Geotechnical Properties of a Glauconite Sand from Belgium

Konstantinou, M.; Piedrabuena, A. R.; Hellebrekers, N.; Elkadi, A.S.; Mento, M.; Gavin, K.

DOI
10.53243/ISFOG2025-65

Publication date
2025

Document Version
Final published version

Published in
Proceedings of ISFOG 2025

Proceedings of ISFOG 2025
5TH INTERNATIONAL SYMPOSIUM ON
FRONTIERS IN OFFSHORE GEOTECHNICS
Nantes, France | June 9-13 2025

ISBN 978-2-85782-758-0

Geotechnical Properties of a Glauconite Sand from Belgium

M. Konstantinou
Deltares, Delft, The Netherlands

A. R. Piedrabuena, N. Hellebrekers, A.S. Elkadi
Deltares, Delft, The Netherlands

M. Mento
IQIP, Sliedrecht, The Netherlands

K. Gavin
Delft University of Technology, Delft, The Netherlands

maria.konstantinou@deltares.nl (corresponding author)

ABSTRACT: Due to the rapid expansion of the offshore wind industry, wind farms are being developed in areas where glauconite soils are encountered. Of particular interest for the development of windfarms in regions dominated by glauconite sand deposits is the risk associated with the presence of this geomaterial. It is acknowledged that glauconitic soils pose significant challenges during pile installation due to their high susceptibility to particle crushing at relatively low stress levels. This transforms the sand into a low-permeable fine-grained clay-like material, leading to a complex response upon shearing as a result of the change in soil behaviour. In this study, the geotechnical behaviour of a glauconite sand from the Antwerp region in Belgium is investigated by means of a laboratory testing program comprising of index classification tests, compression, direct shear and interface shear strength tests. The laboratory test data are interpreted to improve understanding of the geotechnical properties of this peculiar geomaterial and evaluate its potential implications during pile driving.

Keywords: glauconite; internal friction angle; interface friction angle; stress-strain response; glauconite content

1 INTRODUCTION

Glauconite sands are a geotechnically challenging material. Their presence is often linked to high pile wall shear resistance from particle crushing and associated increases in fines content and plasticity (Van Alboom et al., 2012, De Nijs et al., 2015). Offshore monopile installations in glauconite soils is rather restricted as driving in glauconite comes with a high potential of pile refusal. The need for continuous research on the characterization and behaviour of glauconite is therefore needed for monopile design, especially considering the rapid expansion of offshore wind in glauconite dominated regions. To date, there is a limited body of public knowledge on the behaviour of glauconite soils and the development of guidelines related to their testing in the laboratory (Westgate et al., 2022; Westgate et al., 2023; Quinteros et al., 2023).

This paper presents results from a laboratory testing programme on a glauconite sand from Belgium conducted at the Deltares geotechnical laboratory in the Netherlands. The results are analysed with the objective to: (i) provide insights on the behaviour of the tested glauconite sands with respect to stress-strain response, compressibility and interface shear strength and (ii) complement the existing database of laboratory test results on glauconite sands in literature.

It should be noted that in this paper a sand with glauconite is termed "glauconite sand" irrespective of glauconite content.

2 TESTING MATERIAL

The natural glauconite sand used in this study was obtained from Antwerp (Belgium) and belongs to the Kattendijk formation. Before testing, the fine fraction of the sand was removed. A Glauconite Content (GC) of about 10% by weight was measured using magnetic separation. Glauconite particles were also manually separated using a magnet and added to the natural glauconite sand to create a material with a glauconite content of 60% by weight. The choice of 60% was made arbitrarily to investigate the material's behaviour at a relatively high glauconite content. Calibration Chamber tests (CC) were performed using the natural 10% GC sand, in which an instrumented model pile was installed via jacking and impact driving. As shown in the inset diagram in Figure 1, the installation resulted in a shear band of glauconite crushed material around the pile's shaft and toe (Piedrabuena et al., 2024a, Piedrabuena et al., 2024b). The crushed material was collected and used in the tests of this study. Figure 1 presents the particle size distribution curves as obtained using the laser diffraction method for the 10% GC natural and crushed sand.

