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Effect of reconstitution techniques on the triaxial stress-strength behaviour of a very dense sand

L'influence des techniques de reconstitution sur le critère de rupture sous contrainte triaxial d'un sable très dense

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ABSTRACT: Intact sand samples are difficult to retrieve due to the non-cohesive nature of the material. In order to carry out advanced laboratory tests, sand specimens are commonly reconstituted to an estimated *in situ* relative density derived typically from empirical correlations from cone penetration tests (CPTs). The most common specimen reconstitution techniques are moist tamping (MT), wet pluviation (WP) and dry pluviation (DP). A laboratory testing programme was carried out to study the influence of these three different reconstitution methods on the static behaviour of a dense to very dense typical North Sea sand. The static tests included anisotropically consolidated undrained (CAU) and drained triaxial tests (CAD). Effects of pre-shearing, stress levels, overconsolidation ratio and relative density were also investigated for the three reconstitution methods. The results indicate that the MT method impose a stiffer soil behaviour than the WP and DP methods. Achieved initial density and homogeneity appear to be controlled in a more rigorous way with the MT method than with the other two methods. For a consolidation stress of σ'_{ac} = 200 kPa, the three methods return similar undrained effective stress friction angle (ϕ'_u). From the drained tests there is a larger spread in peak friction angle (ϕ'_p) relative to the three methods, where ϕ'_p is higher for MT specimen compared to WP and DP specimens. The drained ultimate friction angle (ϕ'_{cv}) at 10% axial strain does not seem to reflect any method dependency.

RÉSUMÉ: Les échantillons de sable intact sont difficiles à récupérer en raison de la nature non cohésive du matériau. Afin de réaliser des tests de laboratoire avancés, les échantillons de sable sont généralement reconstitués à une densité relative in situ, dont la valeur est habituellement estimée en fonction des corrélations empiriques issues des tests de pénétration au cône (CPT). Les techniques de reconstitution des échantillons les plus courantes sont le damage humide (MT), la pluviation humide (WP) et la pluviation à sec (DP). Un programme d'essais en laboratoire a été mené pour étudier l'influence de ces trois méthodes de reconstitution sur le comportement statique d'un sable dense à très dense typique de la mer du Nord. Les tests statiques comprenaient des tests triaxiaux sur des échantillons consolidés anisotropiquement qui étaient soit drainés (CAD) ou non-drainés (CAU). Les effets du pré-cisaillement, des niveaux de contrainte, du taux de surconsolidation et de la densité relative ont également été étudiés pour les trois méthodes de reconstitution. Les résultats indiquent que la méthode du damage humide impose un comportement de sol plus rigide que les méthodes de pluviation humide et à sec. La densité et l'homogénéité initiales obtenues semblent être contrôlées de manière plus rigoureuse avec la méthode damage humide qu'avec les deux autres méthodes. Pour une contrainte de consolidation de σ'_{ac} = 200 kPa, les trois méthodes renvoient à un angle de frottement de contrainte effective non drainé similaire (ϕ'_u). Les essais drainés montrent une plus grande dispersion du coefficient de frottement maximal (ϕ'_p): ϕ'_p est plus élevé pour les échantillons de damage humide que pour ceux de pluviation humide et à sec. L'angle de frottement ultime drainé (ϕ'_{cv}) à 10% de déformation axiale ne semble refléter aucune dépendance au choix de la méthode.

Keywords: Triaxial test; reconstitution methods; dense sand; stress-strength behaviour; friction angles

1 INTRODUCTION

The laboratory work presented in this paper forms part of a research study on procedures for reconstitution of sand specimens. The overall objective of the project was to quantify the influence of various parameters on the shear strength and stiffness of sand in order to understand the influence of specimen fabric and homogeneity.

