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Influence of reconstituting intact samples of calcareous sands on static strength

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ABSTRACT: This work is a continuation of a lab investigation campaign aimed at revealing the effect of reconstituting cohesionless material by the widely used moist-tamping method. The previous testing campaign focused on silica based cohesionless material from a specific geological age, where initially intact samples were sheared in consolidated drained triaxial tests. The sheared samples were then reconstituted to identical state and sheared again, where the difference in intact and reconstituted behaviour demonstrates the reconstitution effect. This paper presents further consolidated drained triaxial tests on pairs of intact and reconstituted very silty sands and calcareous sands from other geological formations, aiming to reveal the influence of particle mineralogy on the reconstitution of cohesionless samples.

Keywords: drained triaxial test, intact samples, reconstituted samples, grain crushing, fines content

1 INTRODUCTION

Various samples have been extruded from push-sampling tubes from a southern North Sea offshore wind farm (OWF), to assess the triaxial drained behaviour of cohesionless soils. Tests were carried out on both intact and reconstituted samples. The initial aim of the research was to investigate the effect of the soil fabric – as present in the intact samples but erased in the reconstituted samples - on peak friction angle.
The effective strength of cohesionless material is conventionally represented by a drained peak friction angle (φ'), an important input to WTGs (Wind Turbine Generators) foundation design. The parameter is input both to soil springs in 1-D beam elements (e.g. p-y springs of cohesionless soils according to DNVGL-RP-C212) and finite element simulations commonly used to benchmark or calibrate the soil springs.

This paper presents the results of triaxial tests performed on corresponding pairs of intact and reconstituted cohesionless samples, each pair using the same soil and test conditions (density and confining stress). The tests were performed as part of a site investigation campaign for a commercial southern North Sea OWF. This research completes previously published research by Al-Maadheedi et al. in 2023.

2 LITERATURE REVIEW

The assessment of the soil behaviour via critical state soil mechanics (CSSM) is widely used in academia as the Critical State Line (CSL) uniqueness is well accepted by various authors (e.g. Atkinson, 2007; Been and Jefferies,1986; Jefferies and Been, 2006). The soil behaviour can typically be captured by means of the state parameter (ψ), developed by Been and Jefferies in 1985, which measures the difference between the current void ratio and that at critical state, for the same mean effective stress, by combining both the effects of in-situ void ratio and effective confining stress. Jefferies and Bean (1985, 2006) also showed that ψ accurately predicts both the peak strength and dilatancy rate of a sand. Whilst not so widely used in the offshore wind industry, but commonly used for tailings dams, its application might overcome common issues associated with the determination of φ' by means of the relative density.

Besides the in-situ void ratio (i.e. density) and confining stress, other factors also affect the response of cohesionless soils such as the fines content (and particle breakage), the inherent anisotropy (due to particle shape or fabric induced) the induced anisotropy, and the shearing direction. Such factors shouldn't influence the critical state behaviour of the soil, only the soil response between the initial state conditions and its critical state.

However, more recent researchers have concluded that this concept cannot be easily applied to: a) transitional soils, i.e. soils for which initial fabric has a very strong influence on the behaviour (Shipton and Coop, 2015), and b) soils which experience grain crushing due to high carbonate content (Coop et al, 2004; Bandini and Coop, 2011).

Soils with high carbonate content are known for exhibiting grain crushing during shearing, especially if subjected to higher confining stresses (Coop et al, 2004; Bandini and Coop, 2011). Crushable material becomes a series of different materials with different gradings, resulting in a decrease in strength and dilatancy, which has been proven not only under laboratory conditions (Coop et al, 2004; Bandini and Coop, 2011) but also by Discrete Element Method modelling (Ciantia et al, 2014).

Furthermore the behaviour of transitional soils, i.e. soils intermediate to that of clays and poorly graded sands, has also been seen for well-graded sands among others (Shipton and Coop, 2015). Typically these soils due not achieve its CSL, as its behaviour is governed by its fabric, and tens of percent of strain would be required to reach a unique fabric, beyond the strains typically measured under triaxial test conditions.

