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Geo Automation and Integration of Wind Turbine Jack-up Installation Data

Can Mollaibrahimoglu*
Cadeler A/S, Denmark

Erick Kencana, Okky Purwana
Geo Oceanics, Singapore

**can.mollaibrahimoglu@cadeler.com (corresponding author)*

ABSTRACT: Operation of a wind turbine installation jack-up for a wind farm construction campaign requires an extensive engineering and operation planning. Given the significant number of wind turbine locations typically involved in a wind turbine installation campaign, the processing of substantial amount of geotechnical information needed for engineering analyses and the development of mitigation strategy for geotechnical risks is consequently time consuming and can be resource-intensive. Given the projected increase in wind turbine installation projects in coming years, optimizing early-phase geotechnical and jack-up assessment is crucial to efficiently determine the jack-up vessel's operability and assess potential geotechnical risks.

Furthermore, the invaluable jacking data is often not fully consolidated post-installation making it difficult to access key lessons learned for planning future installation campaigns under similar site conditions.

This paper discusses the implementation of geo automation and integration, leveraging advancements in geotechnical predictive frameworks and data analysis. It demonstrates the efficient processing of geotechnical site investigation data, assessment of spudcan performance and integration of actual jacking data for improving the reliability of penetration predictions to enhance geotechnical risk mitigation and improve operational efficiency for future campaigns.

Keywords: jack-up; offshore wind farm; geotechnical risks;

1 INTRODUCTION

In contrast to the single-location assessment typically required for hydrocarbon exploration, which focuses on a specific location, the geotechnical risk assessment of Wind Turbine Installation (WTI) jack-up vessels in offshore wind farm (OWF) construction is significantly more challenging. This is due to the vast size of wind farms, the multiple locations involved and the potential variability in site characteristics across the project area.

Given the large spatial extent, the seabed conditions can vary greatly across a wind farm site resulting in diverse geotechnical risk with varying levels of severity. While site categorisation can help optimise the scope of engineering assessment, some critical details may not be adequately captured if the site is geologically complex or if the categorisation lacks sufficient resolution.

The processing, filtering and interpretations of the substantial amount of the geotechnical data collected from wind farm sites are both time-consuming and resource-intensive. Deriving design geotechnical parameters from the processed data requires not only a high level of expertise but also consistency across the entire wind turbine installation locations at the wind farm.

Moreover, the early-phase WTI jack-up suitability studies often face limitations in data availability and resources, which increases the uncertainty and risk in subsequent engineering stages. For geotechnically complex sites, balancing the available resources with the need to identify major risks is particularly challenging. In such cases, a full-assessment approach is often inevitably taken to mitigate the potential for costly implications arising in the later stage of the project.

2 NEED FOR PARADIGM SHIFT

2.1 Current Practice

Despite the significantly larger scale, the current practice of WTI jack-up geotechnical risk assessment resembles the conventional single-location approach extended to cover multiple locations. Typically, site categorisation is employed based on the similarity in soil profiles, water depth or other characteristics to streamline the otherwise time-consuming engineering analyses. Manual processing of the geotechnical data combined with spreadsheet-based analysis tools remains the preferred method. This approach allows for effective identification of data gaps and facilitates the need for applying geotechnical judgement when required at any stage of the calculation process.

While this traditional approach is widely used and deemed effective for managing the risks, the reliance on manual process can pose hindrance to timely decision-making particularly if multiple candidate WTI jack-ups or various assessment methods need to be considered in a wind farm screening exercise.

2.2 Untapped Potentials

Given the projected increase in wind turbine installation projects in coming years and advancement in geotechnical predictive framework, a paradigm shift is crucial to achieving more efficient geotechnical risk assessments and enhanced risk mitigation for WTI jack-up installations. This shift should focus on leveraging digital tools, data integration, and semi-automation of analysis processes to streamline the assessment process, maintain consistency, reduce uncertainties, and ultimately improve decision-making throughout the project lifecycle.

Accessibility to potential geotechnical risk insights is crucial for effective risk mitigation. The risk assessments of WTI jack-ups can be significantly enhanced if visualisations of patterns or trends inferred from the interpreted data are made available through digitalisation. When presented in the traditional format, such information can become overwhelming and counter-productive hindering the ability for making well-informed decisions.

Furthermore, post-installation data from sites with similar characteristics and any lessons-learned are often not fully leveraged for future installation campaigns. Such invaluable information can be more accessible for future planning if consolidated in a digital format.

