INFLUENCE OF PRE-SHEARING ON THE TRIAXIAL DRAINED STRENGTH AND STIFFNESS OF A MARINE NORTH SEA SAND

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Abstract
It is widely recognized that stress history affects the stress-strain, strength and stiffness behaviour of sands. Since undisturbed sand samples are almost impossible to obtain at an affordable cost, pre-shearing or pre-conditioning of reconstituted sand specimens is commonly justified by the fact that it simulates *in situ* stress history while correcting inhomogeneity issues (as may be the result of the reconstitution procedure), levelling out stress concentrations and may change the soil structure. However, most of the previous studies investigating pre-shearing are related to liquefaction analysis and therefore do not focus on the pre-shearing response of drained dense to very dense sands. The present research examines series of drained triaxial compression tests (CADC) performed on a typical North Sea sand, with and without pre-shearing (degree of pre-shearing expressed by normalized cyclic shear stress, $\tau_{cy}/\sigma`_{vc}$, at 6% and 12% during 400 cycles), at low (10kPa to 50kPa) to high consolidation stresses (50kPa to 200kPa), on reconstituted dense ($D_r \approx 57\%$) to very dense ($D_r \approx 88\%$) sand. The experimental results indicate that pre-shearing does not significantly influence the drained strength nor the stiffness of the sand. Evidence suggests that so-called seating issues seem to be mitigated by pre-shearing. Hence pre-shearing does not necessarily need to be applied in drained triaxial tests on dense sand if the shear strength is the targeted main design parameter, even-though the *in situ* stress history may suggest so.

1. Introduction

Offshore structures are subjected to cyclic loading resulting from wave loading. Pre-storm cyclic loading in sand is replicated in the laboratory by applying a cyclic drained stresses, or more commonly known as pre-shearing, on element tests. Previous studies have shown that pre-shearing has a fundamental effect on sand testing behaviour of reconstituted specimens (e.g. Finn et al., 1970; Ishihara and Okada, 1982; Bobei et al. 2013; Ye et al. 2015). However, those studies were mainly focusing on the liquefaction of loose sand specimens, where a small level of pre-shearing can cause a significant increase in liquefaction resistance, while a high pre-shearing may cause a decrease. Because undisturbed sand samples are almost impossible to obtain at an affordable cost, application of pre-shearing to reconstituted specimens is commonly justified since it may simulate *in situ* stress history and may mitigate inhomogeneity issues by levelling out stress concentrations arising from specimen reconstitution. Pre-shearing influences sand behaviour when tested under direct simple shear boundary conditions (DSS), as shown by Andersen (2015), where also a change of soil structure and an increase of the horizontal stresses have been reported. For a wide range of relative densities (D_r) Andersen (2015) reported also an increase of the cyclic shear strength between 5% and 25% when pre-shearing was applied. However, if large strains are induced by pre-shearing a 'break down' of the sand fabric may develop and the cyclic shear strength may reduce (see Oda et al., 2001 and Wijewickreme and Sanin, 2005).

While pre-shearing effects on DSS have been widely investigated, those effects on the static shear strength of reconstituted sand under triaxial conditions have not. Moreover, the importance of understanding pre-shearing in dense sands at low stresses (mean effective stresses, p' ≤ 50kPa) is justified by the fact that several offshore structures are installed using shallow foundations or suction caissons subjected to cyclic loads, hence pre-shearing. Pre-shearing may also be induced by foreshocks before earthquakes on densified sands, e.g. as in dams, ports or highway abutments.

The laboratory work presented in this paper is part of a research study on interpretation of CPT in dense sands at shallow depths (< 5m depth below surface).

2. Soil and testing program

A pleistocene, North Sea, clean sand from a site near Cuxhaven, Germany, has been used in this study. This sand is part of fluvial or deltaic sediments that were deposited in the German Bight during inter-glacial periods.

2.1 Index characteristics

Cuxhaven sand is a fine to medium, poorly graded quartz sand (d_{10} = 0.10mm, d_{60} = 0.21mm, C_U = 2.1, C_C = 1.1, SiO_2 = 93%). A grain size distribution curve, obtained after NS 8005, is shown in Figure 1.

