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SICMOG: Site Characterization and Monopile Installation in Glauconite Soils

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ABSTRACT: The rapid expansion of the offshore wind industry into regions with complex geomaterials, such as glauconite sands, presents significant geotechnical challenges. Glauconite sands, commonly found in shallow marine environments, are characterized by their susceptibility to particle crushing and complex shearing behavior, which can lead to high soil resistance and pile driving refusal during monopile (MP) installation. Current drivability prediction models often fail to account for these unique behaviors, leading to uncertainties and inefficiencies in offshore wind farm planning and construction. This research initiative, led by Deltares, seeks to address these challenges through a comprehensive 3-year program combining advanced experimental and numerical modeling. The project involves soil characterization via laboratory tests, calibration chamber testing, and Cone Penetration Test (CPT) simulations. The development of constitutive and drivability models tailored for glauconite sands aims to improve MP installation predictability and optimize offshore operations. The research will also establish soil classification guidelines for glauconite deposits, addressing gaps in current practices. The project's findings are expected to provide actionable insights for both the scientific and industrial communities, enhancing the design and installation of offshore monopiles (MPs) in glauconite-bearing soils.

Keywords: Monopile installation, drivability, site investigation, glauconite

1 INTRODUCTION

As the offshore wind industry rapidly expands, new regions are being utilized for the development and installation of wind farms. A significant concern is the risk posed by glauconite sand deposits. These geomaterials are widespread globally, including the US East coast and the southern part of the North Sea, where offshore wind farms are currently under development and construction. Banerjee et al. (2020) reported several glauconite occurrences in the formations of the Paleogene period. Glauconite sand consists of green, sand-sized grains composed primarily of the mineral glauconite, along with other rounded mineral components such as quartz, feldspar, and mica.

Glauconite soils present relevant challenges during monopile (MP) installation due to their susceptibility to particle crushing at relatively low stress levels and their complex response to shearing. The crushing of glauconite particles and the subsequent increase in fines content have been associated with high monopile wall shear resistance and MP driving refusal. Specifically, the combination of high tip resistance - largely from coarse-grained glauconite during initial crushing - and high shaft resistance - mostly from degraded fine-grained glauconite - results in significant soil resistance during driving operations. Figure 1 illustrates examples of crushed glauconite from MP driving. Recent experience in driving monopiles (MPs) in the North Sea confirms that current prediction of drivability in glauconite sands can underestimate driving resistance and may lead to refusal, even with low (5-20%) glauconite content (Perikleous et al., 2023). Understanding the behavior of glauconite materials during MP installations is challenging due to limited data availability. Calibration of MP driving prediction models for these geomaterials is therefore highly uncertain. Consequently, there is a pressing need for knowledge and model development to enhance the accuracy of MP drivability predictions for glauconite sands. In addition, there is a strong demand for soil classification guidelines tailored to glauconites as this material has characteristics that may not be adequately addressed by the existing classification systems for field and lab testing.

2 STATE OF THE ART

Challenges related to the construction of civil infrastructures on glauconite sand were already known from the construction of the ring roads around Antwerp in Belgium, where piles and sheet piles encountered driving refusal (De Nijs et al., 2015). Glauconite soils pose known geohazards also for offshore geotechnics. Investigations at offshore wind development sites in the US and Europe have revealed the presence of glauconite in soils (Perikleous et al., 2023). However, information regarding the characterization and MP installation in glauconite soils remains limited. Experience from offshore MP installations is insufficient to provide a comprehensive framework for minimizing uncertainties in soil characterization and MP driving predictions for glauconite soils.

Recently, some researchers have published information to understand the engineering behavior of glauconites (Geyin et al., 2023). Detecting and understanding the behavior of glauconite materials in an offshore environment is challenging due to the limited availability of data. In this context, in-situ testing, especially Cone Penetration Testing (CPT), is employed to identify glauconite soil. Significant excess pore pressures (u_2) ranging from extreme positive values to extreme negative values are detected for these types of materials, as well as high friction ratios in presence of large cone resistance. Although Cone Penetration Testing (CPT) is recognized as an effective tool for soil identification, glauconite materials are frequently classified as silty sand, leading to considerable uncertainties regarding soil behavior. Conversely, laboratory testing using standard procedures may not capture the true in-situ behavior of glauconite due to its sensitivity to sampling and specimen preparation methods.

Rodríguez (2024) performed calibration chamber tests at Deltares using soil samples provided by IQIP with low-glauconite content (~13%) taken from a shallow (<10m) allogenic deposit in Antwerp, Belgium. The study included one monotonic and cyclic CPT to check the homogeneity of the soil model, one jacked and one impact-driven closed-ended pile, and laboratory testing for soil characterization. The crushing mechanism observed at the pile tip was the same for both jacked and impact-driven installations.