The aim of reconstituting sand specimens in the laboratory is to replicate the *in situ* conditions in terms of fabric (at a given void ratio). The reconstitution method should ideally:

- produce homogeneous specimens
- reflect the *in situ* depositional process: Natural soils are stratified rather than homogeneous
- be simple and practical
- be repeatable (achieve similar void ratios)
- provide for a wide range of void ratios

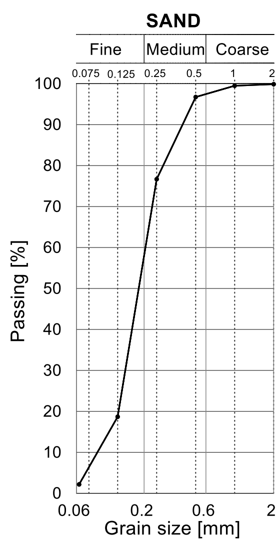
However, in practice it is difficult to appropriately meet all of these conditions with a single method.

2 SOIL AND TESTING PROGRAMME

2.1 Description of sand

A Pleistocene North Sea clean sand was sampled for testing from a site near Cuxhaven, Germany. This sand forms part of fluvial or deltaic sediments deposited in the German Bight during inter-glacial periods. The Cuxhaven sand is a fine to medium, even graded quartz sand with less than 3% fines content (particles less than 0.063 mm). Figure 1 shows a grain size distribution curve together with main properties of Cuxhaven sand.

NGI's in-house methods were used to determine maximum and minimum dry densities that are required for calculating the relative density, D_r. The authors are well aware that these values depend on the method used (Lunne et al., 2019).



Properties
d_{10} = 0.092 mm
d_{60} = 0.205 mm
C_U = 2.17
92% quartz content

Angularity:
<1% angular
12% sub-angular
60% sub-rounded
27% rounded to well rounded

Dry densities by NGI's in-house method:
ρ_{max} = 1.76 g/cm^3
ρ_{min} = 1.52 g/cm^3

Figure 1. Grain size distribution and properties of Cuxhaven sand

2.2 Testing programme

The testing programme consists of anisotropically consolidated undrained (CAU) and drained (CAD) static triaxial tests on specimens with target relative density of 95%. A few undrained tests targeted D_r = 60%. Table 1 shows an overview of the testing programme including a test ID (#) per test. All 25 tests were performed at NGI's laboratory in Oslo, Norway. Some tests were repeated for check of repeatability or if quality could be questioned.

Table 1 Overview of testing programme

D_r %	σ'_{ac} kPa	Pre-sh. -	MT -	WP -	DP -
95	200	Yes	#1, #2	#4	#21
95	200	No	#8	#9	#25rep
60	200	Yes	#6	#7	#23
95	20	Yes	#16	#17rep, #38	#33, 33rep
95	200 OCR=4	Yes	#18, #28	#27	#26
95	*200*	*Yes*	*#3*	*#5*	*#22*
95	*200 OCR=4*	*Yes*	*#28rep*	*#29rep*	*#24*

Text in white = Undrained tests (CAU)
Text in blue, italic font = Drained tests (CAD)

The normally consolidated specimens were consolidated to an axial stress, σ'_{ac} = 200 kPa, except for a few tests taken to lower stresses of σ'_{ac} = 20 kPa. Tests investigating impact of overconsolidation-ratio, OCR = 4, were preloaded to σ'_{ac} = 800 kPa and unloaded to σ'_{ac} = 200 kPa. The triaxial specimens, including specimens with OCR = 4, were consolidated with a radial (horizontal) effective stress, $\sigma'_{rc} = K_0 \cdot \sigma'_{ac} = 0.5 \cdot \sigma'_{ac}$ at both maximum vertical and final consolidation stress levels.

After consolidation, the specimens were either subjected to a pre-shearing of 400 cycles with a cyclic shear stress of $\tau_{cy} = 0.06 \cdot \sigma'_{ac}$ or sheared directly without any pre-shearing.

Effective octahedral consolidation stress, $\sigma'_{oct} = 1/3\ (\sigma'_{ac} + 2 \cdot \sigma'_{rc})$, is used as reference stress level. All friction angles are defined by the secant values and zero cohesion intercept.

Shear wave velocities were measured in the triaxial specimens with bender elements, but results are not included due to space limitations.

