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Strength and dilatancy of intact and reconstituted sands from Atlantic Shores offshore wind farm development

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ABSTRACT: Intact and disturbed samples of very dense sand acquired from the foundation zone sediments at Atlantic Shores offshore wind farm development were subjected to an experimental study consisting of laboratory drained triaxial compression tests performed under isotropic and K_0 consolidation conditions. Triaxial specimens obtained from disturbed sand samples were reconstituted at the same dry density as the initial dry density of intact specimens. Experimental results are presented and discussed in terms of measured stress-strain response and associated strength and dilatancy parameters. Measured shear wave velocity from bender element tests performed on the triaxial specimens was used to evaluate intact sample quality by comparison with the in-situ shear wave velocity measured from seismic cone penetration tests, as well as to assess similarity between intact and reconstituted specimens. The study provides valuable insight into the ability of current laboratory testing practice involving reconstituted sand specimens to provide strength and dilatancy parameters representative for in-situ soil conditions.

Keywords: very dense sands; laboratory triaxial tests; strength and dilatancy

1 INTRODUCTION

Atlantic Shores Offshore Wind, with its Lease Area located approximately 10-20 miles off the coast of New Jersey, represents the largest offshore wind energy development project in New Jersey and the third largest in the United States to date. Extensive geotechnical investigations performed at the Lease Area revealed the presence of dense to very dense sands in considerable proportion within the foundation zone sediments (Trandafir et al., 2023; Varnell et al., 2023).

In light of difficulties associated with obtaining intact samples, current state of laboratory advanced testing practice for sands involves conducting tests on specimens reconstituted at in-situ dry density. However, the relevance of geotechnical parameters derived from tests on reconstituted sand specimens to the actual in-situ soil conditions is currently unknown. This paper aims to evaluate the impact of using reconstituted specimens for laboratory testing by addressing strength and dilatancy characteristics of sands from the Lease Area via a comparative experimental study consisting of triaxial compression tests on intact and reconstituted specimens.

Intact sand samples for the experimental study were obtained from 71-mm diameter by 600-mm long cores acquired using thin-walled (2.5-mm wall thickness) steel tubes from two non-cohesive soil units documented at the Lease Area, denoted as U0 and U1. U0 sand represents the Holocene marine sediments exposed at the seafloor, which are younger than 7400 years. U1 sand belongs to late Pleistocene sediments with an estimated age between 28000 and 39000 years. A detailed description of U0 and U1 non-cohesive units in terms of geotechnical characteristics and depth and thickness distribution throughout the Lease Area, is provided by Varnell et al. (2023).

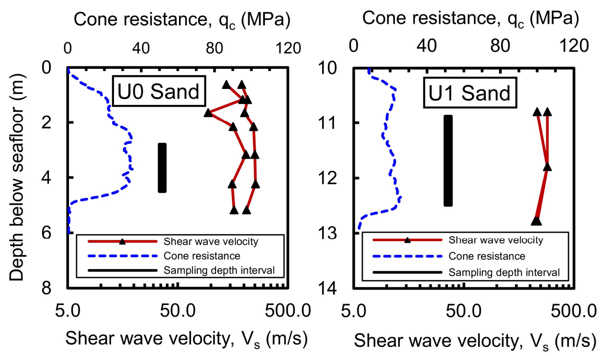

Figure 1. Measured cone resistance and shear wave velocity from in-situ seismic cone penetration tests at selected sampling locations along with sampling depth interval.

Figure 1 shows profiles of measured cone resistance (q_c) and shear wave velocity (V_s) from in-situ seismic cone penetration tests performed at the sampling locations in U0 and U1 non-cohesive soil units. U0 sand exhibits q_c values of 31 MPa to 35 MPa and V_s values of 156 m/s to 254 m/s along the sampling depth interval from 2.8 m to 4.5 m below seafloor. U1 sand is characterized by remarkably lower q_c values of 16 MPa to 26 MPa, whereas V_s ranges from 233 m/s to 288 m/s along a sampling depth interval from 10.9 m to 12.5 m below seafloor.