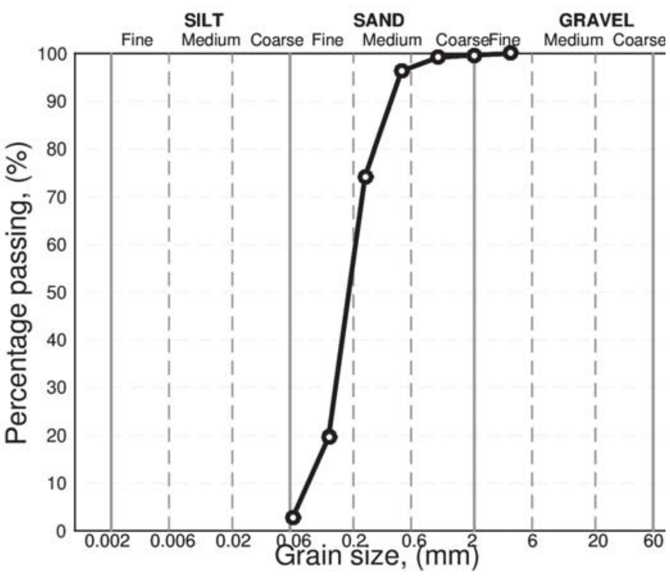

Figure 1: Grain size distribution curve of Cuxhaven sand

The unit weight of solid particles (γ_s) as obtained by NS 8012 is γ_s = 26.2kN/m^3. Sand particles are classified as sub-rounded. The roundness, sphericity and particle regularity are 0.75, 0.90 and 0.82 respectively, after Krumbein and Sloss (1963).

Maximum and minimum dry unit weights ($\gamma_{d,max}$ and $\gamma_{d,min}$) were determined using four different methods as per Table 1. The mentioned methods are NGI's *in-house* method, the *two-prong* impactor after the Deutsches Institute fur Normung (DIN, 1996), a modified method from the Dansk Geoteknisk Forening (DGF, 2001) and finally Geolabs' *in-house* method. As expected, different methods result in different values of $\gamma_{d,max}$ and $\gamma_{d,min}$ and thus, relative density (D_r) can only be used by means of a uncertain reference value to describe the packing of particles. Nevertheless, NGI values of $\gamma_{d,max}$ and $\gamma_{d,min}$ are used for calculating the D_r of the tested specimens in this study.

Table 1: Maximum and minimum dry densities

Method name	Lab.	No.	$\gamma_{d,max}$ (kN/m^3)	$\gamma_{d,min}$ (kN/m^3)
NGI in-house	NGI	1	17.27	14.19
		2	17.19	14.21
Two-prong impactor after DIN	NGI	3	16.83	13.97
		4	16.88	13.97
DGF modified	GEO	5	17.27	14.22
		6	17.36	14.22
Geolabs in-house	Geolabs	7	17.84	14.64

2.2 Testing program

The primary goal of the lab program is to investigate low stresses regime and secondary pre-shearing effects on static strength of anisotropically consolidated drained compression triaxial tests (CADC) at several confining stresses, while considering a variation of D_r. Table 2 presents an overview of the testing program.

Table 2. Test program and variables considered in this study

No. (-)	σ'$_{vc}$ (kPa)	K (-)	τ_{cy}/σ'$_{vc}$ (-)	Comments (-)
1	20	1	-	-
2	20	1	-	Quality control test
3	20	1	0.06	Check pre-shearing
4	20	1	-	Check influence of D_r
5	50	1	0.06	Check D_r, compare with test No. 8
6	20	2	-	Compare test No. 13
7	10	1	0.06	Compare test No. 9 and No. 11 but at different D_r
8	50	1	-	Compare with test No. 5
9	10	1	-	Compare with tests No. 11
10	50	1	0.06	Compare with tests No. 5 and No. 8 at different D_r
11	10	1	0.06	Compare with tests No. 9
12	200	1	0.06	Check high stresses effects
13	20	2	0.12	K effect, compare test No. 6, higher pre-shearing
14	20	1	0.12	Compare with test No. 4
15	200	1	-	Compare with test No. 12
16	200	1	0.12	Compare with tests No. 12 and 15 higher pre-shearing
17	200	1	0.06	Compare with test No. 12
18	200	1	0.12	Compare with test No. 17
19	200	1	-	Compare with tests No. 17 and 18

CADC tests were performed considering following variables: $D_r \approx$ 57% and $D_r \approx$ 88%. Effective vertical consolidation stresses (σ'$_{vc}$) = 10kPa, 20kPa, 50kPa and 200kPa. Anisotropy, K = 1.0 and 2.0. Pre-shearing (τ_{cy}) was not always applied, hence tests are described as 'with' and 'without' pre-shearing (abbreviated as wp and wop respectively). Pre-shearing was applied as either τ_{cy} = 6% or 12% of $\sigma`_{vc}$ both at 400 cycles. A risk at small vertical stresses is that τ_{cy} applied could be insignificantly small (e.g. τ_{cy} = 0.6kPa at σ'_{vc} = 10kPa). Bender elements were used for obtaining the shear wave velocity (v_s) for calculating the initial small-strain shear modulus (G_{max}) of all specimens, results being reported in the next section.