2.1 Effect of inherent anisotropy due to sample preparation method

Gilbert (1984) demonstrated the influence of reconstitution method on voids distribution within samples of comparable total densities. This was achieved by dissecting frozen samples into multiple parts and individually measuring the density of each, where it was demonstrated that moist tamping resulted in larger variation in void ratio when compared to wet pluviation.

Wanatowski and Chu (2008) conducted drained and undrained K0 consolidated plane-strain tests on samples of poorly graded quartz sand prepared by moist-tamping and wet pluviation, and observed that the pluviated samples yielded more strength and high dilatancy. Haung et al. (2015) developed moist pluviation method and compared the result against moist-tamped samples in undrained triaxial test on clean and silty sand, where pluviated samples also exhibited more strength and dilatancy.

2.2 Intact sampling in cohesionless deposits

While there is a scarcer literature on intact sampling of cohesionless material, Høeg et al. (2000) reported obtaining undisturbed silt and silty sands samples using pushed-in tubes. Undrained tests with bender elements were conducted on both the undisturbed samples and moist-tamped samples, where the authors reported significantly higher strength and dilatancy of the undisturbed samples, with higher shear wave velocity measured from the bender elements. Haung (2016) also reports similar observation for soils in Tiawan, where shear wave velocity measured from intact samples corresponding well to that measured from seismic CPTs.

3 METHODOLOGY

This study compares results from intact and reconstituted samples tested in isotropic consolidated triaxial tests sheared in compression (CIDci and CIDcr). Intact samples were collected from several depths and locations across the site, at varying naturally occurring void ratios, and then tested in the triaxial cell following the intact specimen preparation process as described in section 3.1. After shear, the samples were reconstituted using moist tamping to a void ratio comparable to the intact sample, then consolidated and sheared under similar conditions (CIDcr). The testing program allows a meaningful investigation on the influence of moist tamping on the drained response of granular materials, where both

Table 1. Classification of soil units sampled for CID testing

Unit	PSD description	Microscopy description
YR-sand	Dense to very dense slightly silty fine to medium sand (5%<FC<10%)	Subrounded- subangular with medium to high sphericity
YR-silty-sand	Dense to very dense silty to very silty fine to medium sand (10%<FC< 30%)	
SK-silty-sand	Medium dense silty to very silty fine to medium sand (10%<FC< 30%)	Angular- subangular with medium to high sphericity
Po-silty-sand	Loose to medium dense, silty to very silty fine to medium sand (10%< FC< 30%)	Very angular with low sphericity shell fragment / subround-subangular-medium to high sphericity quartz

intrinsic properties and initial conditions are normalised for every pair of samples.

3.1 Testing methodology

Sealed intact samples were extruded from tube, trimmed to a height-to-diameter ratio of 2:1 and tested under CIDc immediately. The testing methodology is described in detail by Al-Maadheedi et al. (2023).

3.2 Soil units allocation

Integrated geotechnical, geophysical and geological ground modelling was conducted for the windfarm site to capture the main geological units. The previous dataset belongs to the Yarmouth Road (YR) formation, where test results on a relatively clean (YR-sand) and siltier (YR-silty-sand) were reported (Al-Maadheedi et al., 2023). This paper reports tests conducted on the Smith's Knoll (SK-silty-sand) and Pliocene or Oligocene (PO-silty-sand) formations. The holisitic characterisitic derived for geotechnical units are presented in Table 1.

3.3 Samples characterisation

A total of 5 CIDc pairs are reported in this work, substantiating the dataset published in the previous work. Figure 1 presents the initial testing conditions for each test pair, where the both initial void ratio and confining stress is comparable for each pair.

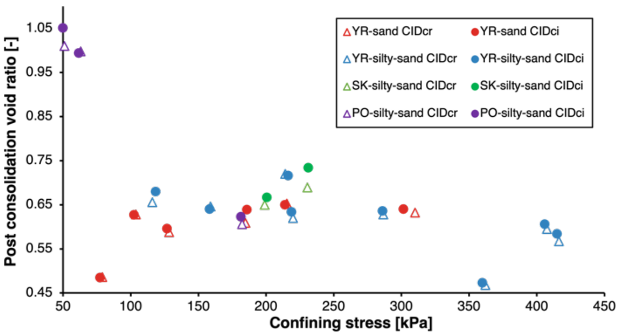

Figure 1. Initial state of intact and reconstituted CIDc pairs.

