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Utilizing constant normal stiffness interface tests to estimate pile skin friction in a glauconite sand

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ABSTRACT: The East Coast of the United States has started surveying, constructing, and operating offshore wind turbines for wind farms from Massachusetts to South Carolina. The foundations of many of these turbines will be situated on driven piles in glauconite deposits. These soils may be difficult for predicting pile driving due to their crushability and changes in plasticity when crushed. While the best way to determine pile skin friction is to run full-scale pile tests, utilizing laboratory equipment to simulate these testing programs could be a suitable option for estimating skin friction. Constant normal load (CNL) interface testing has been performed in laboratories to estimate this engineering property, but it may not be the most direct comparison for driving piles. The immediate area surrounding piles may not necessarily be subject to constant normal stress because of the dilation or contraction of soil under shearing conditions. A good alternative for simulating the effects of pile driving on long term soil response in the laboratory is the constant normal stiffness (CNS) interface shear test. This paper compares the CNL and CNS tests by utilizing an automated direct shear device that is capable of conducting both of these tests. The testing program is performed on glauconite sand from the Navesink Formation in New Jersey. By testing these soils under both CNS and CNL conditions on a rigid base of various roughness the crushability and friction evolution can be assessed to gain insights into the potential responses of these soils during pile driving.

Keywords: Glauconite, Laboratory testing, Interface tests, direct shear, constant normal stiffness

1 INTRODUCTION

As offshore wind farms progress along the Northeastern coast of the United States, new challenges have arose during their construction. One of the issues that has been clearly identified thus far is the presence of glauconite in the locations of wind lease areas off of Massachusetts and New Jersey (Lennon 2023). With a number of developments planned for the regions offshore of New York and New Jersey, glauconite may potentially be a concern for the foreseeable future.

Glauconitic soils are iron and potassium-rich micaceous material that has evolved at the soil-water interface to include microcracks and fissures as well as develop green to black colouring depending on maturity. Glauconite maturity can be classified in four stages: nascent, slightly evolved, evolved, and highly evolved (Odin and Matter, 1981; Obasi, 2011) which could possibly impact their geotechnical properties. In addition to being located offshore of the United States Northeast (Clark 1894; Westgate et al. 2022, 2023; Zeppilli et al. 2024), these soils are also found in regions of the North Sea (Hossain et al. 2009) and Belgium (de Nijs et al. 2015). Some known issues with glauconite include its brittle and crushable nature (Westgate et al. 2022), its ability to change soil classification (Zeppilli 2024), pile drivability and resistance (de Nijs et al. 2015), and its high compressibility (Westgate et al. 2023).

Predicting pile driving forces and hammer sizes in glauconite is a concern to avoid refusal, as the pile skin friction may change when the glauconite crushes and changes from sandy drained behaviour to clayey undrained behaviour. While driving sheet piles and piles in glauconite has been (de Nijs et al. 2015) and is currently of interest (Westgate et al. 2024). Figuring out useful laboratory tools and practices to model field conditions and behaviour is something that is starting to emerge from the ongoing research (Westgate et al. 2023).

Shear interface testing to estimate friction is one of these useful tools for assessing the impact of pile driving in the laboratory (Bromhead 1979, Bromhead and Dixon 1986). While traditionally constant normal load

(CNL) interface testing has been useful for this, research has shown that constant normal stiffness (CNS) testing may be more applicable to modelling the effects of pile driving through laboratory testing. CNS tests involve choosing a representative stiffness as a normal stress per unit height and keeping it constant throughout (Fioravante 2002, Porcino et al 2003, Tabucanon et al 1995, Wang et al 2022).

DS and CNS testing on glauconite sands with three different interface configurations of sand on smooth surface, sand on rough surface, and sand on sand with and relative densities is presented to show the differences in estimating pile skin friction through these two testing methods. Particle crushing (through changes in the particle size distribution), and friction angles will be shown to present comparisons between these tests.

2 METHODS AND MATERIALS

2.1 Materials

The soil in this study is a glauconite sand with less than 5% fines from Poricy Park in New Jersey, USA. This soil is collected from the stream of a creek that goes through the Navesink formation in Monmouth County, New Jersey. The bulk sand sample was homogenised prior to testing.

The geotechnical index properties as reported in of the soil used in this study is presented below in Table 1 (Westgate et al 2023).

Table 1. Poricy Park glauconite sand properties (Westgate et al 2023)

Property	Value
Glauconite Content	54%
Specific Gravity	2.80
Minimum Dry Density	13.7 kN/m^3
Maximum Dry Density	16.1 kN/m^3

The following particle size information, Figure 1 and Table 2, is from an intact sample of Poricy Park sand from this study. A mechanical sieve was performed following ASTM 6913 (ASTM 2023).