3. Test description and procedures

The triaxial equipment used at NGI is described in detail by Berre (1982). However, a short description of testing procedures for monotonic testing and pre-shearing is presented in the following.

3.1 Specimen reconstitution and consolidation

Reconstituted sand specimens are built in using a slightly modified version of undercompaction method as described by Ladd (1978). First the dry soil is mixed with water, to attain a typical water content around 5%. An undercompaction factor U_l of 0.05 or 0.005 for $D_r \approx 57\%$ or 88% respectively. For triaxial specimens the soil is tamped into the mould in six layers. The initial layers are compacted to lower densities than succeeding layers so that the final density of each specimen layer is approximately uniform. For $D_r < 80\%$, compaction is normally done by hand tamping only. For $D_r > 80\%$, both hand tamping and vertical vibrations are required in order to achieve the specified densities.

After reconstitution the specimen in mounted in the triaxial cell and consolidation is achieved by loading the specimen to the specified vertical and horizontal consolidation stresses in steps.

3.2 Bender element testing

The small strain shear modulus (G_{max}), which is normally associated with shear strain levels of about 0.001% and below, was obtained in all test. Measurements of G_{max} are made by using the bender element technique. Readings can be done at any stage of whatever advanced tests without interfering with the particular test. Reference is made to Dyvik and Madshus (1985) and Dyvik and Olsen (1989) for details on the test setup. The peak to peak travel time and length travelled return the shear wave velocity.

3.3 Pre-shearing

After the specimen is mounted, consolidated and bender element measurements are performed as previously described, the specimen is then subjected to two-way cyclic loading (τ_{cy}). For this study, pre-shearing was applied with a period of 10 sec (frequency of 0.1 Hz) under drained conditions.

3.4 Shearing

The specimen is sheared at a constant rate of axial strain. The total radial stress is kept constant while the total axial stress is increased in compression tests. Drainage is allowed during shearing so no excess pore pressures may develop. The rate of strain was chosen as low enough to avoid development of excess pore water pressure.

4. Experimental results

Results are presented in Table 3 in terms of achieved D_r after consolidation, mean effective stress (p'), pre-shearing stress applied (τ_{cy}), peak friction angle ($\phi'_{p,txl}$), and at end of consolidation: v_s, G_{max} and void ratio (e_c). $\phi'_{p,txl}$ is calculated after Bolton (1986) at peak stress ratio (σ'_v/σ'_h) or peak strength as in Equation 1, while the large strain friction angle ($\phi'_{ls,txl}$) was obtained using the same formula but at ≥8% axial strain (ε_a).

$$\phi'_{p,txl} = \sin^{-1}\frac{(\sigma'_v/\sigma'_h)_{max}-1}{(\sigma'_v/\sigma'_h)_{max}+1} \quad (1)$$

where σ'_v = effective vertical stress (kPa) and σ'_h = effective horizontal or radial stress (kPa).

Table 3. Results of triaxial CADC testing progam

No.	D_r (%)	p' (kPa)	τ_{cy} (kPa)	$\phi_{p,txl}$ (°)	v_s (m/s)	G_{max} (MPa)	e_c (-)
1	56.7	20	-	45.0	136	37.6	0.652
2	56.6	20	-	44.6	130	34.1	0.665
3	56.3	20	1.2	44.0	126	32.2	0.658
4	86.6	20	-	51.4	133	36.9	0.563
5	87.1	50	3.0	50.3	189	74.7	0.559
6	86.6	30	-	50.3	154	49.6	0.559
7	86.1	10	0.6	52.4	96	19.2	0.566
8	86.7	50	-	49.5	192	76.8	0.565
9	56.5	10	-	44.6	106	22.6	0.671
10	56.8	50	3.0	42.0	182	67.2	0.656
11	55.7	10	0.6	43.4	92	17.2	0.655
12	57.7	200	12.0	38.4	265	142.9	0.649
13	85.2	30	2.4	48.9	130	35.2	0.568
14	85.9	20	2.4	50.1	127	33.5	0.571
15	57.1	200	-	38.6	256	131.5	0.659
16	57.7	200	24.0	38.5	268	144.1	0.658
17	89.0	200	12.0	46.8	319	211.6	0.555
18	91.7	200	24.0	46.0	306	195.1	0.542
19	89.9	200	-	46.7	288	172.0	0.548

The dilation angle is calculated after Andersen and Schjetne (2013) by Equation 2:

$$\psi_{max} = \sin^{-1}\frac{-\Delta\varepsilon_{vol}}{(2\Delta\varepsilon_a-\Delta\varepsilon_{vol})} \quad (2)$$

where $\Delta\varepsilon_{vol}$ = change in volumetric strains (%) and $\Delta\varepsilon_a$ = change in axial strains (%).