2 TESTED SPECIMENS

Best-quality intact specimens for advanced laboratory testing were selected by examining X-ray computed tomography (XCT) scans of the cores inside the steel tubes. Intact specimens for triaxial compression tests, as well as intact specimens used in a series of companion one dimensional (1D) consolidation tests for stress history evaluations, are delineated on the XCTs of U0 and U1 cores shown in Figure 2.

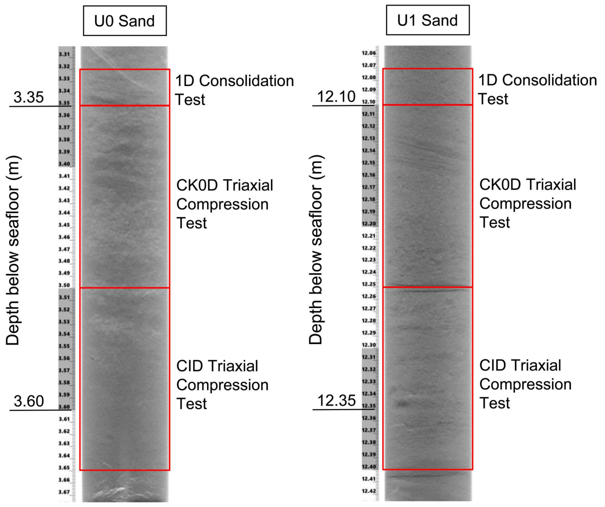

Figure 2. XCT images of the intact sand cores along with location along the core of specimens selected for advanced laboratory tests.

To eliminate vibration induced potential sample disturbance, steel tube cutting was performed manually using a hand pipe cutter. The cutting process involved slow unidirectional rotational motion of the cutter while applying a gentle pressure on the cutting blades against the horizontally oriented steel tube until full blade penetration through the steel wall was achieved. After the steel wall has been cut, further cutting through the sand sample progressed using a hand wire saw.

The cut sections of the core were frozen prior to extrusion to maintain intact sample integrity during the extrusion process. Additionally, prior to freezing, the sample was allowed to lose moisture in order to prevent changes in void ratio by allowing for free expansion of ice crystals formed in the pores during freezing. A photo of extruded frozen intact sand specimen for triaxial testing is provided in Figure 3.

Particle size distribution curves of tested sands are presented in Figure 3. Both U0 and U1 sands are categorized as poorly graded, with mean grain size (i.e., D_{50}) of 0.20 mm and 0.34 mm, and uniformity coefficient (C_u) of 1.6 and 1.9, respectively. U0 sand consists of quartz grains, and also has shell fragments in proportion of 5%-10%. Mineralogy analyses revealed the presence of mica in proportion of 2%-5% in addition to quartz in the U1 sand samples.

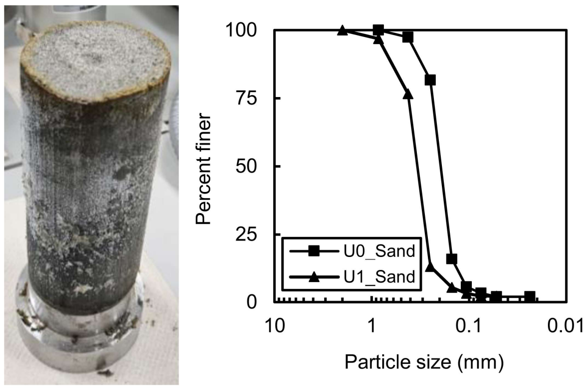

Figure 3. Photo of extruded frozen intact sand specimen for triaxial testing, and particle size distribution curves.

Table 1 summarizes the specific gravity (G_s) and initial dry density of intact specimens (ρ_{d0}), along with minimum ($\rho_{d\text{-}min}$) and maximum ($\rho_{d\text{-}max}$) dry densities determined on disturbed samples. Based on the information provided in Table 1, tested U0 and U1 sands qualify as very dense with relative densities of 93% and 86%, respectively.

Table 1. Index properties of tested sands.