3 TEST DESCRIPTION AND PROCEDURES

Figure 2 illustrates the three different reconstitution techniques used.

Moist tamping (MT) is the technique used at NGI and many European laboratories in commercial projects. The NGI in-house procedure is a slightly modified version of the undercompaction method as described by Ladd (1978). A variation to this procedure is implemented at NGI as a constant height of soil is used in each layer rather than a constant mass. Hence, the initial layer is compacted to lower density than succeeding layers so that the final density of each specimen layer is approximately uniform. For triaxial specimens the soil is tamped into the mould in six layers. Water content for tamping was 3% (depending on material) and undercompaction factors of 0.0025 and 0.01 were selected for target densities of 95% and 60%, respectively.

Wet pluviation with tapping (WP) is a technique where fully saturated sand is introduced from a flask to the triaxial mould filled with water. Sand deposits into the mould, whereas water from the mould flows back into the flask. The triaxial mould is gently tapped horizontally by a rubber hammer about 200 times in a symmetrical pattern to achieve a very dense specimen. The soil is placed into the mould in four layers for very dense sand and two layers for medium dense sand.

Dry pluviation with tapping (DP) is a technique where dry sand is introduced through a funnel into the triaxial mould. The outside of the triaxial mould is gently tapped horizontally by a rubber hammer in a symmetrical pattern until reaching the desired layer height. The soil is placed into the mould in four layers poured in two portions per layer for very dense sand and two layers for medium dense sand.

The number of layers used for each reconstitution method was chosen based on experience (MT) and initial trials for the pluviation methods.

4 EXPERIMENTAL RESULTS

4.1 Performance of reconstitution methods

The obtained range and average relative densities are summarised in Table 2. The initial relative density (D_{ri}) is calculated from measurements of specimen geometry immediately after completion of the reconstitution procedure (prior to any loading). For tests targeting a relative density of 95%, the repeatability is found to generally be better for the MT method compared to WP and DP methods.

Six specimens representing each of the three reconstitution methods at two different target relative densities were selected for scanning with Computed Tomography (CT). Observations from the scans, see Figure 2, indicate that the MT and DP methods produce fairly uniform specimens, while DP seemingly involves segregation of larger grains to the edges of the specimen. The WP method has a visible layering with segregation of fines at top of each layer.

Table 2 Summary of obtained D_{ri} for target D_{rc}=95%

Method -	Number of tests	Range in D_{ri} %	Average D_{ri} %
MT	12	90.6 – 94.1	92.5
WP	12	84.5 – 93.0	88.7
DP	10	85.3 – 93.0	89.6

4.2 CAU results

CAU testing on dense sand generally result in an undrained effective stress friction angle, ϕ'_u, that defines the failure line of the stress path at large strains. ϕ'_u is reported as the maximum undrained effective stress friction angle of the stress path, $\phi'_{u\,max}$, and also at axial strain, ε_a = 3% (equal to shear strain γ = 4.5%).