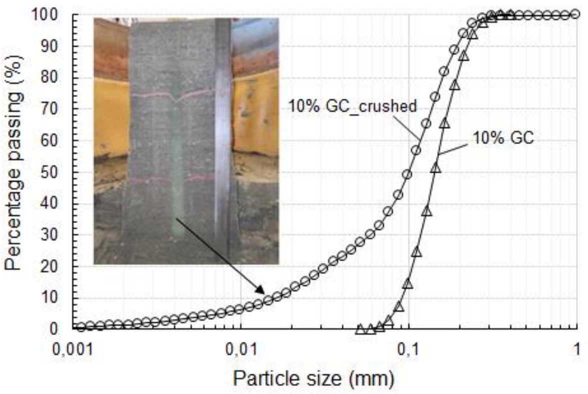

Figure 1. Particle size distribution curves of 10% GC and 10% GC crushed glauconite sand; the inset diagram shows a cross-section of the glauconite soil around the model pile's shaft in CC testing.

The latter has a fines and clay content of 35 and 1.4%, respectively and it is classified as a low plasticity silty sand. Optical microscope images and photographs of a 10% GC, magnetically separated 100% GC and 10% GC crushed sand material are illustrated in Figure 2. Table 1 summarizes the material's geotechnical properties.

Table 1. Index properties of the tested glauconite sands.

Parameter	**10% GC**	**60% GC**	**10% GC crushed**
G_s [g/cm^3]	2.69	2.80	2.68
$\rho_{d,max}$ [g/cm^3]	1.64	1.69	1.72
$\rho_{d,min}$ [g/cm^3]	1.33	1.40	1.34
FC [%]	<0.5	-	35
CC [%]	0	-	1.4
D_{50} [mm]	0.144	-	0.098
LL [%]	-	-	23.7
PL [%]	-	-	18.1

Note: G_s, particle density; $\rho_{d,max}$ and $\rho_{d,min}$, maximum and minimum dry density respectively; FC, Fines Content; CC, Clay Content; D_{50}, mean particle size; LL and PL, Liquid and Plastic Limit respectively.

3 DESCRIPTION OF TESTS

Direct Shear Sand-to-Sand (DS-SS) and Interface Shear sand-to-steel tests (DS-IS) were performed under Constant Normal Load (CNL) conditions. To assess the impact of boundary conditions, Constant Normal Stiffness (CNS) interface tests (DS-SI-CNS) were also conducted and sheared at a constant normal stiffness value of K = 1000 kPa/mm. An overview of the sample characteristics is given in Table 2.