Sample	G_s	ρ_{d0} (g/cm^3)	$\rho_{d\text{-}min}$ (g/cm^3)	$\rho_{d\text{-}max}$ (g/cm^3)
U0 Sand	2.66	1.70	1.40	1.73
U1 Sand	2.67	1.69	1.44	1.74

Reconstituted U0 and U1 sand specimens for advanced laboratory testing were prepared at the corresponding initial dry densities listed in Table 1 using material from depths adjacent to the intact cores shown in Figure 2. Moist tamping of sand samples with an initial water content of 10% along with the undercompaction method were employed in the reconstitution process. Triaxial tests reported in this paper were performed on intact and reconstituted specimens with a diameter of 71 mm and heights between 142 mm and 150 mm. All laboratory index and advanced tests were performed according to the corresponding ASTM standards.

3 TEST PROCEDURES AND CONSOLIDATION TEST RESULTS

The experimental program consisted of triaxial (TX) compression tests performed in drained conditions on isotropically consolidated (CID) and K_0 – consolidated (CK0D) specimens. K_0 represents the coefficient of lateral earth pressure at rest and is defined as the ratio between the effective horizontal stress (σ'_h) and effective vertical stress (σ'_v), required to produce zero horizontal strains in a soil element subjected to increasing effective vertical stress (i.e., $K_0 = \sigma'_h / \sigma'_v$). Prior to consolidation, the specimens were flushed with deaired water under a chamber pressure of 15 kPa for at least 36 hrs, followed by back-pressure saturation while maintaining a difference between the chamber pressure and the back pressure of 15 kPa to 20 kPa, until a Skempton's B-value of at least 0.95 was measured. A seating deviator stress of 2 kPa was applied and maintained during flushing and back-pressure saturation stages to ensure full contact between the upper end of the specimen and the top cap of the triaxial system. A photo of the triaxial test setup is shown in Figure 4.

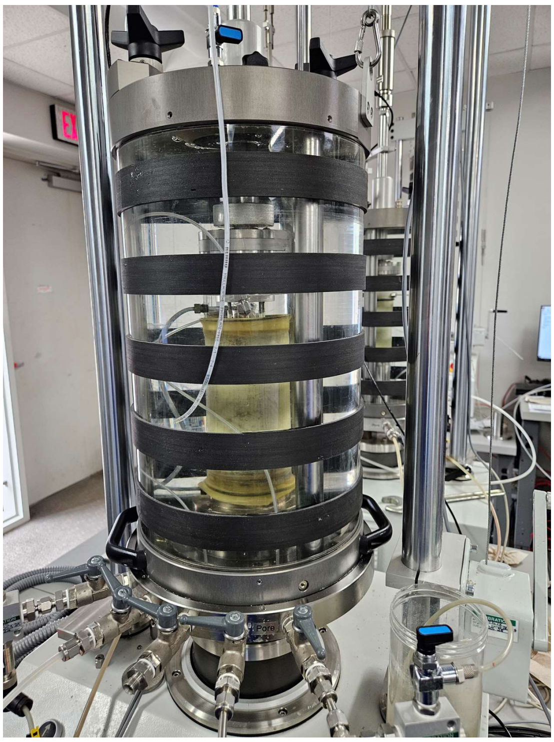

Figure 4. Triaxial test setup.

In the CID TX tests, the specimens were isotropically consolidated to an effective vertical stress, σ'_{vc}, equal to the in-situ effective overburden pressure at the sampling depth. σ'_{vc} is 35 kPa for U0 sand specimens and 103 kPa for U1 sand specimens. A creep period of 24 hrs was allowed after consolidation to σ'_{vc} in the CID TX tests.

In the CK0D TX tests, the specimens were first K_0 – consolidated to an effective vertical stress equal to the yield stress (σ'_{vy}) determined from 1D consolidation tests, followed by K_0 – unloading to σ'_{vc}. Such K_0 – consolidation procedure incorporates stress history effects into the final stress state achieved at the end of the consolidation process. It is noteworthy that K_0 – consolidation was achieved in this study by automatically adjusting the chamber pressure in order to synchronize the volumetric strain rate with the axial strain rate so that the average cross-sectional area of the specimen remains constant during the consolidation process, thus reproducing the zero radial strain condition. This approach enables direct determination of K_0 as the ratio of measured radial and axial effective stresses during consolidation. An axial strain rate of 0.05 %/h was used for K_0 – consolidation. Additionally, a creep period of 24 hrs was allowed after consolidation to σ'_{vy} and after unloading to σ'_{vc} in the CK0D TX tests.