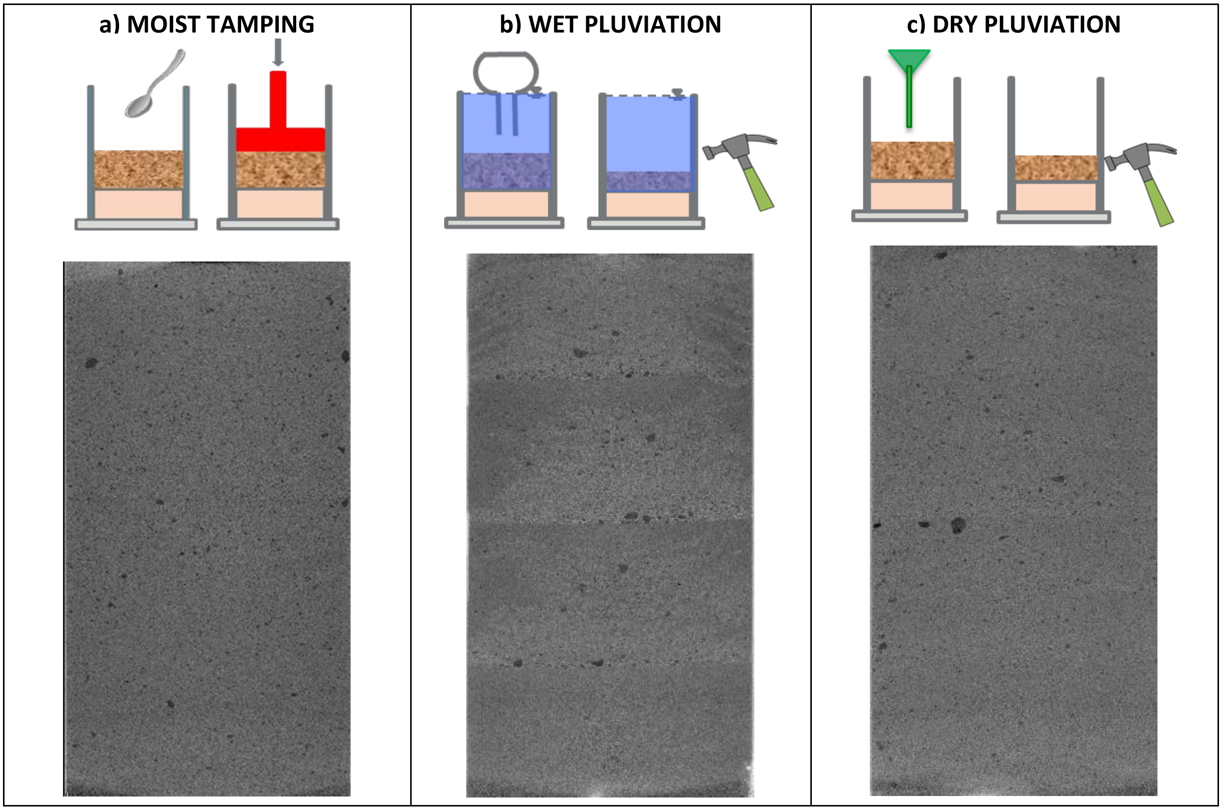


Figure 2. Principles of the three reconstitution methods used and corresponding representative CT scans of a) MT at D_{ri} = 90.6%, b) WP at D_{ri} = 88.6% and c) DP at D_{ri} = 93.0%