For checking the repeatability of CADC tests at low stresses, a test at σ'_{vc} = 20kPa was repeated (namely tests No. 01 and No. 02). Based on those results, it can be concluded that the peak friction angle in CADC can be obtained to an accuracy of ± 0.5° at NGI.

CADC results for tests performed at $D_r \approx 88\%$ are shown in Figure 2 and for $D_r \approx 57\%$ in Figure 3. Results are given in terms of σ_v'/σ_h' versus ε_a in Figures 2a and 3a and in terms of volumetric strain (ε_{vol}) versus ε_a in Figures 2b and 3b. For comparison purposes, tests without pre-shearing are represented by black symbols and black lines, while tests with pre-shearing are given in red symbols and red lines in all subsequent figures.

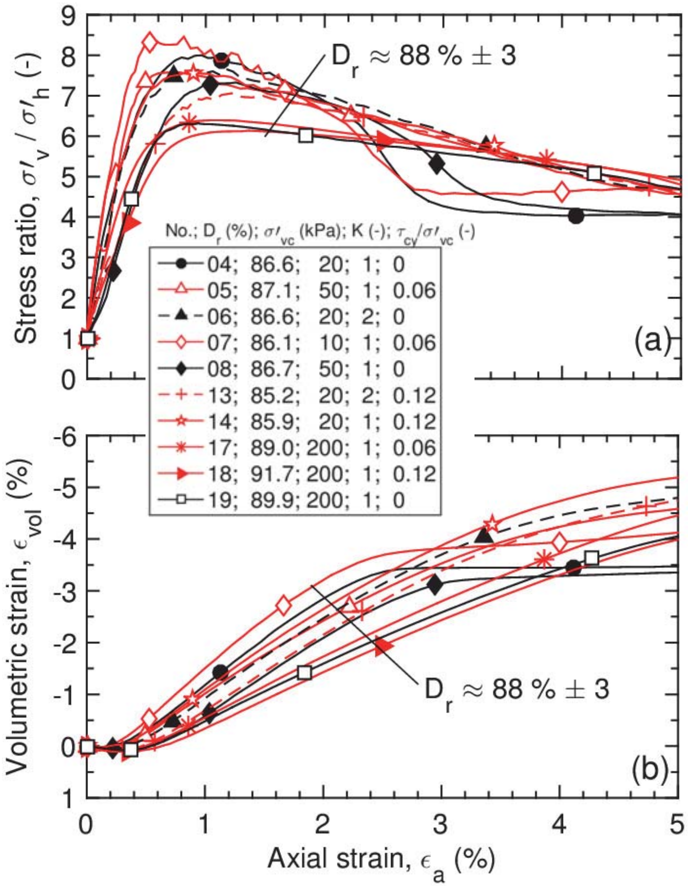

Figure 2: CADC results at $D_r \approx 88\%$; (a) shear stress ratio vs. axial strain, (b) volumetric strain vs. axial strain

By comparing Figure 2a with 3a it is clear that the effect of D_r significantly affects the stress ratio as expected. Tests at $D_r \approx 88\%$ show consistently higher σ'_v/σ'_h than tests at $D_r \approx 57\%$. The effect of p' on the sand stress-strain behaviour is also significant. The lower p', the higher σ_v'/σ_h'. By comparing Figure 2b with 3b it is clear that tests at $D_r \approx 88\%$ have consistently higher negative ε_{vol} (volume increase) with increasing ε_a, than the tests with lower $D_r \approx 57\%$. $\phi'_{p,txl}$ and the dilation angle (ψ) are strongly influenced by both D_r and p'. The higher D_r and the lower p'. The higher $\phi'_{p,txl}$ and ψ (see also Figure 4).

