approach quantifying the liquefaction resistance of a sand with a given relative density also changes accordingly, with increases of 13-32% for dense sand and 20-57% for the medium dense sand.

The tests with a preconsolidation leading to an OCR of 3 showed an even greater effect of preloading on the liquefaction resistance than of preshearing. The characteristic parameter $CSR_{Nliq=10}$ increased by 65% for dense sand and 96% for medium dense sand.

In summary, it is shown that preconditioning of sand samples in advance of a cyclic direct simple shear test under CV conditions can strongly affect the determined soil behavior.

However, the test results indicate that the presented scaling approach can generally be used because the normalized liquefaction curve does not change significantly due to preshearing or preconsolidation.

The results of this study need to be supplemented insofar as only two possible preshearing measures and one possible preconsolidation measure were investigated. In further tests, the number of load cycles for preshearing should also be varied and the influence of different vertical preloads should also be investigated. Anyhow, the presented test results clearly show an effect of preshearing and preconsolidation and thus indicate a need for research into the effect of preconditioning of samples.

Acknowledgments

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