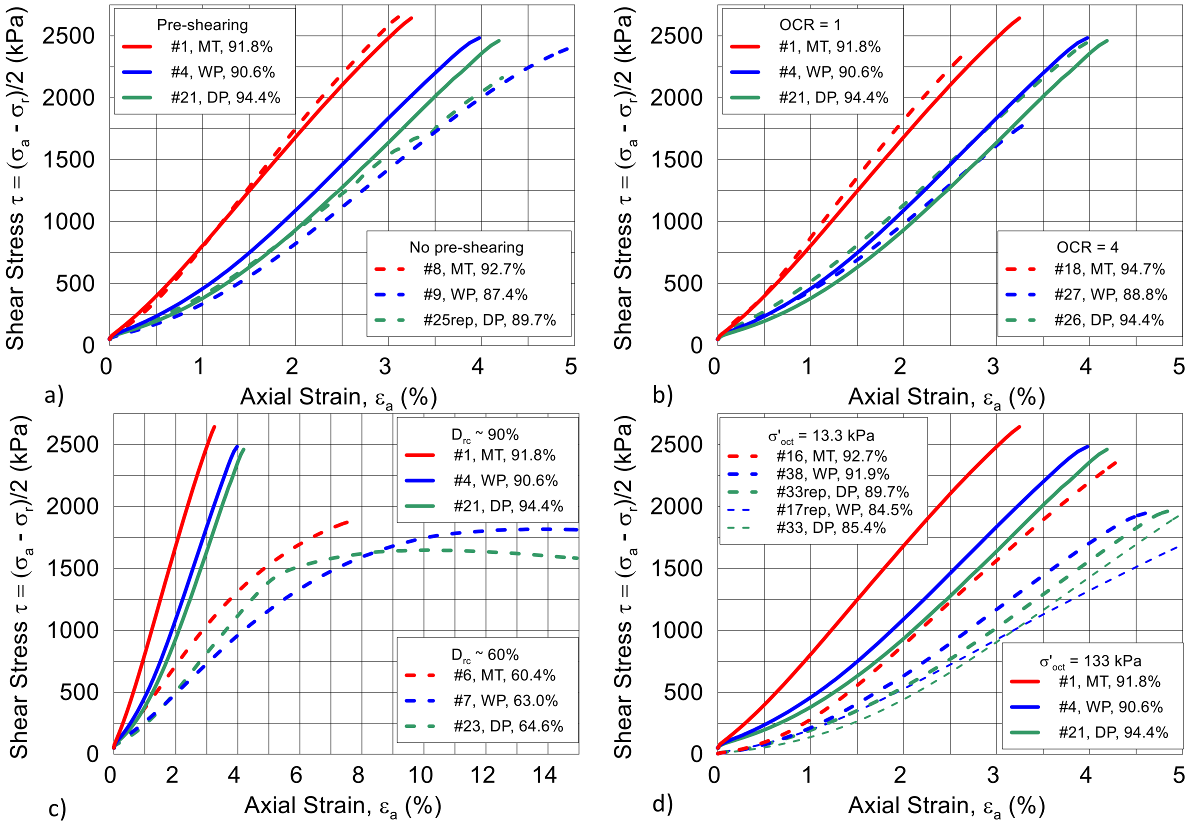


Figure 3. CAU test results. Comparison of reconstitution methods with focus on effect of a) pre-shearing, b) OCR, c) D_r, d) stress level. Legend next to curve line is; Test ID, Method, D_{rc}

Figure 3 presents shear stress-strain curves from the various CAU tests for various test conditions. Table 3 gives an overview of CAU results, where D_{rc} is the obtained relative density after consolidation. E^* is the Young's secant modulus at 50% of the shear stress at 3% axial strain (ε_a). With reference to the conditions of very dense pre-sheared specimens, OCR = 1 and σ'_{oct} = 133 kPa (reference tests), the following results are observed:

Two sets of tests qualify as check of repeatability for MT; #1 and #2 (reference) and #18 and #28 (OCR = 4). Both $\phi'_{u\,max}$ and ϕ'_u are within 1° difference for the pair of comparable tests. Hence, the repeatability is considered as good for the very dense MT tests.

The **Young's secant modulus at 50% of the shear stress at ε_a = 3%, E^***, is higher, around 85-90 MPa for MT tests compared to the 40-50 MPa for WP and DP tests, i.e. a factor of about 2. If pre-shearing is not applied, the E^* decreases for WP specimen, but only marginally changes for MT and DP specimens. If an OCR = 4 is introduced, E^* increases for MT and DP specimens and decreases for the WP specimen. For D_{rc} ~ 60%, E^* decreases to about 40-50% of the reference value for all three methods. For low stresses, σ'_{oct} = 13 kPa, E^* decreases to about 50-60% of the reference value for all three methods. MT specimens prove a stiffer behaviour compared to WP and DP specimens for all conditions.

The **maximum undrained effective stress friction angle, $\phi'_{u\,max}$** (see Figure 4) is higher, around 45°, for MT tests compared to WP and DP results, which cluster around 39°. Only minor changes are observed in case of no pre-shearing. If an OCR = 4 is introduced, $\phi'_{u\,max}$ increases by

Table 3 Overview of results from CAU tests performed on specimens reconstituted by three different methods