3 ENHANCED APPROACH FOR INSTALLATION RISK ASSESSMENT

3.1 Overview

A new framework has been developed to enable semi-automation, integration and centralisation of information from site surveys, pre-installation engineering analyses and field observations within a digital platform. The primary objective of this framework is to improve risk identification and risk mitigation assessments while optimising engineering resources. The framework is built around three key elements, i.e. geo-automation, geo-integration and geo-repository, as described schematically in Figure 1. It is implementable through a graphical user interface integrated with a python-based calculation engine.

The geo-automation element streamlines the process of data preparation, design parameters derivation and repetitive analytical calculations allowing geotechnical engineers to focus on critical tasks as elaborated in Section 4. Despite the semi-automation, the role of geotechnical engineers remains essential in reviewing input information, exercising judgement, addressing gaps and performing QAQC on the output.

The framework also includes a comprehensive toolset for conducting critical spudcan analyses enabling both comprehensive and quantitative risk assessment through its geo-integration capabilities. Additionally, the geo-repository feature organises key post-installation data, which can be leveraged to improve existing ground models and risk mitigation strategies for future installation campaigns.

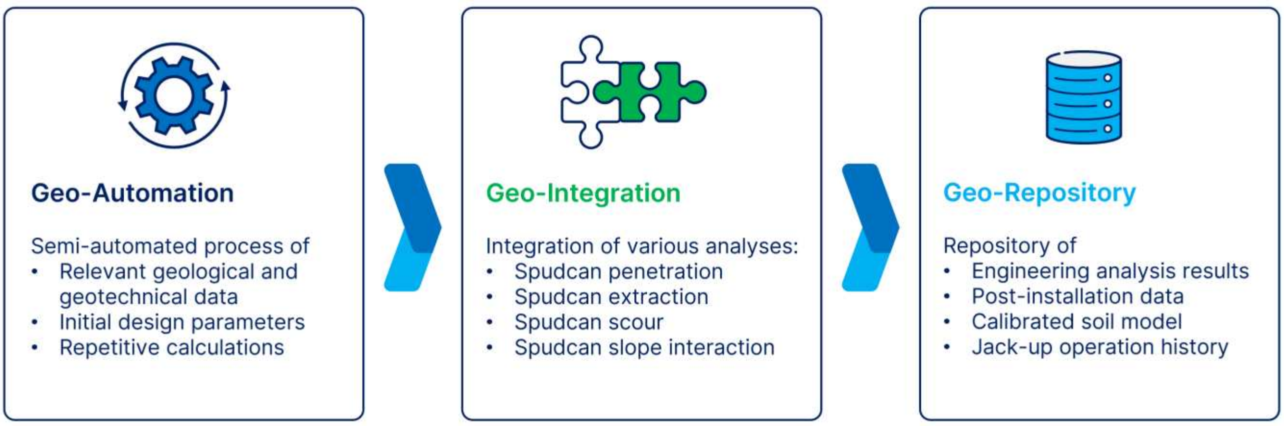

Figure 1. Overview of new framework for WTI jack-up geotechnical risk assessment

3.2 Key Objectives

The new framework aims to achieve the following objectives:

- Transparent, easily accessible, significantly faster and resource-efficient process compared to the conventional approach
- Enhanced decision-making through insightful and interactive visualisations
- Integrated post-installation data improving safety and efficiency of future installation campaigns

Despite the semi-automation, key control points are included for specialists to make manual decisions before advancing to the next calculation stage, ensuring accuracy and quality throughout the process.

4 CASE STUDY

The implementation of the framework is demonstrated for a retrospective geotechnical risk assessment of a past WTI jack-up installation campaign for an offshore wind farm (OWF) construction with a large quantity of Wind Turbine Generator (WTG) locations. This showcases the enhanced framework's efficiency and the more holistic insights for making well-informed engineering decisions for mitigating installation risks.

4.1 General Site and Jack-up Characteristics

The offshore wind farm site consists of 132 wind turbine installation locations including 18 jacking trial sites and covers an area of approximately 500 km^2. The water depth varies from approximately 40m to 60m across the site.

Over 450 CPT and sampling boreholes combined were supplied with 3-4 boreholes typically available for each WTG location. Cadeler's O-Class jack-up unit was deployed to install the wind turbines. The WTI jack-up consists of six lattice legs with a total leg length of 105m and a 11m nominal spudcan diameter.

4.2 Swift Site Data Overview

In this framework, the WTG layout, CPT data, and sampling borehole information, along with their distribution within the OWF can be plotted directly from an input file in AGS format eliminating the need for manual processing and plotting. Selected geophysical data such as bathymetry and geological formation boundaries can be imported from supplied GIS data. This automated overview can quickly identify any gaps in geotechnical data required for a complete risk assessment at the individual WTG locations.