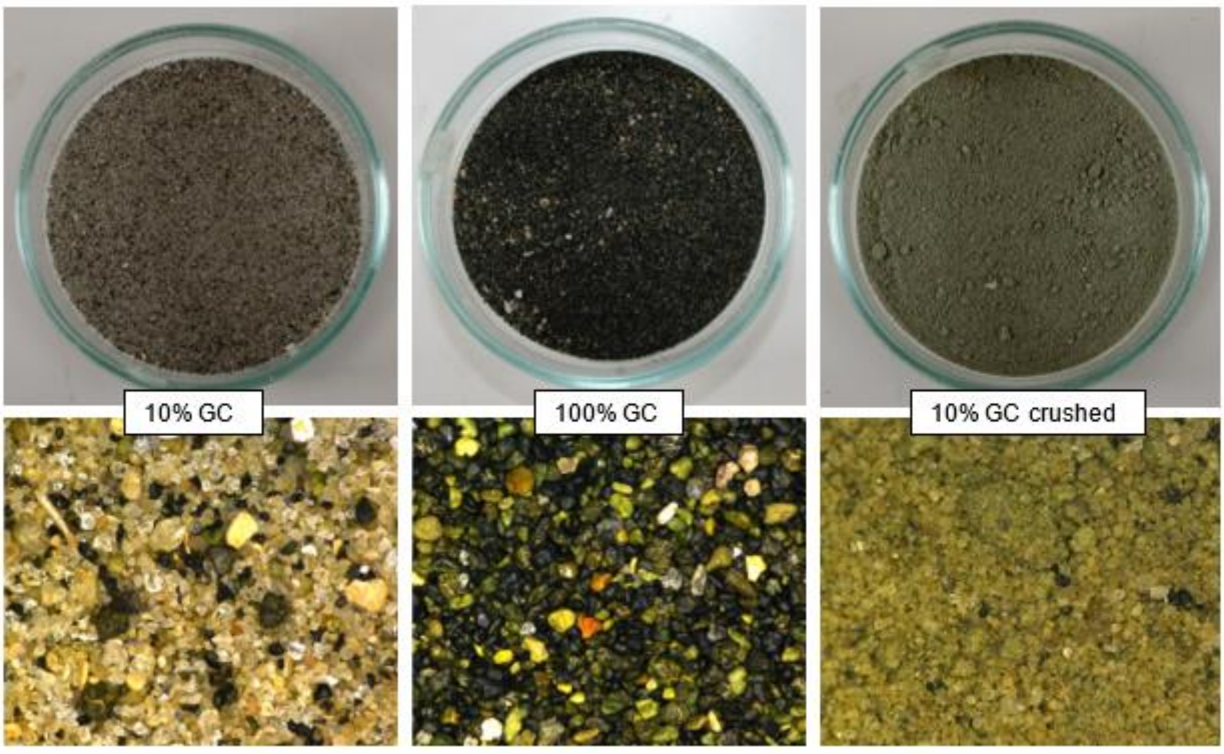

Figure 2. Microscopic images and photographs of the Antwerp glauconite sand: 10% GC sand (left), 100% GC manually separated with a magnet sand (center) and 10% GC crushed sand (right).

All tests were performed on cylindrical samples having a diameter of 63 mm and a height at preparation of approximately 20 mm and were prepared both by wet and dry pluviation at a relative density of 70%. The samples were subjected to consolidation stresses ranging from σ_{vc}' = 100 to 400 kPa and sheared at a rate of 0.5 mm/min. Only for the finer, crushed material, a slower rate of 0.05 mm/min was applied. For the interface tests, a rusty steel plate with an averaged roughness of R_a = 40 µm was used.

4 TEST RESULTS

All samples were subjected to a pressure of about 2 kPa before loading to the designated consolidation stress levels. In Figure 3, the compressibility curves obtained for the samples prepared with wet pluviation are plotted in terms of axial strain, ε_{axial}, versus vertical stress, σ_v'. The crushed glauconite sand shows higher compressibility while an increase in glauconite content from 10% to 60% does not appear to influence the response to compression. A Constant Rate of Strain, CRS, test was also performed on a slightly denser 10% glauconite sample ($D_r \approx 80\%$) loaded up to 10 MPa with a strain rate of 0.01 mm/min. As can be seen in the inset diagram in Figure 3, the stress level at the point of maximum curvature is about 2000 kPa. Loading beyond this stress level, possibly leads to particle crushing. This observation is in agreement with the findings of Belotti et al. (1992) who reported that crushing of glauconite sands initiates at 2 MPa in oedometer testing. It should be noted that during pile driving compressive stresses which can reach values of 50 MPa or higher in dense sands are developed (Mao et al., 2020; Peng et al., 2021; Westgate et al., 2023).

The dry pluviated glauconite samples of this study were soaked in water prior to start of consolidation by maintaining the sample height – and thus sample volume – constant. Notably, the samples developed a swelling pressure, σ_s, which increases with glauconite content; σ_s = 26 and 115 kPa for the 10% and 60% GC samples respectively. According to Odin and Matter (1981) the mineral glauconite has a high swelling potential. Conversely, the crushed glauconite did not exhibit any swelling tendencies.

DS-SS test results are presented in Figure 4 showing the shear stress ratio, τ/σ_v', (Figure 4a) and vertical displacement (Figure 4b) versus horizontal displacement for different glauconite samples at σ_{vc}' = 400 kPa. For comparison purposes, the response of a standard research sand, the Toyoura Sand (TS), tested under similar conditions is also shown in Figure 4.

Table 2. Sample characteristics.

GC [%]	T.T [-]	P.M [-]	σ_s [kPa]	σ_{vc}' [kPa]	φ_{res}' [^{0}]
10	SS	WP	-	100	37.6
10	SS	DP	29.6	100	35.6
10	SS	DP	26.4	200	34.8
10	SS	DP	21.3	400	32.0
10	SS	WP	-	400	32.2
60	SS	DP	113	200	33.8
60	SS	DP	117	400	31.8
10-C	SS	WP	-	400	35.0
10-C	SS	DP	1.2	200	33.2
10-C	SS	WP	-	400	32.4
10	SI	WP	-	200	27.2
10	SI	WP	-	400	27.4
60	SI	WP	-	200	27.0
60	SI	WP	-	400	27.9
10-C	SI	WP	-	200	24.6
10-C	SI	WP	-	400	27.6
10-C	SI	WP	-	400	29.9
10	SI-CNS	WP	-	400	27.5
10-C	SI-CNS	WP	-	400	29.1