Method (Test ID)	D_{rc} %	E^* MPa	$\phi'_{u\,max}$ °	ϕ'_u (ε_a=3%) °
Reference				
MT (#1)	91.8	83	43.8	38.4
MT (#2)	*94.7*	*72*	*44.9*	*38.4*
WP (#4)	90.6	52	39.5	38.8
DP (#21)	94.4	45	38.5	38.1
No pre-shearing				
MT (#8)	92.7	85	44.1	38.3
WP (#9)	87.4	39	38.7	38.4
DP (#25rep)	89.7	44	39.1	38.3
OCR = 4				
MT (#18)	94.7	90	45.7	39.1
MT (#28)	*94.5*	*93*	*46.8*	*40.4*
WP (#27)	88.8	47	38.6	38.0
DP (#26)	94.4	55	38.5	37.9
D_r = 60%				
MT (#6)	60.4	36	38.5	36.1
WP (#7)	63.0	25	35.5	35.2
DP+ (#23)	64.6	24	36.1	36.0
Low stresses				
MT (#16)	92.7	42	44.5	40.1
WP (#38)	91.9	31	39.9	37.9
DP (#33rep)	89.7	27	39.9	38.4
WP (#17rep)	*84.5*	*25*	*38.5*	*36.9*
DP (#33)	*85.3*	*22*	*39.4*	*38.4*

+Initial procedure (four layers, one portion per layer)

Data in italic font are for information

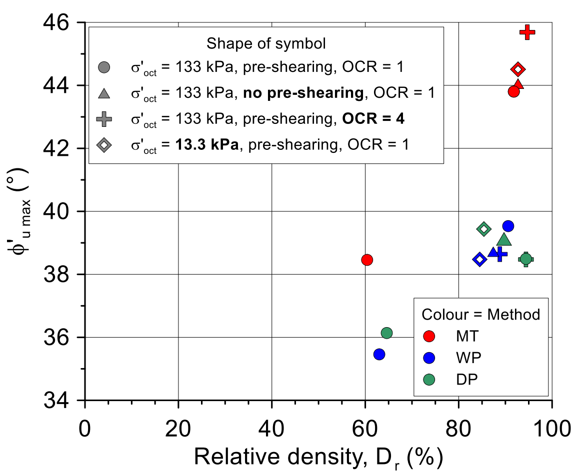


Figure 4. $\phi'_{u\,max}$ versus relative density

4% for the MT test, whereas only minor changes are observed for WP and DP tests. For D_{rc} ~ 60%, the $\phi'_{u\,max}$ values decreases to 39° for MT and to 36° for WP and DP tests. For low stresses, σ'_{oct} = 13 kPa, the $\phi'_{u\,max}$ values increases slightly (about 1°) for all tests. MT specimens return a higher $\phi'_{u\,max}$ compared to WP and DP specimens for all conditions tested.

The **undrained effective stress friction angles ϕ'_u at γ = 4.5%** (see Figure 5 with trend lines from Andersen and Schjetne, 2013, where the MT method was used for all tests) are around 38.5° for all three reconstitutions methods. Only minor changes are observed if pre-shearing is not applied or if an OCR = 4 is introduced. For D_{rc} ~ 60%, ϕ'_u decreases to about 36° for all three methods. The reconstitution method does not seem to influence ϕ'_u, except at low stresses, σ'_{oct} = 13 kPa, where an increase to 40° is observed for the MT test.

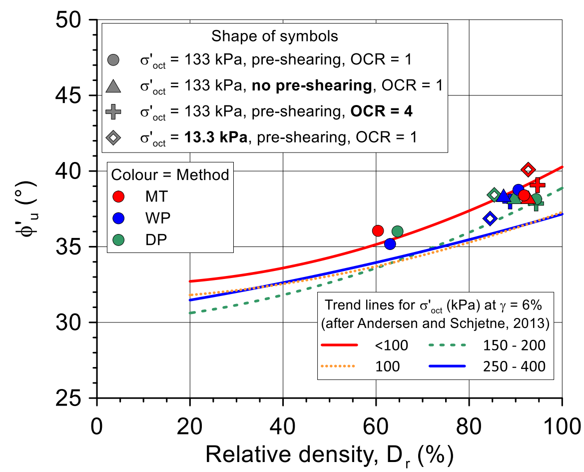


Figure 5. ϕ'_u at γ = 4.5% versus relative density

4.3 CAD results

CAD testing on dense sand generally result in a peak friction angle, ϕ'_p, followed by an ultimate constant volume value, ϕ'_{cv}. Herein ϕ'_{cv} is reported at ε_a = 10% for consistent comparison.