Results from 1D consolidation tests performed in the incremental load oedometer and presented in Figure 5, revealed yield stresses (σ'_{vy}) of 350 kPa and 300 kPa for K_0 – consolidation of U0 and U1 triaxial specimens, respectively. σ'_{vy} was interpreted based on the extent of the initial loglinear portion of the compression curves measured on intact specimens. U0 intact and reconstituted compression curves agree quite well, indicating that stress history represents the main ageing mechanism controlling stress-strain characteristics of Holocene marine sediments. In addition to stress history, other ageing mechanisms also appear to significantly contribute to the behaviour of Pleistocene intact sands, resulting in a much lower compressibility displayed by the compression curve of the U1 intact specimen.

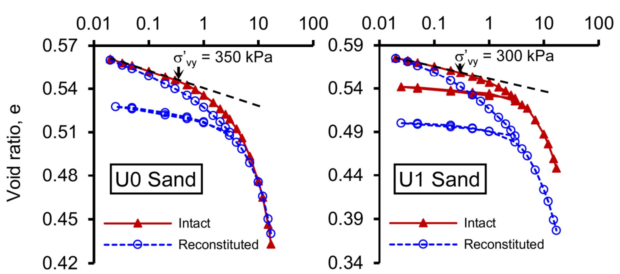

Figure 5. 1D consolidation test results.

Figure 6 shows results of the consolidation stage in the triaxial in terms of measured volumetric strain (ε_v) and K_0 in relation to effective vertical (axial) stress.

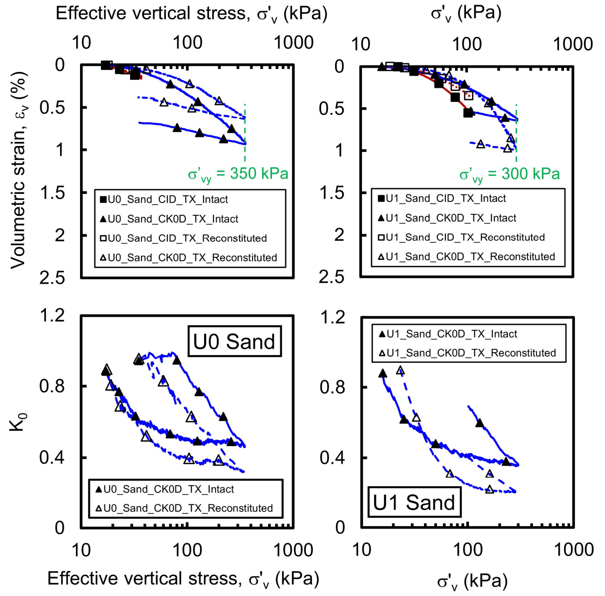

Figure 6. Triaxial test consolidation stage results.

U0 intact and reconstituted specimens feature K_0 values of 0.46 and 0.32 at $\sigma'_v = \sigma'_{vy}$, along with (almost identical) K_0 values of 0.94 and 0.95 after unloading at $\sigma'_v = \sigma'_{vc}$, respectively. U1 intact and reconstituted specimens are characterized by K_0 values of 0.36 and 0.20 at $\sigma'_v = \sigma'_{vy}$, and K_0 values of 0.69 and 0.40 after unloading at $\sigma'_v = \sigma'_{vc}$, respectively. The large discrepancy observed in K_0 values at the end of consolidation between intact and reconstituted U1 specimens is most likely due to ageing mechanisms other than stress history which appear to also have a significant impact on the stress-strain characteristics of intact Pleistocene sands, as discussed previously. Additionally, the relatively low K_0 value measured at $\sigma'_v = \sigma'_{vy}$ for reconstituted U1 sample is attributed to the presence of mica, well known to have a major influence on compressibility.

4 SAMPLE QUALITY ASSESSMENT

In addition to visual examination of core XCTs (Figure 2), the quality of tested intact sand specimens was also evaluated by comparing in-situ and laboratory measured shear wave velocities. Figure 7 shows the shear wave velocity (V_s) measured from bender element tests performed in the triaxial equipment on consolidated specimens. V_s at the end of consolidation (i.e., $\sigma'_v = \sigma'_{vc}$) ranges from 135 m/s to 172 m/s for U0 intact sand specimens, and from 196 m/s to 221 m/s for U1 intact sand specimens. These ranges are within more than 86% and within more than 84% of the interval of corresponding in-situ measured V_s at U0 and U1 sampling locations, respectively (Figure 1). The quality of laboratory tested intact sands is therefore assessed as excellent for U0 specimens and very good to excellent for U1 specimens according to the V_s based sample quality assessment criteria proposed by Ferreira et al. (2011).