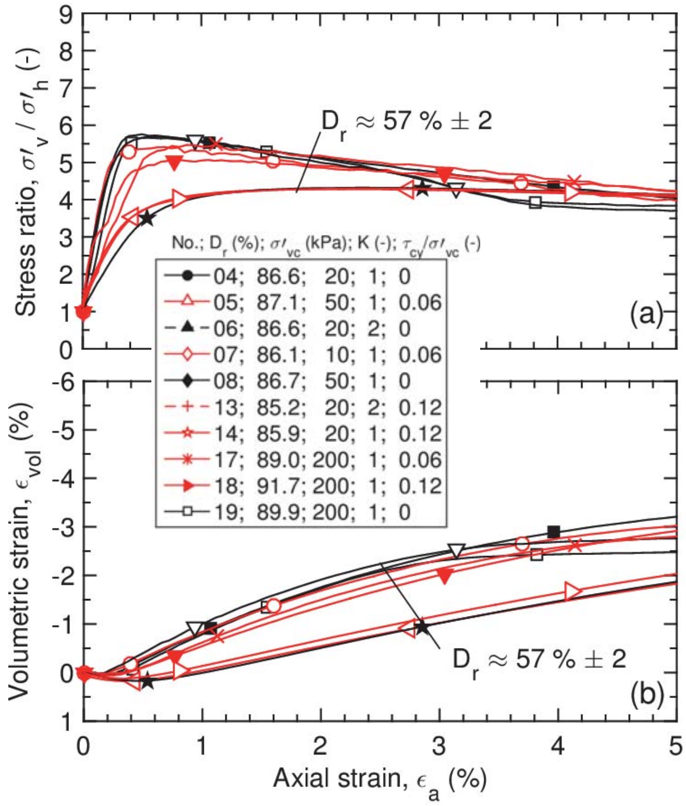

Figure 3: CADC results at $D_r \approx 57$ %; (a) shear stress ratio vs. axial strain, (b) volumetric strain vs. axial strain

5. Analysis and discussion of experimental results

5.1 Pre-shearing effects on strength

Figure 4 summarizes the values of $\phi'_{p,txl}$ obtained from CADC tests performed in this investigation. Tests performed at $D_r \approx 88\%$ are shown as open circles and tests at $D_r \approx 57\%$ in open squares.

The variation of $\phi'_{p,txl}$ due to pre-shearing is less than ± 1° and about ± 2° for ψ. Moreover, ψ varies more than $\phi'_{p,txl}$ due to the inherent nature of determining ψ from the ε_{vol}-ε_a measurements. Tests performed at K = 2 (instead of K = 1) does not show substantial pre-shearing effects on $\phi'_{p,txl}$, ψ and ϕ'_{ls}. Remember that the applied τ_{cy} may be insignificant at the very low p' values.

For a better overview of the effect of pre-shearing on $\phi'_{p,txl}$ and the overall stress-strain behaviour of sand, comparison plots of shear stress as a function of axial strain are show in Figures 5 and 6. Direct comparison of test with and without pre-shearing and at different pre-shearing and consolidation levels are shown in these figures too. As seen in Figure 5a, where tests No. 01, 02 and 03 (at $D_r \approx 57\%$, p'=20kPa and K = 1) are compared, the maximum shear strength (τ_{max}) of all tests are similar. As tests No. 01 and No. 02 are exactly the same (test No. 02 being a quality control test to gauge experimental variability), it is evident that pre-shearing does not significantly affect the strength of this sand.

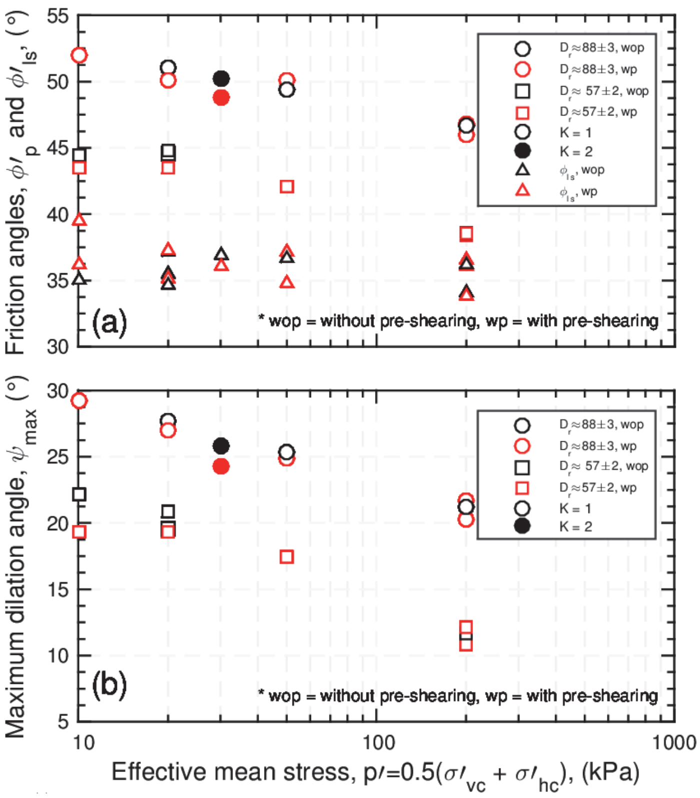

Figure 4: CADC results in terms of peak friction angle as function of effective mean stress