Individual CPT and/or borehole profiles for specific cross-sections are displayed providing a quick overview of soil profile variations and anticipated general leg penetration behaviour at the individual WTG locations. Suitable design CPT profiles for each jacking location can be identified and further processed, if necessary, for interpreting design parameters at later stages. Additionally, plots of design CPT depths offer insights into the adequacy of borehole data for subsequent leg penetration analysis.

Other site characteristics, such as sub-seabed lateral variation and water depth variation at the jacking locations, can be interactively visualised in graphical format. The latter enables preliminary insights into the jack-up unit's leg length utilisation and elevated performance. An example overview of key site characteristics within the OWF is shown in Figure 2.

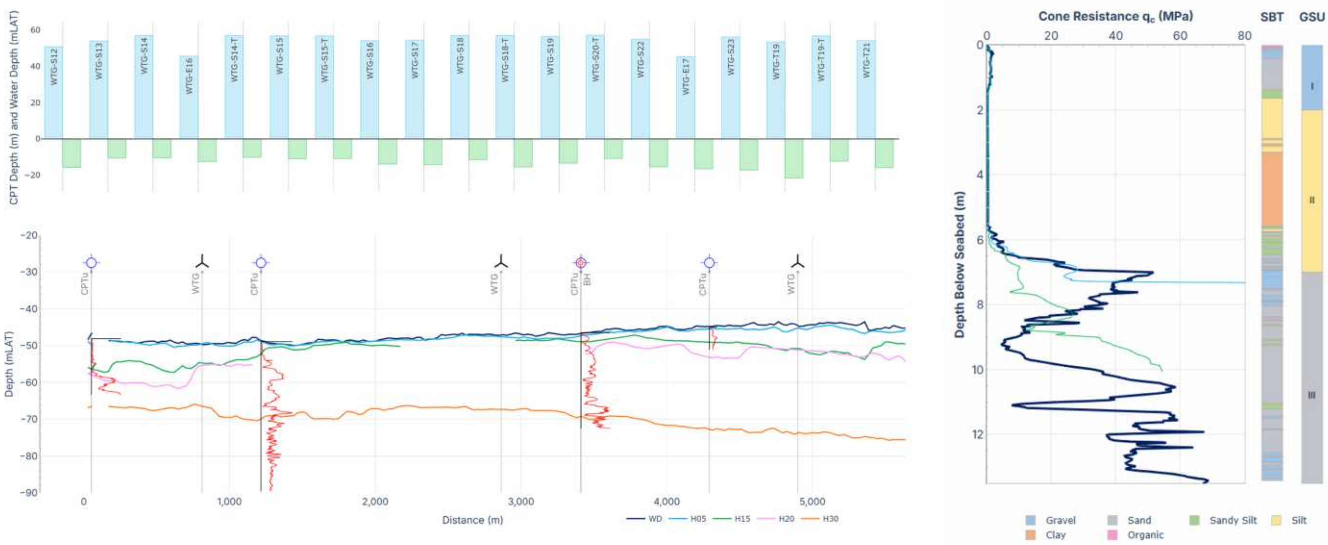

Figure 2. Overview of site data at subject offshore wind farm

4.3 Streamlined Process of Design Parameters Selection

The determination of design geotechnical parameters is a critical step in jack-up foundation assessments which often requires sound geotechnical judgement. In this enhanced approach, the detailed processing of raw CPT and borehole data, parameter correlations, and the generation of initial design parameters are automated simplifying the overall data preparation process.

The integration with ground model data from the GIS database of the offshore wind farm also enhances the geotechnical engineering process. In the absence of CPT data at the WTG or jacking position, tie-in of soil profile from the nearest available CPTs or boreholes can be performed. In addition, the automated detection of seabed slope from the bathymetry data at the planned vessel jacking position allows for the quantification of potential spudcan-seabed interactions and their implications to the vessel's structural integrity during installation.

Unlike in the conventional approach where these activities can be time consuming, the semi-automation allows the geotechnical engineer to focus on more critical tasks. These include developing suitable design soil profiles, calibrating shear strength parameters, refining the default initial parameters and ensuring sensible and sound input parameters for subsequent geotechnical analyses.