Bender element measured V_s values during unloading from σ'_{vy} to σ'_{vc} for K_0 – consolidated specimens illustrate the high sensitivity of V_s to changes in effective vertical stress (Figure 7). For example, V_s of U1 specimens decreased by 50 m/s for a reduction in σ'_v of about 200 kPa in the context of a very minor (i.e., 0.1%) change in volumetric strain. As also illustrated in Figure 7, ranges of V_s values for reconstituted specimens after consolidation are within more than 92% of the V_s interval corresponding to intact specimens, thus quite reasonable with regard to V_s similarity between intact and reconstituted sands.

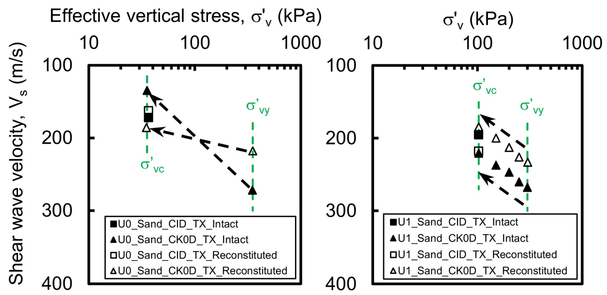

Figure 7. Shear wave velocity from bender element tests on consolidated specimens in the triaxial equipment.

5 TRIAXIAL COMPRESSION TEST RESULTS

Figure 8 presents the results from drained triaxial compression tests in terms of stress ratio (σ'_1/σ'_3) and volumetric strain (ε_v) in relation to axial strain (ε_a). All tests were conducted in the strain-controlled mode using an axial strain rate of 0.3 %/h. σ'_1 and σ'_3 represent the major and minor principal effective stresses, which for samples subjected to axial compression correspond to the axial and radial effective stresses, respectively.

K_0 – consolidated specimens demonstrated a stiffer stress-strain response compared to isotropically consolidated specimens, culminating in peak stress ratios attained at lower axial strain levels. This outcome demonstrates that K_0 – consolidated specimens exhibited a greater degree of particle interlocking as a result of incorporating stress history