It is noted that the two PO-silty-sand pairs with void ratios greater than 0.95 have CaCO3 content of around 55%, while the denser sample have a CaCO3 content of 12%. It is hypothesised that the increase in carbonate content is related to an increase in shells and shell fragments, which was typical for this unit especially at shallow depth. The very high void ratio noted for the two PO-silty-sand samples with high CaCO3 is consisted with Dogs Bay biogenic sand reported by Coop and Lee (1993).

4 RESULTS

4.1 Samples behaviour in drained shearing

Figure 2 compares CIDci and CIDcr responses for the SK-silty-sand tests, where intact samples yield a greater deviatoric stress at smaller strain. This is associated with a more dilatant behaviour evident by a less pronounced peak in the stress and a slight increase in volume (especially for the denser pair). While the deviatoric stress appears to reach a constant value for both CIDci and CIDcr at around 20% strain, this is not the case for the volumetric change. Overall, this observation is consistent with the YR dataset soil previously published.

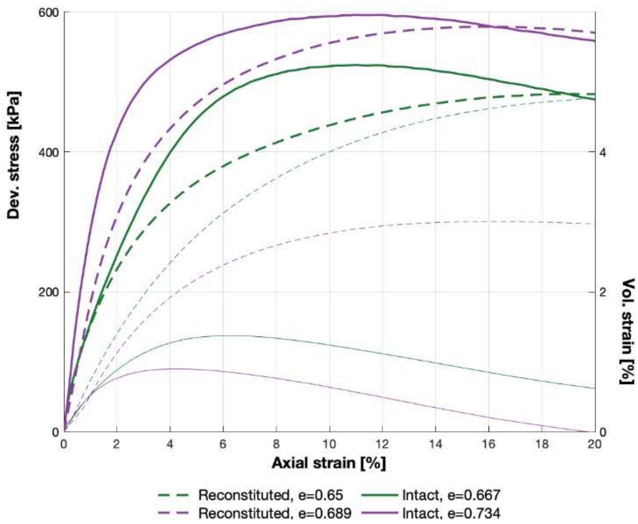

Figure 2. stress/strain and volumetric-change/strain response of SK-silty-sand CIDci and CIDcr.

Figure 3 compares CIDci and CIDcr responses for the PO-silty-sand tests. Similar observations regarding dilantancy of intact samples compared to reconsituited ones are drawn. The test pairs also appear to reach a unique deviatoric stress at the end of shearing, albeit at a looser state for the intact tests.

4.2 Friction angle comparison

The friction angle of every test is calculated using the ratio of deviatoric stress over confining stress. For tests exhibiting a distinctive peak in stress, φ is calculated at peak stress ratio (i.e. dilative behaviour). For tests not exhibiting a distinctive peak, φ is calculated using the stress ratio at 10% axial strain (i.e. contractive sample).

For the purpose of comparing φ on intact and reconstituted pairs for tests exhibiting irregular stress/strain behaviour or peak stress ratio at axial strains exceeding 10%, a strain level is selected for φ determination for each pair. For the SK dataset showing more contractive behaviour overall, φ is calculated at 5% strain for both CIDcr and CIDci (figure 2). For the densest sample in the PO dataset (green curve in figure3), *φ* is calculated at 2.5% strain. These modifications are introduced to allow meaningful quantification of difference in dilatancy between intact and reconstituted tests, which essentially captures the variation in the shape of the stress-strain curves .