Note: GC, Glauconite Content; T.T, Testing Type; P.M, Preparation Method; σ_s, swelling pressure; σ_{vc}', consolidation stress; φ_{res}', residual friction angle; SS, SI, SI-CNS, direct shear Soil to Soil, Soil to Interface and Soil to Interface Constant Normal Stiffness tests respectively; C, Crushed; WP, DP, Wet and Dry Pluviation respectively.

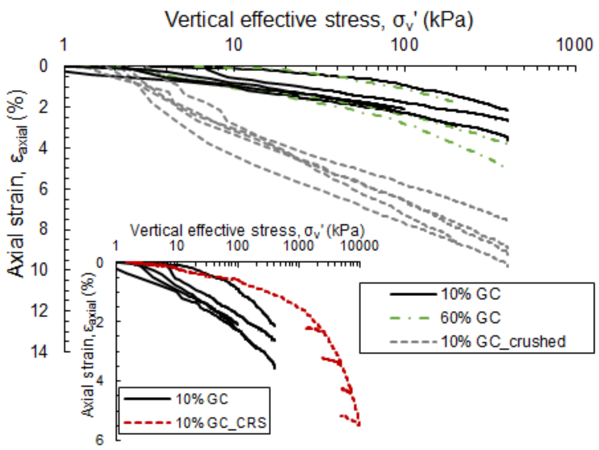

Figure 3. Vertical effective stress, σ_v', against axial strain, ε_{axial}, during consolidation and CRS testing of 10% GC, 60% GC and 10% GC crushed glauconite samples.

The 10% and 60% GC samples exhibit similar trends with Toyoura sand and show peak resistance and dilative behaviour which is, however, hampered at higher glauconite contents. In contrast, the crushed glauconite sand is fully contractile with no strain softening behaviour and with shear stress ratios that remain well below the corresponding values for the

10% and 60% GC sand at small displacements. In contrast, at higher displacements, the shear strength ratios of all samples approach an almost unique value.

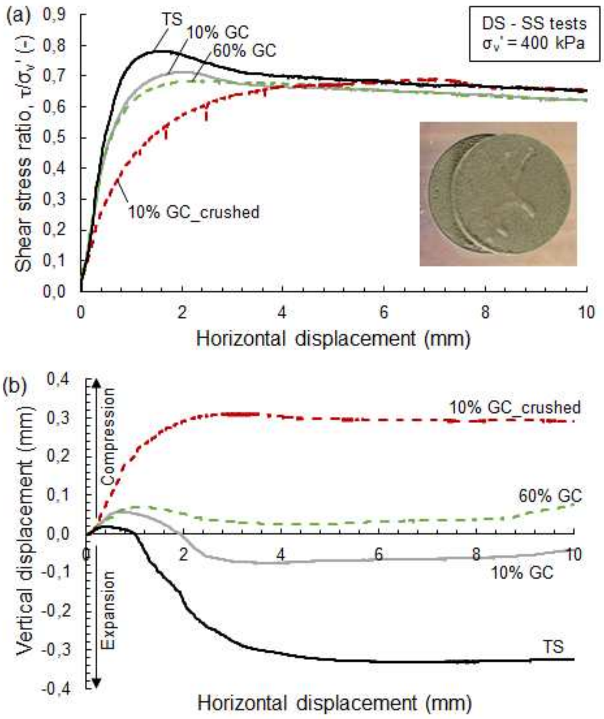

Figure 4. DS-SS test results on 10% GC, 60% GC and 10% GC crushed glauconite samples: (a) shear stress ratio, τ/σ_v' and (b) vertical displacement against horizontal displacement.