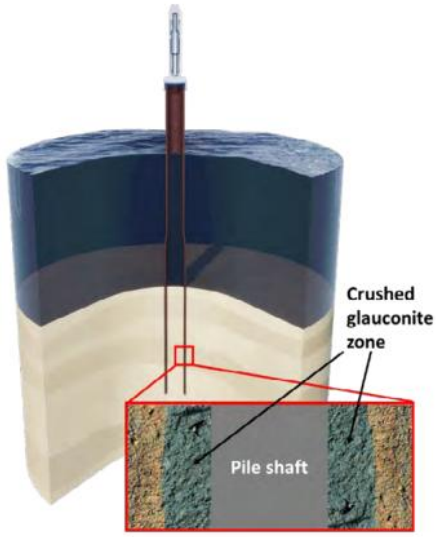

Figure 1: Creation of crushed glauconite sand shear zone adjacent to MP shaft (after Perikleous et al., 2023).

Currently, there is only limited knowledge on site characterization and drivability models for this type of materials (Perikleous et al. 2023; Westgate et al., 2023; DeGroot et al., 2023). This marks the starting point for the proposed research, in which the aim is twofold: (1) improving drivability modeling for monopiles and, (2) site characterization of glauconite deposits.

3 SICMOG'S RESEARCH PROGRAMME

3.1 Main research goal

The primary objective of this project is to minimize uncertainty in the characterization and monopile driving predictions in glauconite sands. The project will concentrate on developing (and validating) a Soil Resistance to Driving (SRD) model (including driving parameters, such as quake and damping values) and a constitutive model suitable for glauconite soils.

To achieve this goal and gain a comprehensive understanding of glauconite soil behavior during MP installation, an extensive range of experimental data will be collected. This data will come from analyses conducted on soil samples obtained from two distinct geological formations in Belgium, characterized by soils with varying glauconite content, maturity, and grain size distribution. The first material is sourced from the shallower, younger *Kattendijk* formation (allogenic), while the second is from the deeper, older *Berchem* formation (authigenic). Comprehensive site investigation, including laboratory testing and sample characterization will be executed during the project on samples taken from the above two geological formations in Belgium. Granulometry, carbonate, and glauconite content for the Antwerp area have already been documented in recent work by Deckers et al. (2023), providing preliminary insights into expected site characteristics.

This research will encompass Cone Penetration Tests (CPT) and lab-scale MP installations within chamber tests, and extensive soil element tests. These combined efforts will facilitate a thorough investigation into the behavior of glauconite soils across various conditions and scenarios, including variations in grain size distribution, fine content, glauconite content, relative density and confining stress. The behavior will consistently be compared against well-characterized sands that lack glauconite minerals. This dataset will be used to select and calibrate a drivability model, which includes SRD model.

Moreover, to facilitate applications in full-scale installations, some partners within the project will use their expert knowledge – based on available experiences of offshore MP installation in glauconite sediments, exhibiting similar behavior, such as high resistance to driving and particle crushing – to confirm the suitability of the drivability model and provide suitable "range" of input parameters for this type of material. The drivability model, constitutive model and classification guidelines can be used by the scientific community to further improve and validate drivability and constitutive models for glauconite sands, and by the industry to optimize offshore operations.

The project will be managed by Deltares, and it is structured in 4 Working Packages (WP), as outlined below:

<u>WP1 – Element Testing</u>

WP1 includes the execution and interpretation of soil element tests. In this WP, comprehensive laboratory element tests will be performed to better understand the geotechnical properties of glauconite soils, including their strength, stiffness, compressibility and deformation characteristics. Mineralogy and crushability will also be evaluated due to their influence on soil behavior during pile installation. The soil element tests will be performed on samples taken from both the authigenic and allogenic formations in Belgium.

A broad parametric study of soil characteristics will be undertaken to systematically evaluate the critical parameters that affect the behavior of glauconite soils, especially in relation to MP installation. In the lab-testing phase, key parameters such as glauconite content, grain size distribution, relative density, confining pressure, and fine content will be varied. The experimental test data obtained in WP1 will be utilized to:

(A) Provide recommendations and guidelines for characterization of glauconite sands:
- Guidance in handling glauconite material for lab testing.
- Guidance on defining experiments for WP2 based on the critical parameters identified in WP1.

(B) Calibrate and validate the following:
- Drivability model in WP3.
- Numerical models in WP4.