Tests No. 15, 12 and 16 are compared in Figure 5b, common denominators for these three tests are $D_r \approx$ 57% and p' = 200kPa. However, the pre-shearing conditions differ from test to test. Test No. 15 was performed without pre-shearing (τ_{cy} = 0kPa), while test No. 12 was pre-sheared with τ_{cy} = 12kPa and test No. 16 with τ_{cy} = 24kPa. From Figure 5b it can be inferred that τ_{max} in all tests is the same, hence no difference in $\phi'_{p,txl}$ as previously mentioned. Moreover, increasing pre-shearing from τ_{cy}/σ'_{vc} = 6% to 12%, does not have a significant effect on the maximum strength. In Figures 5a and 5b pre-shearing seems to mitigate seating issues, since the shear stress increase earlier (with increasing ε_a) when pre-shearing is applied.

Figure 5c shows a comparison of tests No. 17, No. 18 and No. 19 (all performed at $D_r \approx$ 90% and p' = 200k Pa, with different levels of pre-shearing, i.e. τ_{cy} = 12kPa, 24kPa and 0kPa respectively). The τ_{max} of test No. 17 was marginally higher than obtained in test No. 18, while test No. 19 without pre-shearing lies in between the other two pre-sheared tests. Nevertheless, the difference in peak friction angle between all the tests is less than 1°.

Additional comparisons are presented in Figure 6. As seen in Figure 6a, test No. 04 without pre-shearing and test No. 14 with pre-shearing show almost identical behaviour in terms of peak shear strength. As seen in Figures 6b and 6c the peak shear strength of the pre-sheared test (No. 05) is higher than the tests without pre-shearing (No. 08) while the opposite is observed for tests No. 06 and No. 13 (see Figure 6c).

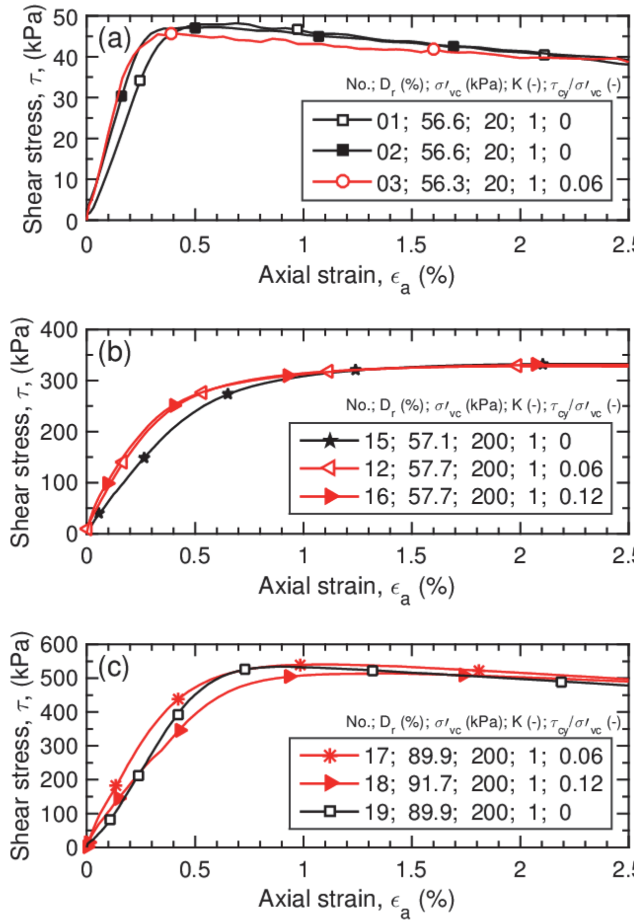

Figure 5: Comparison of CADC results in terms of shear stress vs. axial strain; tests No. 01, 02, 03, 12, 15, 16, 17, 18 and 19

Nevertheless, in terms of friction angle the difference is less than < 2°. Moreover, the compared pair of tests have different K values. All pre-sheared tests in Figure 6 (tests No. 14, No. 05 and No. 13) show a sudden decrease of the shear strength at about 0.2% to 0.3% ε_a, which may suggest that pre-shearing is affecting the structure (fabric) of the sand. This sudden decrease is quite obvious in Figure 6b (test No. 05) where the shear stress decrease from almost 55kPa to 50kPa at $\varepsilon_a \approx$ 0.1%. However, there is no quantitative evidence to support this speculation. A possible cause of the sudden decrease of strength may be due to difficulties in maintaining effective stresses constant, especially at low stresses (p' ≤ 50kPa).