The residual internal friction angles, φ_{res}', obtained from the direct shear soil to soil tests are displayed as function of the glauconite content in Figure 5(a). Similarly, the soil to steel residual interface friction angles, δ_{res}, for both the CNL and CNS interface direct shear tests are plotted in Figure 5(b). The residual angles are defined at the horizontal displacement of 10 mm. Figure 5 also includes data from different dense glauconite sands in the literature. A direct comparison of the data is hindered by differences in the testing specifications and procedures (e.g., interface roughness, sample preparation, fines content, etc). Nevertheless, it can be observed that the relationship between the residual internal/interface friction angle and glauconite content can be approximated by a straight line. The δ_{res} decrease with increasing glauconite content. The rate of this decrease for φ_{res}' is minimal and can be considered negligible or very low. By using the best fit lines to the experimental data as shown in Figure 5, the values of the ratio of the interface friction angle to the angle of internal friction, $\delta_{res}/\varphi_{res}'$, for two extremes of glauconite contents, 10% and 100%, is 0.82 and 0.72, respectively. Note that for the highest glauconite content, the $\delta_{res}/\varphi_{res}'$ ratio is in close agreement with the design approach of accepting for all pile materials an interface friction angle that equals 2/3 of the internal friction angle.

It should be noted that the relationship between internal/interface friction angle and glauconite content illustrated in Figure 5, is indicative for glauconite sands at natural state or for degraded glauconite sands for which crushing in the field or pre-crushing in the laboratory has not resulted in a clay-dominated soil fabric. A clay-like response might well be the case for the ring shear tests performed on manually pre-crushed glauconite sand in the study of Quinteros et al. (2023). These tests exhibited low values of δ_{res} as shown with the arrows in Figure 5(b) and are excluded from the derivation of the best-fit line in the same figure. Consistency limits for these tests have not been reported. Bear in mind that sieving tests performed in this study before and after interface testing on selected samples indicated negligible crushing as result of the shearing process. It is also worth noting that shear-induced crushing at the interface is not visually observed after removal of the soil sample from the apparatus at the end of testing.

5 DISCUSSION

During pile driving, a glauconite sand can transform into a fine-grained soil as result of particle crushing, leading to an increase in shaft resistance and a higher risk of early pile driving refusal (De Nijs et al., 2015). For the calculation of shaft capacity in monopile design, knowledge of the interface friction angle is important. For sands containing glauconite, reliable determination of the interface friction angle in the laboratory is challenging as this requires replicating the degradation condition of the material in the soil-steel interface in the field. The level of degradation depends on several factors such as effective stress level, degree of particle crushing and origin of the material. A way forward can be to determine δ_{res} for two extremes of the in-situ conditions. That is: (i) testing of the material as collected from the field capturing the global response and (ii) testing of the same material after being subjected to extensive (full) degradation to capture the local (soil-pile) response. For the latter, it is important to develop a unified framework for inducing material degradation in lab environment.

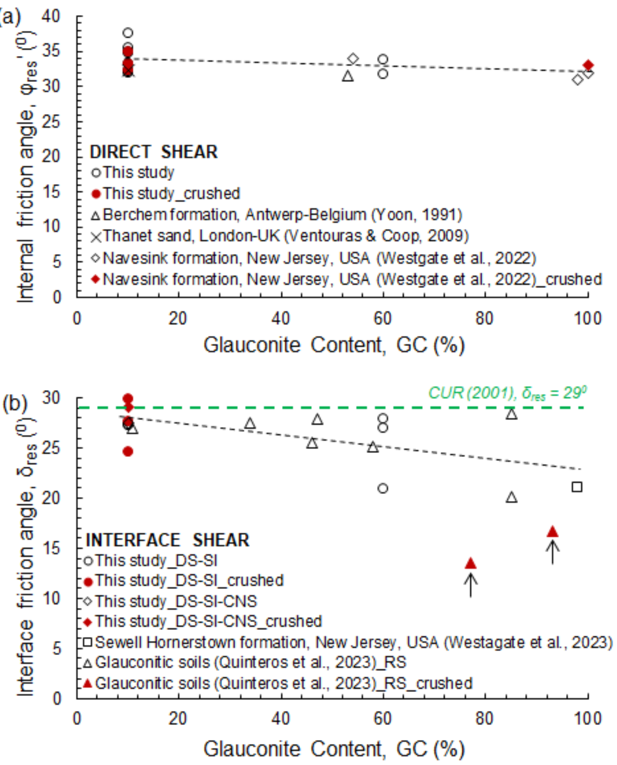

Figure 5. (a) Residual internal, φ_{res}', and (b) interface friction angle, δ_{res} as a function of glauconite content; comparison between glauconite sands in this study and literature.