4.4 Semi-Automated and Integrated Geotechnical Analyses

The conventional method of spudcan penetration analysis using spreadsheets typically requires users to predefine suitable spudcan bearing capacity failure mechanisms for each soil layer such as general shear, squeezing or punch-through, and to select preferred methods. Manual adjustment is also often needed to correct details of the predicted load penetration curves.

An example of an automation framework for spudcan bearing capacity calculation in multiple soil layers was demonstrated in Xie et al. (2010). In the enhanced framework, the appropriate spudcan bearing capacity mechanism for a two-layered system is automatically determined based on soil type and corresponding shear strength with preferred methods for specific mechanisms predefined. While semi-automating these tasks is challenging, it significantly enhances the efficiency of spudcan penetration analysis enabling the simultaneous assessment of multiple WTI jack-up units and facilitating risk assessment using various criteria when required. Various predictive methods, e.g. ISO 19905-1 and SNAME 5-7, can also be integrated providing a robust predictive framework for the risk assessment.

Once the design input parameters are confirmed, a batch run of 132 sets of spudcan penetration analyses can be initiated and completed within minutes using the semi-automation. Additionally, a manual post-processing feature is also available enabling the geotechnical engineer to refine the automated results for specific WTG locations for improved accuracy.

Besides predicting range of possible spudcan penetration depths, the current framework also enable other critical spudcan asssessment, such as spudcan extraction, spudcan scour, spudcan-slope interaction, as shown in Figure 3. This integrated approach enables comprehensive and quantitative geotechnical risk assessments for WTI jack-ups in offshore wind farm projects offering a more efficient and robust analysis process.

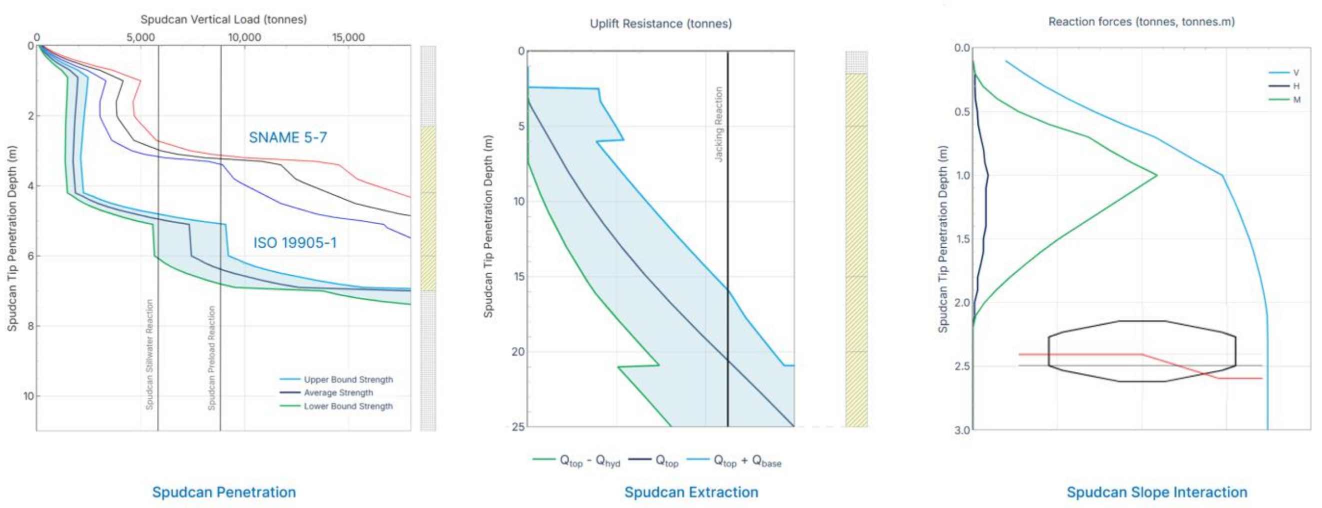

Figure 3. Integrated spudcan analyses for WTI jack-up at subject offshore wind farm

Presenting key statistics such as percentage of WTG locations subject to specific risk types or predominant risks provides valuable insights into the need for more advanced analyses, such as finite element simulations or other enginering measures, to further refine risk mitigation strategies and understand the potential cost and/or schedule implications.

With the semi-automation of spudcan analyses, WTI jack-up screening for offshore wind farms can now be performed swiftly and efficiently. Unlike conventional methods, this semi-automated process allows for an almost instant basic leg-length check across multiple candidate WTI jack-ups, streamlining the selection of competitive and suitable options for offshore wind projects.