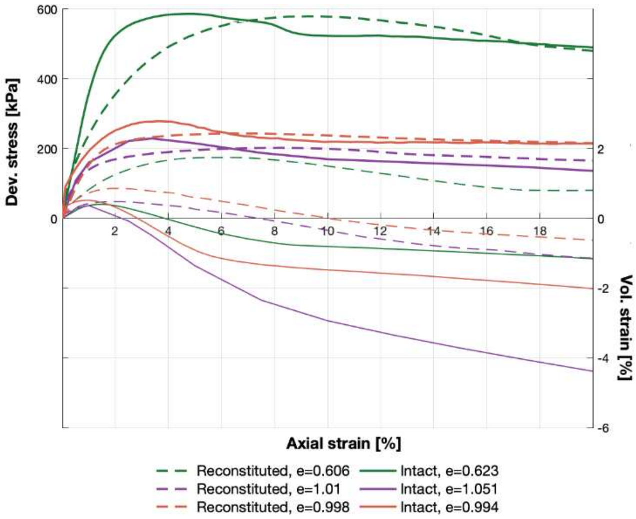

Figure 3. stress/strain and volumetric-change/strain response of PO-silty-sand CIDci and CIDcr.

As the void ratio and confining stress for every pair of tests are comparable, the difference in φ' between intact and reconstituted test pairs (named φ_i-φr hereafter) for a given pair is expected to reflect the influence of reconstitution on replicating in-situ soil fabric. The difference in maximum rate of dilation, defined as $-d\varepsilon_v / d\varepsilon_1$ (e.g. Bolton, 1986 and Chakraborty and Salgado, 2009), is also correlated with φ'i-φ'r as shown in Figure 5.

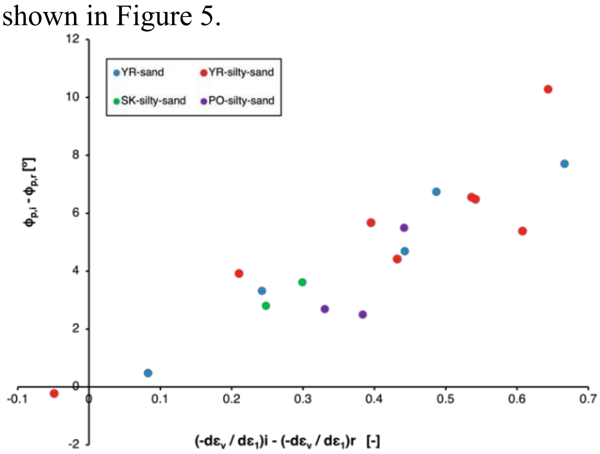

Figure 4. Correlation between φ'i- φ'r with difference in maximum rate of CIDci and CIDcr ($d\varepsilon_v / d\varepsilon_1$ is calculated at the same strain where φ' is determined).

Figure 4 shows a good overall correlation between φ'i-φ'r and maximum rate of dilation, which further demonstrate that the difference in friction angle and behaviour stems from intact samples being more dilative for the explored soils. All in all, the new tests in SK and PO units also yield higher friction angles from the intact samples despite differences in mineralogy and age compared to the YR dataset, and therefore the findings are considered to substantiate the conclusions of the previous work.

5 DISCUSSION

5.1 Influence of sample properties on soil fabric

Figure 5 presents a more detailed analysis of the results, where test pairs are grouped by soil unit, void ratio, fines content and coefficient of uniformity (Uc). The one test with clay content exceeding 5% is also marked. In the previous work, it was identified that void ratio governs soil fabric effect at constant Uc for tests with FC<20%, where it was hypothesised that to achieve a very dense state requires relatively consistent particle arrangement and therefore minimising soil fabric effect. It was also noted that at a void ratio around 0.62, the increase in Uc appears to result in an increasing soil fabric effect. It was therefore concluded that cohesionless deposits with wider range of particle sizes and intermediate densities are more likely to exhibit soil fabric effect and are therefore more affected by reconstitution.