5.2 Pre-shearing effects on large strain stiffness

From Figure 5 it can be inferred that the stiffness of the pre-sheared test either slightly increases in comparison with the tests without pre-shearing or remain almost constant. Only once does the stiffness decrease with increasing pre-shearing even below the stiffness of a test without pre-shearing (see Figure 5c). This inconsistent behaviour may be explained by an induced change of fabric of tests No. 18 at $\varepsilon_a \approx 0.4\%$.

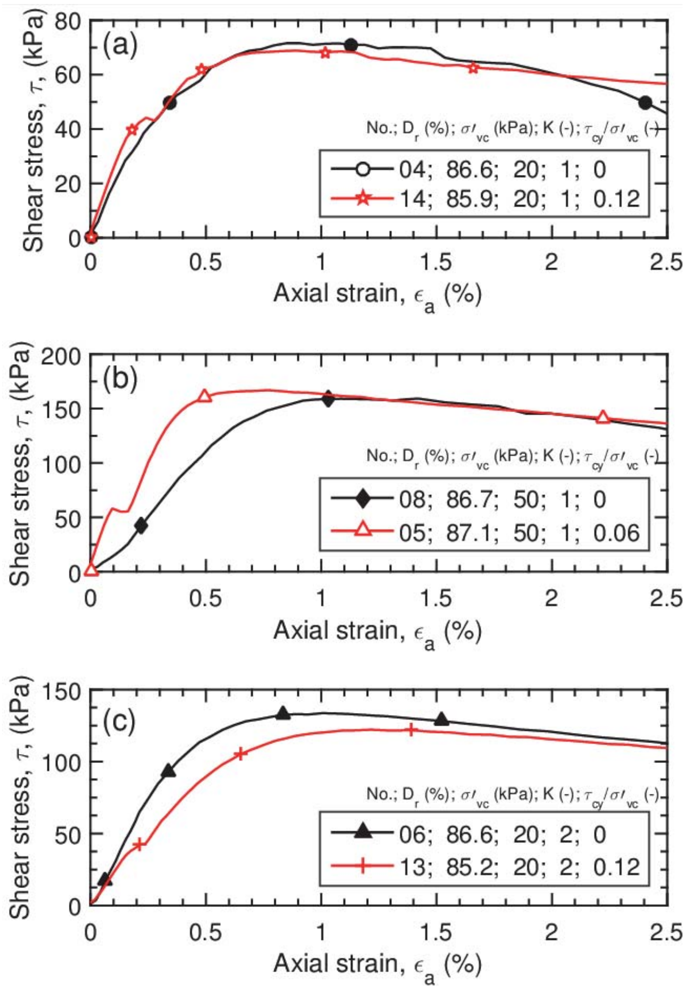

Figure 6: Comparison of CADC results in terms of shear stress vs. axial strain; tests No. 04, 05, 06, 08, 13 and 14

As seen in Figure 6a, the stiffness of the pre-sheared test (No. 14) increases slightly in comparison with the test without pre-shearing (No. 04).

In Figure 6b, the stiffness of the pre-sheared test significantly increases in comparison with the test without pre-shearing and seating issues are observed in the test without pre-shearing (No. 08) at initial axial strains. Similar issues seem to be mitigated in the pre-sheared test (No. 05), since the shear stress increases steeply with ε_a.

As seen in Figure 6c, the stiffness of both tests (with and without pre-shearing) is almost the same at the beginning or the test ($\varepsilon_a < 0.1\%$). Pre-sheared test No. 13 shows a low strength-strain curve in comparison with the test without pre-shearing (No. 6); this behaviour does not agree with any of the remaining tests. This may again be explained by difficulties of maintaining low confining stresses (σ_h < 20kPa) constant during the shearing phase of CADC tests. A sudden change on the effective confining stresses, e.g. ± 2kPa, would result in a corresponding increase or decrease of $\phi'_{p,txl}$ of ± 2 degrees.

From Figures 5, 6a and 6b it is concluded that a pre-sheared test tend to be stiffer than a test without pre-shearing. This behaviour is, however, not observed in Figure 6c.