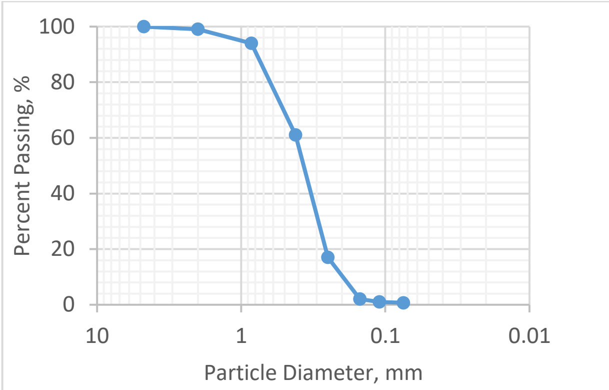

Figure 1. Particle size distribution of untested Poricy Park glauconite sand

Table 2. Particle size distribution properties for untested Poricy Park glauconite sand

Property	Value
Median Grain Size, D_{50}	0.37 mm
Effective Grain Size, D_{10}	0.20 mm
Uniformity Coefficient, C_u	2.13
Degree of Curvature, C_c	1.04
Fines Content	0.7%

2.2 Sample Preparation

Samples were prepared using the moist tamping method (Ladd 1974) to create samples of two relative densities, 40% and 85%. The samples were prepared at 5% moisture content and tamped using a small hand held metal tamper into shear boxes. The samples were created in three configurations: sand on rough metal face, sand on smooth metal face, and sand on sand.

The two sided metal disk that fits in the bottom of the shear box was created for this testing program. The metal disk is of diameter 63.02 mm and height 20.58 mm. This disk was fitted into the bottom of the shear box such that the shear plane of the soil failure was along this interface. One side of the disk had a smooth face while the other side was made rough by using a lathe with a grooving tool to create a roughness on the face. The average roughness of the rough face was 5.32 μm and the smooth face was 1.04 μm. The faces of these disks can be seen in Figure 2. The dimensions of the sand on sand configuration involve a 25.4 mm high by 63.5 mm diameter sample.

Figure 2 - Smooth (left) and rough (right) faces of the steel disk used as the shear interface for constant normal load and constant normal stiffness interface tests

2.3 Equipment and Testing

This testing program was carried out on Geocomp ShearTrac-II testing equipment using Geocomp DS and Geocomp CNS testing software. This shear testing equipment is capable of running direct shear and direct residual shear, static and cyclic direct simple shear, as well as constant normal stiffness tests due to its high rigidity. Figure 3 shows the Geocomp ShearTrac-II equipment in the direct shear setup which was used for this testing.

Figure 3 - Geocomp ShearTrac-II set up for direct shear and constant normal stiffness testing

The six sample combinations were tested in DS, CNL, and CNS for a total of 12 tests. DS tests shear soil and interfaces with a constant normal stress throughout the shearing process while CNS tests adjust the stiffness on the specimen by adjusting the applied normal stress depending on the change in vertical height of the soil through the following Equation 1:

$$K = \frac{\sigma_N}{\Delta h}$$

Where K is normal stiffness, σ_N is the applied normal stress, and Δh is the change of the height of the sample.

From there, friction angle can be calculated from the ratio of normal stress to the applied shear stress of the system and followed by the calculation of the frictional coefficient.

$$\phi = tan^{-1}\frac{\tau}{\sigma_N}$$

Where ϕ is the friction angle at the shear plane, τ is the applied shear stress on the system.

In the CNL tests, a normal stress of 100 kPa was chosen which in the CNS tests, and a stiffness of *K*=100 kPa/mm was picked with a consolidation stress of 100 kPa like that of the DS tests.

Finally, particle size distributions before and after testing are used to give an idea of the amount of crushing that occurs for this brittle material in the sample. This testing is done by mechanical sieve of the sand material with a starting fines content of 0.7%.

3 RESULTS

In this section the results of the CNL and CNS tests will be presented as well as the particle size distributions of the post-test material.

3.1 Constant Normal Load Test Results

Constant normal load interface and direct shear tests were performed on the six sample configurations. Table 3 summarizes the friction angle or interface friction angle at 15% horizontal strain for different combinations of testing and peak friction angles for dense samples while Figure 4 shows the shear stress and stress ratio trends versus axial strain for the tests.

Table 3. Friction angles for the different constant normal load interface and direct shear tests.