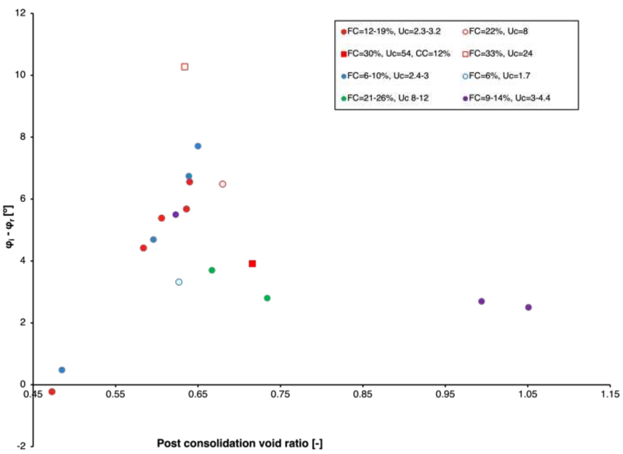

Figure 5. The influence of void ratio, uniformity coefficient and PSD on reconstituted samples (where blue point are YR-sand, red points are YR-silty-sand, green points are SK-silty-sand and purple points are PO-silty-sand)

5.1.1 SK-silty-sand

Two pairs of CID tests are presented for the SK unit, where the denser sample have both higher FC and Uc values. Tests on SK-silty-sand yield less fabric effect when compared to YR-silty-sand test with comparable PSD (c.f. Figure 6: red-hollow point) and exhibit a less dilative behaviour (c.f. Figure 4) at comparable void ratio. This suggests that the CSL in e-p' space is lower for SK unit given the angularity of the unit, potentially leading to the different soil fabric when compared to the YR-silty-sand.

5.1.2 PO-silty-sand

The three test pairs on the PO unit have comparable PSDs with the YR dataset, where the CaCO3 content appears to influence the difference between CIDci and CIDcr. Interestingly, the tests with CaCO3 of 12% is denser and fits well within the YR dataset. It is suspected that the lower CaCO3 content reflects lower shell content, where the sample comprises of more rounded and spherical quartz material. In contrast, the two pairs with CaCO3 content of around 55% reflects lower soil fabric which result of mineralogy, particle breakage, or their loose state (in absence of denser samples to compare against).

All in all, particle mineralogy and shape appear to have a significant role on the performance of reconstitution method for the determination of effective strength parameters.

5.2 Friction angle prediction from intact sampling

While the previous work presented that void ratios obtained from intact samples correlated well with that calculated from CPT correlation, this is extended to direct applications for determining friction angle from CPT. Figure 6 presents a comparison of *φ*' determined from CPT measurement using Robertson (2010) correlation against that obtained from triaxial tests on each unit (where solid points are intact sample and hollow triangle are reconstituted samples). The intact samples are overall closer to the unity line showing better agreement to the CPT correlation. It can also be seen that developing a site-specific correlation for reconstituted samples would be more punitive relative to friction angles determined from intact sampling.

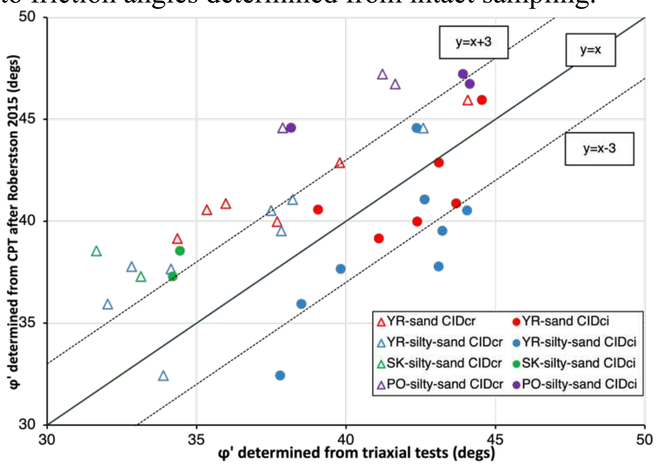

Figure 6. Comparison of CPT prediction of friction angle from intact and reconstituted samples (Intact R^2=0.22 and reconstituted R^2=-0.27).

5.3 Critical state comparison

Figure 7 plots the CID tests on the void ratio (*e*) and mean effective stress (*p'*) space. Consistent with previous observations made in section 4 (and YR dataset in previous work), a more dilative response is observed for the intact samples in the *e-p'* space. This is evident by the greater p' developed during shearing, and the increase in void ratio towards the end of shearing.