Currently, in laboratory practise, different methods are employed to intentionally degrade glauconite sands for replicating soil-pile interface conditions more realistically: (i) dispersion in water, (ii) ball milling, (iii) Proctor testing and (iv) hand grinding with mortar and pestle. Westgate et al. (2023) concluded that the dispersion in water creates the greatest degradation resulting in a significant increase in clay fraction and plasticity. In the absence of experimental data and in design practice, the residual interface friction angle, δ_{res}, can be obtained from charts relating δ_{res} with mean particle size D_{50} - for the case of sands - and plasticity index, PI - for the case of clays - as shown in Figure 6 (Jardine et al., 2005). The applicability of these charts for glauconite sands with different degrees of degradation is yet to be evaluated. It is therefore important that researchers testing glauconite report, together with the results, the particle size distribution and Atterberg limits of the tested material and define guidelines for the performance of these tests. In addition, when site specific testing is not possible, CUR (2001) recommends the use of a residual interface friction angle of $\delta_{res} = 29^0$. As can be seen in Figure 5(b) and Figure 6, the selection of $\delta_{res} = 29^0$ is a rather conservative choice for sands with glauconite. Furthermore, degradation of glauconite sand leads to an increase in PI. Figure 6 indicates, despite the large scatter in the data, that the general trend is a decrease in δ_{res} with PI. It can thus be concluded that in driveability assessment calculations, an accurate determination of the residual interface friction angle along the pile shaft becomes less relevant since the adoption of a $\delta_{res} = 29^0$ will result in a more conservative calculation of soil resistance to driving, provided that an SRD model for sands is used. What becomes more important in driveability assessments is the selection of the modelling approach for glauconite sands. Perikleous et al. (2023) have shown that the behaviour of glauconite soils during driving is better modelled using a clay Soil Resistance to Driving, SRD, model.

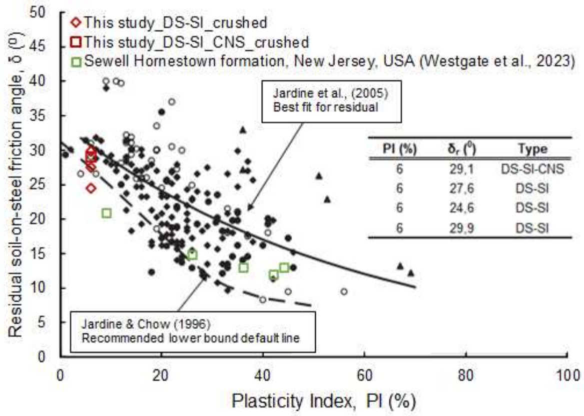

Figure 6. Interface friction angle, δ_{res} as a function of plasticity index, PI (modified after Jardine et al., 2005).

6 CONCLUSIONS

This paper presents experimental data on a glauconite sand from Belgium. A series of soil-soil and soil-interface tests on dense sand samples were performed considering different glauconite contents and stress levels on both natural and degraded (crushed) samples. The results suggest that crushing of glauconite alters the material response leading to a higher compressibility and contractive tendency in shearing. A decrease of the interface friction angle is observed with increasing glauconite content. The ratio of the interface friction angle to the angle of internal friction, for the plate roughness in use, ranges from 0.82 for the 10% GC sand to 0.72 for the 100% GC sand. For all conditions tested, the values of the interface friction angle, δ_{res}, are about equal or lower than the value of $\delta_{res} = 29^0$ recommended for the design of monopiles, indicating that the adoption of $\delta_{res} = 29^0$ for glauconite sands is conservative.

Data in literature highlight that the factor that exerts the most pronounced influence on the response of glauconite sands is the level of degradation of the material in the laboratory and the extent to which this replicates the conditions in the field. Developing a unified framework for testing glauconite sands in the laboratory is of high importance. To contribute towards this effort, any laboratory testing program on glauconite sands should include, as a minimum, glauconite content determination, Atterberg limits, particle size distribution and a detailed description of the applied material degradation method.

AUTHOR CONTRIBUTION STATEMENT

M. Konstantinou: Writing - Original draft, Supervision, Conceptualization, Investigation, Visualization. **A. R. Piedrabuena, N. Hellebrekers**: Conceptualization, Investigation, Writing - Reviewing and Editing. **A.S. Elkadi**: Writing- Reviewing and Editing. **M. Mento, K. Gavin**: Conceptualization, Writing- Reviewing and Editing.