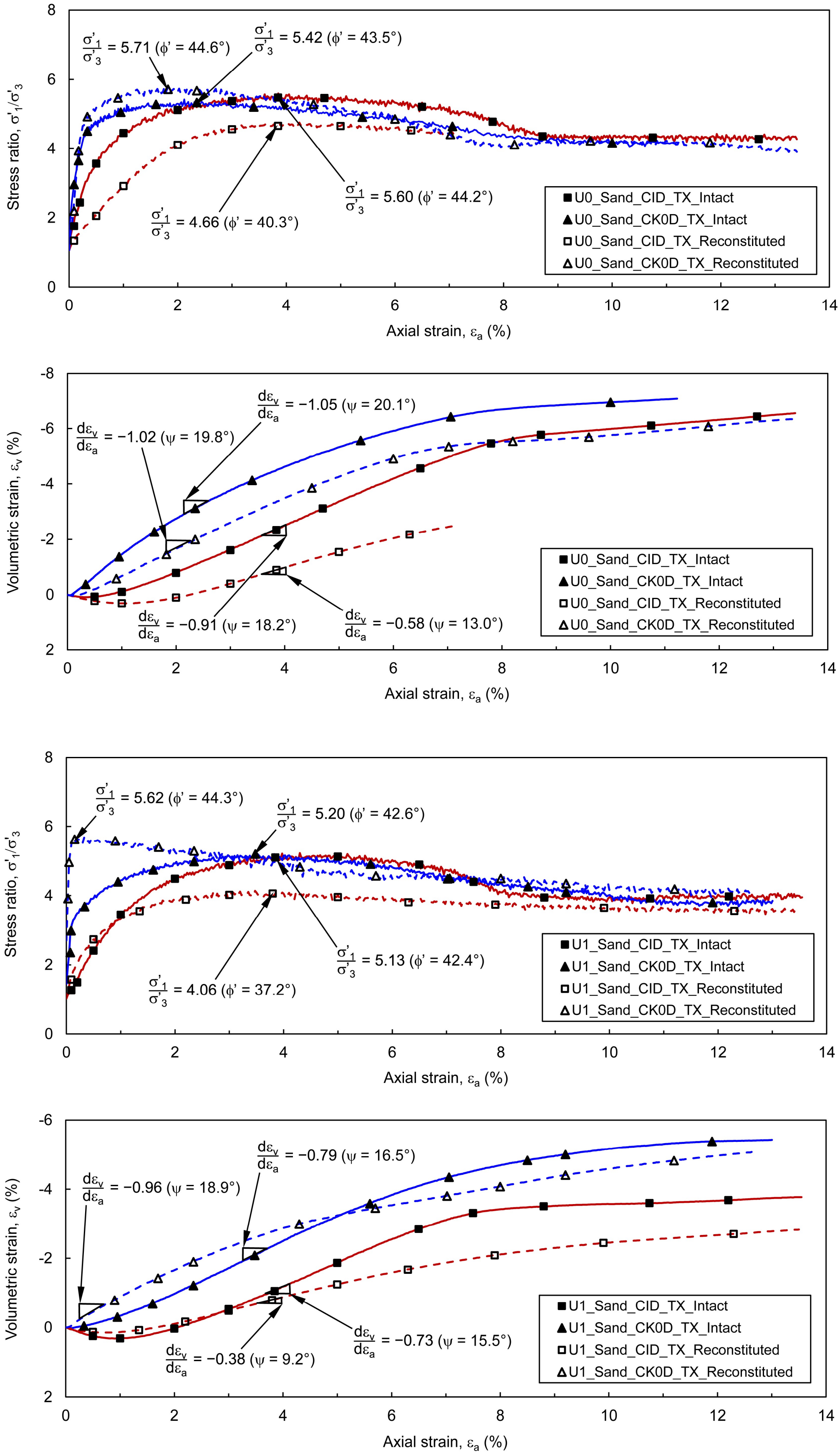

Figure 8. Stress ratio and volumetric strain versus axial strain relationships from drained triaxial compression tests on intact and reconstituted sand specimens.

in the consolidation process, unlike specimens consolidated isotropically directly to the in-situ effective overburden pressure. The same aspect is illustrated by the significantly lower axial strain required for the onset of dilative behaviour in CK0D TX tests, compared with results from CID TX tests (Figure 8).

Geotechnical parameters of interest for foundation engineering analyses determined from the experimental results presented in this study, included effective friction angle (ϕ') and dilatancy angle (ψ). ϕ' describes the strength of tested sands and was calculated using the peak stress ratio measured from triaxial compression tests (Figure 8) according to the following equation based on the Mohr-Coulomb yield function:

$$\phi' = \sin^{-1}\frac{\frac{\sigma'_1}{\sigma'_3}-1}{\frac{\sigma'_1}{\sigma'_3}+1} \tag{1}$$

ψ characterizes the change in plastic volumetric strain ($d\varepsilon_v^p$) in relation to change in plastic axial strain ($d\varepsilon_a^p$). In this study, ψ is calculated using the slope of the tangent to the $\varepsilon_v - \varepsilon_a$ curve at an axial strain level corresponding to the peak stress ratio (Figure 8). At such strain level, elastic strains are negligible, hence $d\varepsilon_v^p = d\varepsilon_v$ and $d\varepsilon_a^p = d\varepsilon_a$. Accordingly, ψ is determined using the following equation (Vermeer and de Borst, 1984):

$$\psi = \sin^{-1}\frac{\frac{d\varepsilon_v}{d\varepsilon_a}}{\frac{d\varepsilon_v}{d\varepsilon_a}-2} \tag{2}$$