Figure 6 presents stress-strain curves from the various CAD tests for all reference and OCR = 4 tests. Table 4 presents the overview of results.

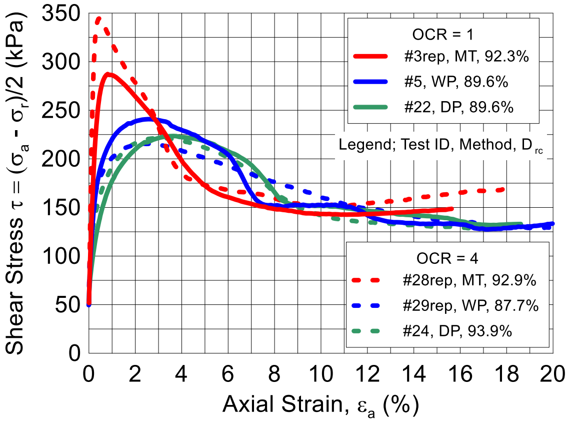


Figure 6. CAD test results. Comparison of reconstitution methods and effect of OCR

With reference to the conditions of very dense pre-sheared specimens, OCR = 1 and σ'_{oct} = 133 kPa (reference tests), the following results are observed:

The **Young's secant modulus at 50% of the peak shear stress, E_{50}** is higher, 100-115 MPa for MT and WP tests compared to 45 MPa for DP. If an OCR = 4 is introduced, the E_{50} increases significantly for all methods, by a factor of 2 for MT and WP and a factor of 2.8 for DP tests. The MT and WP specimens thus prove a similar and stiffer behaviour compared to the DP specimen.

The **normalised peak shear stress, τ_f/σ'_{ac}** is higher, around 1.4 for the MT test compared to a ratio of 1.2 and 1.1 for the WP and DP tests, respectively. For an OCR = 4, the MT ratio increases to 1.7, whereas the WP ratio decreases to 1.1, and the DP ratio remains unchanged at 1.1, which is unexpected compared to the effect on E_{50}. The MT specimen results in higher τ_f/σ'_{ac} than for WP and DP specimens.

The **peak friction angle, ϕ'_p** (see Figure 7) is higher for the MT test (48°) compared to WP and DP tests, which are both around 44°. For an OCR = 4, the ϕ'_p increases by 3° to 51° for MT specimen, whereas the WP and DP decreases to about 43°. The MT specimen results in higher ϕ'_p compared to WP and DP specimens.

Table 4 Overview of results from CAD tests performed on specimens reconstituted by three different methods

Method (Test ID)	D_{rc} %	E_{50} MPa	τ_f/σ'_{ac} -	ϕ'_p °	$\phi_{cv}'(\varepsilon_a=10\%)$ °
Reference					
MT (#3rep)	92.3	115	1.44	47.7	35.9
WP (#5)	89.6	100	1.20	44.7	37.2
DP+ (#22)	89.6	45	1.12	43.6	37.1
OCR = 4					
MT (#28rep)	92.9	208	1.72	50.8	36.4
WP (#29rep)	87.7	202	1.08	42.8	37.8
DP (#24)	93.9	124	1.10	43.3	35.4

+ Initial procedure (four layers, one portion per layer)