Test	Residual Friction Angle	Test	Residual Friction Angle	Peak Friction Angle
40%-Rough	31.4°	85%-Rough	30.0°	32.9°
40%-Smooth	25.1°	85%-Smooth	32.6°	33.9°
40%-Sand	39.1°	85%-Sand	37.0°	44.4°

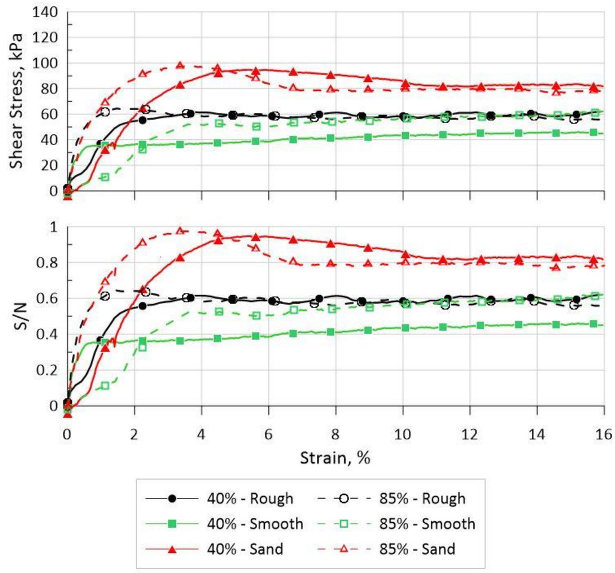

Figure 4 - Shear stress and stress ratio plots vs axial strain of DS and CNL interface tests.

3.2 Constant Normal Stiffness Test Results

Six constant normal stiffness tests were performed on the same sample configurations and resulted in the following friction angles (Table 4) and shear and stiffness plots (Figure 5).

Table 4. Resulting friction angles from constant normal stiffness and interface tests

Test	Residual Friction Angle	Test	Residual Friction Angle	Peak Friction Angle
40%-Rough	33.5°	85%-Rough	32.4°	33.7°
40%-Smooth	26.7°	85%-Smooth	30.5°	31.2°
40%-Sand	36.9°	85%-Sand	38.4°	45.4°

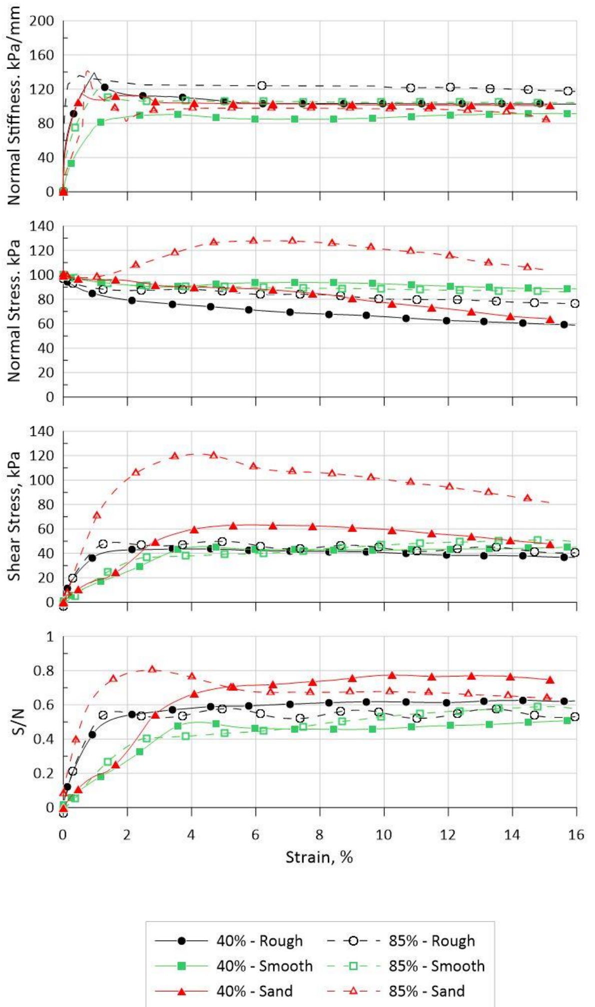

Figure 5. Results of the constant normal stiffness tests showing trends of constant normal stiffness, normal stress, shear stress, and stress ratio over the axial strain of the shearing process

3.3 Crushing Results

Particle size distributions performed after post-CNL CNS, and DS tests are used to find the change in fines content from these tests. Table 5 displays the post-test fines contents for the CNL tests and Table 6 shows the same information for the CNS tests.