<u>WP2 – Calibration-Chamber Testing</u>

WP2 includes the execution and interpretation of Calibration Chamber testing (CC) to model Cone Penetration Tests, CPTs (WP2a) and simulate MP driving scenarios at lab scale (WP2b). While the exact range of monopile geometries will be finalized after the project kick-off, the study will focus on monopiles typical of offshore wind foundations, selected based on industry relevance and partner input.

Calibration Chamber tests will focus on simulating the stresses and interactions that occur during CPT and MP penetration in glauconite sands. These tests aim to replicate field conditions and enhance our understanding of the behavior of glauconite soils during installation processes. The calibration chamber apparatus is illustrated in Figure 2, and it has an approximate diameter of 90 cm, with a variable height ranging from 100 to 180 cm, depending on the number of rings used in the setup. The system allows for the application of an overburden pressure of up to approximately 200 kPa, replicating in-situ conditions equivalent to 20 m below the seabed.

It is worth noting that, for what concern CPT modelling, Deltares has a new apparatus – the half-Calibration chamber – illustrated in Figure 2, which allows the penetration of half-probes and monitors displacements/strains in the soil through the glass.

This apparatus has the size of approximately 100 x 90 x 80 cm (length, height, width) and allows a half-CPT probe to penetrate adjacent to the front glass, as well as the execution of mini-CPTs in the middle of the chamber. This setup will be used in this project to study glauconite sands' behavior during CPT and mini-MP installations, complementing the full-size calibration chamber tests and supporting numerical model validation in WP4.

The number and characteristics of the CC tests will be determined after WP1, once the results from the element tests provide insights into the critical parameters influencing glauconite soil behavior. Ideally, the aim is to identify the turning point at which material behavior deviates significantly between glauconite sands and clean sand, specifically under various conditions, including stress levels, glauconite content, and relative densities. The experimental test data obtained in WP2 will be utilized to:

(A) Provide recommendations and guidelines for characterization of glauconite sands, specifically, guidance in execution of lab testing to resemble stresses developed in the field during CPT or MP penetration.

(B) Calibrate and validate the following:
- Drivability model in WP3.
- Numerical models in WP4.

<u>WP3 – Drivability analysis</u>

Drivability analysis is essential for risk management in optimizing MP driving operations, particularly in challenging soil conditions like glauconite. Various SRD models are available for wave equation analysis in MP driving, each offering a specific level of approximation and requiring corresponding input parameters. Calibrating the most suitable SRD and driving parameters for precise predictions in glauconite soils ensures effective and reliable predictions of monopile drivability.

WP3 focuses on the calibration/validation of a drivability model based on industry-standard wave equation models. While MPs differ from slender piles in terms of soil-structure interaction, existing SRD models can still be applied with appropriate parameter adjustments. This study will evaluate their applicability to glauconite sands and explore refinements as needed.

Wave equation analysis is a widely used method in geotechnical engineering for analyzing pile drivability (e.g. Goble et al., 1981). It models the pile-soil interaction as a dynamic system, where the impact of the pile hammer generates stress waves that propagate through the pile and surrounding soil. In this study, aspects of wave equation analysis models, such as SRD models, and driving parameters (i.e., quake and damping) will be optimized for installation of MP in glauconite soils. While the 1D wave equation approach is well-established for slender piles, its applicability to large-diameter MPs requires consideration of additional effects such as radial expansion and energy losses, particularly in thin-walled sections.

The project will focus on a comprehensive parametric study of soil characteristics influencing MP drivability, including (not limited to) grain size distribution, glauconite content, relative density and confining pressure.

A major advantage of the CC tests is that they will include both Cone Penetration Tests (CPTs) and lab-scale monopile installations (jacked and impact-driven installations). This allows for a direct comparison between the measurements obtained from the CPTs and the lab-scale drivability assessments, which is crucial for identifying the relevant parameters that a drivability model should incorporate.

Figure 2: The Deltares calibration chamber (CC) test devices: (left) cylindrical CC and (right) half-CC with glass.

It is worth noting that deriving drivability parameters suitable for offshore monopile installations directly from lab-scale monopile installations in CC tests is quite challenging. Therefore, the work in this package is divided into two parts (WP3a & WP3b). WP3a will focus on defining the drivability model and highlighting the important factors that the model should take into account. The validation aspect will occur in WP3b, where partners within the project will use their expertise - based on their experience with XXL monopile installation in glauconite soils - to confirm the suitability of the drivability model and provide calibrated “range” of drivability input parameters for offshore installations.

<u>WP4 – Numerical modelling</u>

To further advance our understanding on the behavior of glauconite soils, numerical modelling, which includes the development of a constitutive model and large deformation numerical simulations is envisioned in WP4. Specifically, in WP4a the selection of potential constitutive models capable of accurately describing the behavior of glauconite will be explored. For this, the project will investigate existing classes of constitutive models available in literature that can be suitable to simulate the behavior of glauconite soils. Model performance will be evaluated by comparing results against laboratory test data obtained in the experimental campaign (WP1). If no suitable model is found, an existing framework will be refined to incorporate relevant features of glauconite behavior.