As seen in Figure 8, TX tests performed on intact specimens consolidated under both K_0 and isotropic conditions produced quite similar effective friction angles (i.e., 43.5°- 44.2° and 42.4°- 42.6° for U0 and U1 sands, respectively). It may therefore be inferred that the intact specimens retained, to a great extent, the in-situ degree of particle interlocking even without consolidation to the yield stress (σ'_{vy}) in the laboratory. It is noteworthy that unlike K_0 – consolidated U0 specimens featuring nearly isotropic (i.e., $K_0 \cong 1.0$) stress conditions at the end of the consolidation process, the mean effective stress at the end of consolidation (i.e., $\sigma'_{mc} = (1+2K_0)\sigma'_{vc}/3$) for the K_0 – consolidated intact U1 specimen is only $0.79\sigma'_{vc}$. However, K_0 and isotropically consolidated intact U1 specimens still resulted in almost identical ϕ' values despite a significant difference in σ'_{mc}. In comparison with TX test results on intact specimens, ϕ' values smaller by 3°- 4° and 5° were obtained from TX tests on isotropically consolidated reconstituted U0 and U1 sands, respectively (Figure 8). On the other hand, ϕ' values greater by only 1° and less than 2° were derived from TX tests on K_0 – consolidated reconstituted U0 and U1 specimens, respectively.

The significantly stiffer stress – strain response measured for the K_0 – consolidated reconstituted U1 specimen versus the other U1 TX test results is mainly due to large differences in σ'_{mc}. σ'_{mc} of the CK0D TX reconstituted U1 sample is the lowest among the tested U1 specimens, specifically, only $0.6\sigma'_{vc}$ based on the corresponding K_0 = 0.4 measured at the end of consolidation stage (Figure 6). This much smaller mean effective confining stress along with the denser state achieved at the end of K_0 consolidation (Figure 6) for the CK0D TX reconstituted U1 sample, facilitated the onset of a dilative behaviour almost immediately after the beginning of the shear phase, as seen in Figure 8, thus culminating into the much lower axial strain required to reach the peak strength compared to the other U1 TX test results.

Overall, differences observed in calculated dilatancy angle (Figure 8) among various tested U0 and U1 sand specimens, correlate well with differences in the effective friction angles discussed previously. Isotropically consolidated reconstituted specimens exhibited ψ values much smaller (i.e., 5°- 7° less) compared to ψ values obtained for intact K_0 and isotropically consolidated specimens.

6 CONCLUSIONS

The present experimental study demonstrated that CID TX compression tests on reconstituted very dense marine sands consolidated directly to effective vertical stresses equal to in-situ effective overburden pressure, may significantly underestimate in-situ strength (i.e., 3°- 5° smaller ϕ') and dilatancy (i.e., 5° - 7° smaller ψ) parameters, as they fail to capture the enhanced degree of particle interlocking associated with in-situ stress history and (for sands older than Holocene) other ageing mechanisms. These findings are consistent with outcomes of previous similar experimental studies based on drained TX compression tests, showing for intact Holocene and Pleistocene sands ϕ' values in general greater by 3°-6°, along with proportionally greater ψ, compared to values representative for reconstituted samples (Lunne et al., 2003; Esposito and Andrus, 2017). Lower ϕ' values associated with CID TX tests on reconstituted specimens, will result in underestimates of the geotechnical load carrying capacity thus culminating in overdesigned and therefore less economical foundation systems.

Parameters derived from CK0D TX tests on reconstituted specimens, following the consolidation procedure described in this paper, are regarded as more relevant for in-situ conditions. CK0D TX tests on reconstituted specimens resulted in overestimates of intact sand ϕ' by less than 2°, despite large differences in σ'_{mc} achieved during K_0 consolidation for one of the tested sands. Such ϕ' values are considered appropriate for foundation installation feasibility assessments (e.g., monopile driveability studies) in particular, as they provide a reasonable high estimate of the in-situ effective friction angle. In the absence of intact sand specimens, laboratory 1D consolidation tests on reconstituted specimens may be used to derive with a good degree of approximation yield stresses required for K_0 – consolidation in the CK0D TX tests.

AUTHOR CONTRIBUTION STATEMENT

A.C. Trandafir: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing – original draft. **J. Fraser and S. Kaur**: Conceptualization, Resources, Supervision, Writing – review & editing. **D. Hargrave**: Conceptualization, Funding acquisition, Project administration, Writing – review & editing.

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