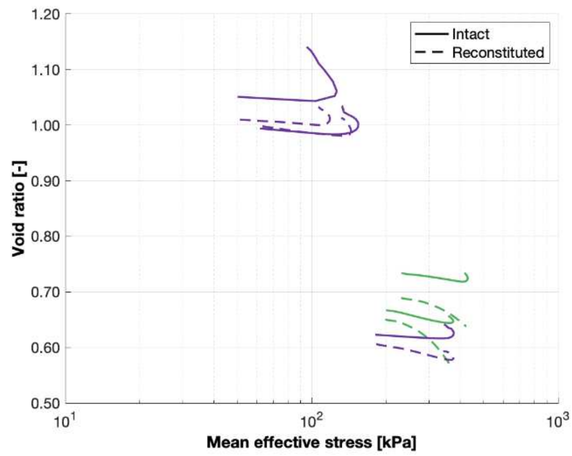

Figure 7. Behaviour of intact and reconstituted samples in e-p' space (where green pairs are tests on SK-silty-sand and purple pairs are test on PO-silty-sand)

Interestingly, figures 2 and 3 show that the deviatoric stresses of each pair appear to converge towards the end of shearing, indicating test samples approaching unique CSLs. Conversely, the behaviour in the e-p' space indicate that the CSL is situated higher for the intact samples. This observation is consistent for the YR dataset presented in the previous work.

Multiple studies explored the influence of inherent anisotropy on the behaviour of cohesionless deposits sharing comparable *e* and *p'* (e.g. Yang et al., 2008 based on reconstitution method and Yu et al., 2013 based on deposition angle). It is hypothesised that the difference in behaviour stems from a combination of void distribution (section 2.1) and inherent anisotropy, where the lower CSL line for CIDcr would increase the state parameter and therefore reduce the dilatancy and friction angles relative to intact sampling. This effect has also been observed by Shipton and Coop, 2015, which argue that tens of percent of strain would be required to reach a unique fabric.

It is also interesting to note that, albeit the limited dataset available, PO-silty-sands seem to exhibit a bifurcation of the CSL potentially caused by grain crushing, evident by increased steepness of the CSL at increasing confining pressure (also shown by Coop et al, 2004; Bandini and Coop, 2011), regardless of the reconstitution method.

It is noted that a CS approach where state parameter is correlated with peak friction angle (e.g. in tailing design) as done by Jefferies and Been (2006), where soil reconstitution may not be appropriate. Nonetheless, a CSL approach based on intact samples may be appropriate for cases with limited variability within geotechnical units.

6 CONCLUSION

A systematic laboratory programme was carried out to explore the influence of reconstituting cohesionless soil samples on their drained shearing behaviour for effective strength determination. This paper complements a previous work comprising of 14 CIDc test pairs on slightly silty to very silty silica sands, where this work presents 5 more test pairs on sampled deposits originating from different ages.

The current work concluded that reconstitution leads to less dilative behaviour for the extended dataset of different mineralogies and particle shapes. This is believed to be a result of CSL lowering upon reconstitution, which was evident by differences in final void ratios after shearing. Reconstitution is also shown to result in more punitive friction angle determination from the CPT.

As the observations in this work are consistent with that of samples reconstitution using pluviation method, it is concluded that the use of intact sampling would bring forward the benefits of more of state-of-the-art reconstitution methods that are less widely used in the industry.

While this work extended the dataset previously established with wider ranges of soils, it is noted that the effect of soil state could not be decoupled from that of mineralogy due to the smaller dataset. It is therefore recommended to further extend this work with test pairs conducted on a wider range of densities and mean effective stresses. It is also recommended to undertake discrete element modelling (DEM) of the test results to replicate effects such as particle breakage, voids distribution and inherent anistropy.

AUTHOR CONTRIBUTION STATEMENT

First Author: Conceptualization, writing – original draft, analysis, data curation, visualization, methodology. **Second Author**: Conceptualization, writing – review and editing, writing – original draft, methodology. **Additional Authors**: Methodology, validation, investigation, writing – review and editing, funding.

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