In WP4b, the constitutive model identified or developed in WP4a, will be used to simulate the chamber test data generated during the experimental campaign performed in WP2. Large deformation modelling of CC tests, based on Material Point Method (MPM), will be performed to simulate penetration problems. The MPM has been used to simulate standard CPT (e.g., Martinelli and Galavi, 2021, 2022; Martinelli and Pisano, 2022), jacked piles (e.g., Phuong et al., 2016), and suction piles (e.g., Martinelli et al., 2020; Stapelfeldt et al., 2021), under quasi-static conditions. Additionally, it has been applied to simulate impact-driven piles (e.g., Al-Kafaji, 2013; Galavi et al., 2019; Galavi and Martinelli, 2024) and vibro-driven piles (e.g., Galavi et al., 2017) under full dynamic conditions.

An example of the CPT simulation in sand is depicted in the Figure 3, where not only the cone resistance is in good agreement with the values of the experimental data, but also good agreement is met in terms of horizontal and radial displacements.

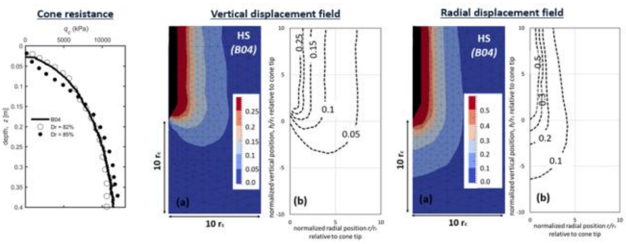

Figure 3: Chamber CPT simulation in sand. Comparison between numerical simulations using the Material Point Method and the experimental data (Martinelli and Galavi, 2021).

This simulation process aims to validate the effectiveness of the selected constitutive model in capturing the behavior of glauconite under controlled laboratory conditions. By comparing the simulated results with actual chamber test data, the project will assess the accuracy and reliability of the constitutive model in representing glauconite behavior, as well as the predictive capabilities of the numerical approach to reproduce the observed behavior, starting with quasi-static penetration problems.

Demonstrating the ability of the MPM numerical model to replicate CPT tests in glauconite soils will be a significant advancement in site characterization. Such validation will not only enhance our understanding of the soil's behaviour under various conditions but also lay the foundation for improving the accuracy of pile driving predictions.

WP overall interaction

The interactions between the different working packages are shown in Figure 4. The planned duration of this project is 34 months. The start of the project is on the 1st of January 2025 and the project end date is envisioned for the 31th of October 2027.

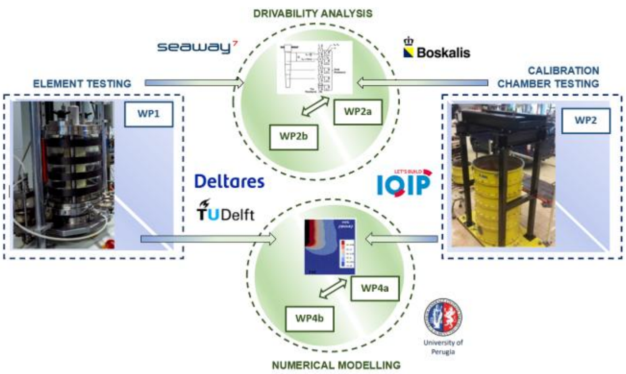

Figure 4: Organization of project tasks and interaction among WPs.

4 CONCLUDING REMARKS

This paper has outlined the motivation, objectives, and methodology of SICMOG, an ongoing research initiative aimed at addressing the unique challenges of glauconite sands in offshore MP installations. Scheduled to commence in January 2025, the 34-month project will be led by Deltares in collaboration with academic and industry partners. Central to this effort is the integration of advanced experimental and numerical modeling approaches, including extensive laboratory testing, calibration chamber tests, and the development of tailored constitutive and drivability models.

This initiative is poised to significantly advance the current state of knowledge and industry practices for offshore foundations in challenging geomaterials, contributing to the broader efforts of cost reduction and efficiency in renewable energy infrastructure development. Findings will be disseminated through peer-reviewed journal articles and conference presentations (e.g. at ISFOG, OSIG), with the focus on soil characterization, calibration chamber testing, drivability modeling, and numerical simulations.

AUTHOR CONTRIBUTION STATEMENT

Mario Martinelli: Writing- Original draft. **Other Authors**: Reviewing and editing.

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