Table 5. Post-test change in fines contents for the constant load CNL and CNL interface tests

Test	Fines Content	Test	Fines Content
40%-Rough	2.3%	85%-Rough	0.4%
40%-Smooth	1.4%	85%-Smooth	1.7%
40%-Sand	1.0%	85%-Sand	1.5%

Table 6. Post-test fines contents for the constant normal stiffness and interface tests

Test	Fines Content	Test	Fines Content
40%-Rough	1.3%	85%-Rough	1.8%
40%-Smooth	1.5%	85%-Smooth	1.9%
40%-Sand	0.6%	85%-Sand	2.5%

4 DISCUSSION

Trends show that the soil on soil behaviour for these tests results in the highest friction angles for both direct shear and constant normal stiffness tests. The differences between the CNS and DS tests' friction angles were 6% and 4% (relatively small) for the 40% and 85% relative density tests respectively for the sand on sand tests. It should be noted here that in comparison to the direct shear critical state friction angle from Westgate et al (2023) on the same soil sample resulted in a critical state friction angle of 34°, which is lower than the soil on soil friction angles in this study of 39° and 37° for direct shear and 37° and 38° for CNS at 15% strain for 40% and 85% relative density respectively.

When comparing the different roughness in CNL interface testing to the DS testing, the resulting friction angles for the rough faces reduced the friction angle by 20% for the rough face in the looser sample and 19% for the denser sample. When comparing to the smooth face the CNL interface tests resulted in a friction angle reduction of 36% for the looser sample and 12% for the dense sample.

When making the same comparisons for the CNS interface tests to the direct shear CNS tests, the friction angle reduced by 9% for those in loose sample configuration with a rough face and 16% for the dense sample on the rough face. For the smooth face, friction angle reduced by 28% and 21% for the loose and dense samples respectively. These reductions in friction angle are less in each configuration of the constant normal stiffness tests than they are in direct shear tests except for the 85% dense sample on a smooth face.

When comparing the trends of the direct shear versus the constant normal stiffness tests, there does not appear to be significant differences between the tests, all tests were within 2.6° when comparing direct shear to CNS. When comparing the 40% relative density tests, the direct shear tests resulted in friction angles lower than the constant normal stiffness tests for both rough and smooth faces of the metal disk, but the sand on sand behaviour of the direct shear resulted in a higher friction angle than in the constant normal stiffness test. In the 85% relative density tests, the sand on sand and the sand on rough interface resulted in lower friction angles in CNL than the CNS test, but the CNL interface test of sand against the smooth interface resulted in a higher friction angle than the CNS test. The small difference could be due to the creation of clay at the interface due to crushing of the grains. In undrained conditions clay behaviour is independent of normal stress. This would mean that test boundary conditions are not significant as long as crushing has been initiated.

From the results of the post-test particle size distributions, there does not seem to be a notable trend in more or less crushing between DS and CNS testing. On average the 40% density direct shear tests results in an average fines content of 1.6%, while the 85% relative density samples had 1.6% fines on average as well. The CNS tests resulted in 1.1% fines and 2.0%. These fines content increases are underestimated as this particle size data is from the entire shear sample and not only from the shear zone. While the loose constant normal stiffness tests resulted in less fines than the direct shear tests, the denser CNS samples resulted in more fines than the direct shear tests.

5 CONCLUSIONS

In this study, four constant normal load shear interface, four constant normal stiffness interface, two CNL direct shear and two CNS direct shear tests were run to compare the behavior of glauconite soil in direct shear and constant normal stiffness tests. The following conclusions were drawn from the differences in fricition angle and shear stress trends between the two test types.

- Constant normal stiffness tests appear to be a valid comparison test to constant normal load tests in both direct shear and sand on interface set ups based on friction angle results.
- The resulting friction angles for the constant normal stiffness tests are comparable to the constant normal load tests. With a 2.6° or less difference between CNL and CNS. This could be the result of the formation of clay during particle crushing along the interface whose behavior would be stress independent.
- There was a reduction of friction angle from the direct shear to the CNL and CNS interface tests. The reductions in friction angle from DS to CNL tests are smaller than the reductions in friction angle in the CNS, indicating that the CNS tests may lead to slightly different results.
- There did not appear to be any quantifiable trends for the differences in the amount of crushing between the constant normal stiffness and constant normal load tests.

AUTHOR CONTRIBUTION STATEMENT

Danilo Zeppilli: Project management, Formal Analysis, Writing- Original draft.
Jonathan Wiggins: Soil testing
Artur Apostolov: Data Curation, Software and Mechanics
Ryan Beemer: Editing and research consultation

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