REFERENCES

Belotti, R., Fretti, C., Ghionna, V.N. and Pedroni, S. (1992). Compressibility and crushability of sands at high stresses. Calibration Chamber Testing. *Proceedings of the 1st International Symposium on Calibration Chamber Testing*. Postdam, NY, Elsevier, pp. 79-90.

CUR (2001). Bearing capacity of steel pipe piles. *Report 2001-8 Centre for Civil Engineering Research and Codes*, Gouda, The Netherlands.

De Nijs, R.E.P., Kaalberg, F.J., Osselaer, G., Couck, J. and van Royen, K. (2015). Full-scale field test pile drivability in Antwerp. *Geotechnical Engineering for Infrastructure and Development*, pp. 1085-1090.

Jardine, R.J., Chow, F.C., Overy, R.F. and Standing, J.R. (2005). ICP design methods for driven piles in sands and clays. Thomas Telford, London.

Mao, W., Hamaguchi, H. and Koseki, J. (2020). Discrimination of Particle Breakage below Pile Tip after Model Pile Penetration in Sand Using Image Analysis. *International Journal of Geomechanics*, 20(1). https://doi.org/10.1061/(ASCE)GM.1943-5622.0001535

Odin, G.S. and Matter, A. (1981). De glauconite origine. *Sedimentology*, 28: pp. 611-641.

Peng, Y., Lui, H., Ding, X., Deng, X. and Wang, C. (2021). The detailed particle breakage around the pile in coral sand. *Acta Geotechnica*, 16, pp. 1971-1981.https://doi.org/10.1007/s11440-020-01089-2.

Perikleous, G., Meissl, S., Diaz, A.T., Stergiou, T. and Ridgway-Hill, A. (2023). Monopile installation in glauconitic sands. *Proceedings of the 9th International Offshore Site Investigation and Geotechnics Conference*. Society of Underwater Technology, pp. 132-138(7). https://doi.org/10.3723/JBWL5180

Piedrabuena, A. R. (2024a). First step into the calibration chamber pile tests with glauconitic sands. On the behaviour of the sand fraction from glauconitic sand of the Kattendijk formation in Antwerp, Belgium. Master thesis. Civil Engineering & Geosciences, TU Delft. https://resolver.tudelft.nl/uuid:c0e89fe5-bc26-4f68-a965-5017ab58bc9c

Piedrabuena, A. R., Mento, M., de Lange, D. A. and Flessati, L. (2024b). How do deal with glauconite sands in physical models. *Proceedings of the 5th European Conference on Physical Modelling in Geotechnics*, Delft, the Netherlands. https://doi.org/10.53243/ECPMG2024-20

Quinteros, V.S., Westgate, Z., Vinck, K., Dantal, V., Lindtorp, A. and Toma, M.A. (2023). Interface friction angle of glauconite sands for pile design. *Proceedings of the 9th International Offshore Site Investigation and Geotechnics Conference*. Society of Underwater Technology, pp. 155-161(7). https://doi.org/10.3723/LKRI8285

Van Alboom, G., Maertens, J., Dupont, H. and Haelterma, K. (2012). Glauconite Holding Sands, *Géotechnique*, pp. 32-37.

Ventouras, K. And Coop, M. R. (2009). On the behaviour of Thanet sand: an example of an uncemented natural sand. *Géotechnique,* 59(9), pp. 727-738. https://doi.org/10.1680/geot.7.00061

Westgate, Z.J., DeGroot, D.J., McMullin, C., Zou, Y., Guo, D., Van Haren, S., Beemer, R.D., Zeppilli, D., Miller, K.G. and Browning, J.V. (2023). Effect of degradation on geotechnical behavior of glauconite sands from the U.S. Mid-Atlantic Coastal Plain. *Ocean Engineering,* 283. https://doi.org/10.1016/j.oceaneng.2023.115081

Westgate, Z.J., McMullin, C., Zeppilli, D., Beemer, R.D. and DeGroot, D.J. (2022). Geological and Geotechnical Characteristics of Glauconite Sands. *Proceedings of the Geo-Congress 2022.* https://doi.org/10.1061/9780784484036.012

Yoon, Y.W. (1991). Static and Dynamic Behavior of Crushable and Non-Crushable Sands. Manuscript submitted to the Faculty of Applied Science of State University of Ghent for the award of Doctor’s degree in Applied Science.