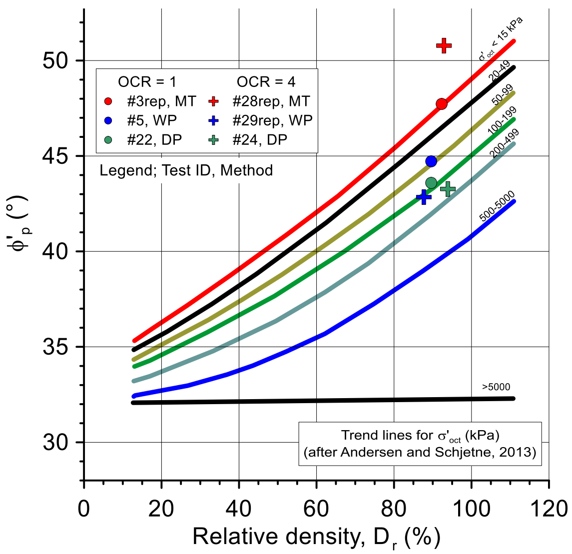


Figure 7. ϕ'_p versus relative density

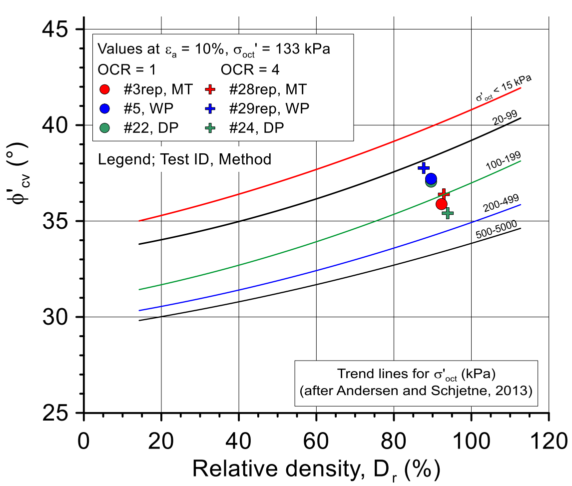


Figure 8. ϕ'_{cv} versus relative density

The **ultimate value ϕ'_{cv} at ε_a = 10%** (see Figure 8) is similar for the three methods, around 36.5°. For an OCR = 4, the DP ϕ'_{cv} decreases by 2° to 35°, whereas the MT and WP angles marginally increase by 0.5° to about 37°. As expected, the reconstitution method does not seem to influence ϕ'_{cv}.

Tests on MT specimens result in higher and more distinct peak shear stress than tests on WP and DP specimens (see Figure 6). ϕ'_p is method dependent, where MT gives the higher values compared to WP and DP, especially for over-consolidated specimens (see Figure 7). A difference of up to 8° is found. The ϕ'_p from MT test (47.7°) is to the high side compared to trend lines from Andersen and Schjetne (2013), who present values of ϕ_p' up to 46° for tests with D_r ~ 90% and consolidation stress in the range 100 - 199 kPa.

5 CONCLUSIONS

The present test program systematically investigates varying test conditions and test types. Some trends in relation to the influence of the investigated reconstitution methods on triaxial test results have been identified. However, even with 25 different advanced tests in a rigorous testing scheme, the results are not fully conclusive. Based on the evaluation of the various parameters and conditions tested, the following main observations are found:

Reconstitution method; MT has a more consistent initial density control and shows better homogeneity than what is achieved with WP and DP. MT specimens present more distinct behaviour than WP and DP specimens (higher E^*, $\phi'_{u\,max}$, ϕ'_p). ϕ'_u at γ = 4.5% is similar for the three methods except at low stresses where an increase is observed for the MT method. ϕ'_{cv} at ε_a = 10% is similar for the three methods.

Pre-shearing increases stiffness of WP, but appears to have limited effect on DP and MT. Pre-shearing does not seem to influence ϕ'_u.

An **OCR = 4** decreases E^* and increases E_{50} for WP and DP, whereas increases of both E^* and E_{50} are observed for MT. OCR = 4 increases $\phi'_{u\,max}$ and ϕ'_p for MT, but returns a marginal effect on WP and DP.

A lower consolidation stress level decreases E^* for all methods as expected and also decreases E_{50} for MT, but with unknown effect on WP and DP (no tests). A lower consolidation stress level increases ϕ'_u and ϕ'_p for MT, but marginal effect on WP and DP.

Based on the results, it is concluded that MT appears to generally produce stiffer and stronger response that WP and DP. The observations and conclusion stated are to be considered valid for tests on sands similar to the investigated Cuxhaven sand and for conditions as addressed with the present programme.

6 ACKNOWLEDGEMENTS

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