5.3 Pre-shearing effects on small strain stiffness

Since G_{max} was obtained for all tests, it is possible to assess pre-shearing effects on the small strain stiffness. Figure 7 shows results of G_{max} versus the effective mean stress for all tests performed in this study. As seen in this figure, G_{max} immediately appears to insignificantly decrease (ca. 5%) when pre-shearing is applied at p' ≤ 50kPa, on the other hand G_{max} seems to slightly increase at p' = 200kPa with pre-shearing and D_r. The best fit curve given in Figure 7 suggest that G_{max} varies as square root of p', independent of D_r at low stresses.

It is commonly understood though that G_{max} is stress and relative density dependent (among other intrinsic and extrinsic variables). G_{max} tends typically to increase with increasing p' and D_r. However, no clear D_r dependency is observed at p' < 50kPa for the results shown in Figure 7; and thus, this needs further investigation. Nevertheless, it can be concluded that pre-shearing appears to not significantly influence the sand small strain stiffness when tested under CADC boundary conditions at low stresses but it on the contrary appears to influence G_{max} at higher confining stresses.

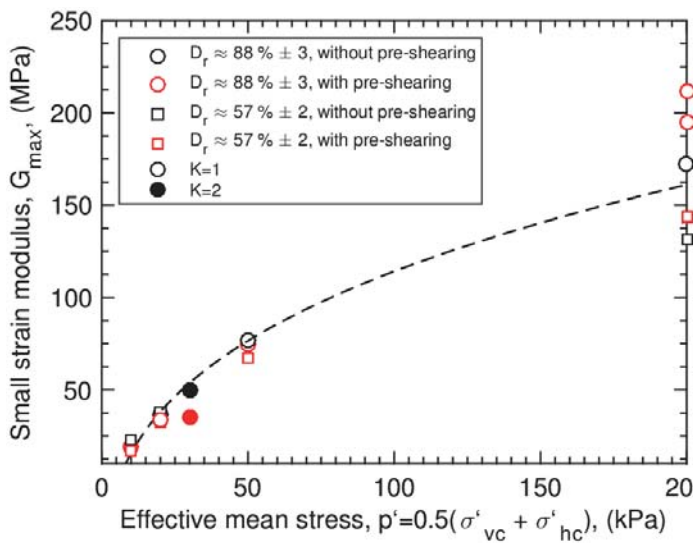

Figure 7: G_{max} vs. effective mean stress of CADC tests

In order to understand better the pre-shearing effects on the small strain stiffness, G_{max} was measured before and after pre-shearing within the same test for some of the tests at p`=200kPa, with results presented in Table 4. As seen in this table the applied pre-shearing level (given as τ_{cy} in kPa) does not affect neither v_s nor G_{max}, it almost tends to decrease values by up to approximately 5%.

Table 4: v_s and G_{max} before and after pre-shearing

No (-)	τ_{cy} (kPa)	v_s before τ_{cy} (m/s)	v_s after τ_{cy} (m/s)	G_{max} before τ_{cy} (MPa)	G_{max} after τ_{cy} (MPa)
16	24	268	266	144	143
17	12	319	319	212	212
18	24	306	299	195	186

5. Observations and implications of findings

From the experimental evidence presented in the form of CADC tests on dense to very dense Cuxhaven sand, it can be concluded that:

- neither the peak, the residual shear strength, nor the dilatancy appear to be influenced by the levels of pre-shearing considered in this study (τ_{cy} / σ'_{vc} = 6% and 12%);
- pre-shearing tends to slightly increase the large strain stiffness;
- the small strain stiffness seems not be influenced at p' < 50kPa, but increase slightly at p' < 200kPa. Additionally, the relative density dependency of G_{max} was not observed at p' < 50kPa; and
- seating issues at the beginning of a CADC tests may be mitigated by pre-shearing.

The implications of the findings listed above are:

- if pre-shearing is required in CADC element tests (e.g. to achieve seating or to homogenise sample after reconstitution), it will not affect either ϕ or G_{max}; and,
- there is apparently no need to measure G_{max} before and after pre-shearing, at least when North Sea type of sands in CADC conditions are tested, because pre-shearing may decrease G_{max} insignificantly (less than approximately 5%).

The findings presented in this study are bounded to sand tested under triaxial CADC conditions and the variables considered herein, extrapolation of these results should be made with care (e.g. pre-shearing during foreshock earthquakes may have a higher degree of pre-shearing than considered in this study targeting marine North Sea environment). However, pre-shearing may still have an important effect on DSS test results, even under drained shearing conditions.

6. Acknowledgements

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