4.5 Interactive Visualisation of Geotechnical Risks

In addition to tabulating detailed geotechnical risks derived from the preceding analyses, the decision-making process can be enhanced through interactive visualisations of key risk factors and their statistics as illustrated in Figure 4. For instance, understanding the spatial distribution of certain risks across the OWF can be leveraged for optimising the installation sequence and planning operational logistics. Furthermore, linking the predicted spudcan penetration depths to the corresponding design soil profiles and their spatial distribution enables quick identification of high-risk areas.

Figure 4. Visualisations of risk factors and key statistics (pre installation)

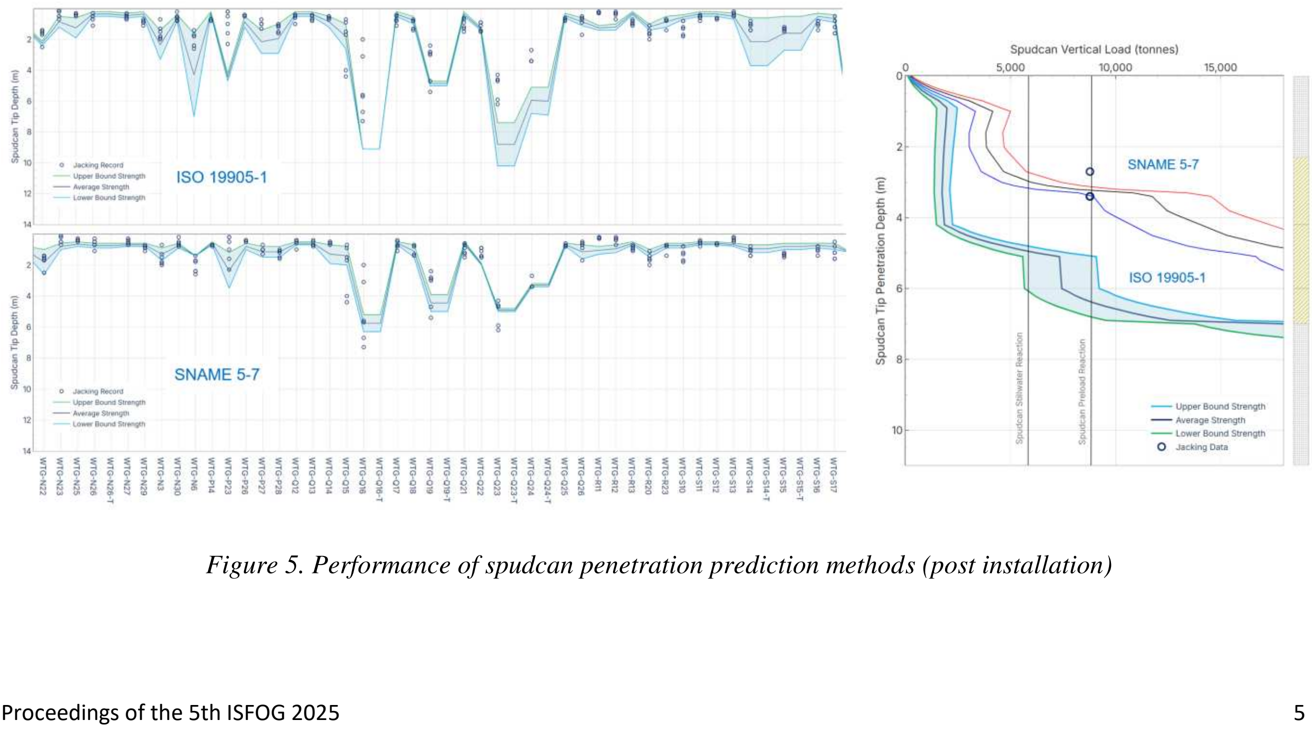

Figure 5. Performance of spudcan penetration prediction methods (post installation)

4.6 Centralised Post-Installation Data

Post-installation data is invaluable for jack-up foundation assessments considering the inherent uncertainties associated with factors such as the limitations of predictive methods, spatial variations of seabed conditions and the relatively limited borehole that can be practically obtained. This framework enables the assessment of predictive models' performance and their calibration against reposited actual jacking data which can benefit future installation campaigns at adjacent sites or in similar soil conditions.

Figure 5 illustrates the performance of spudcan penetration prediction frameworks based on the ISO 19905-1 and SNAME 5-7 methods. The observed variation in the actual spudcan penetration depths at the individual WTG locations can be attributed to the inherent lateral soil variability which cannot be fully captured by tie-in of soil profile due to the absence of CPT data at the exact jacking location.

For the soil profiles in the Offshore Wind Farm (OWF), both methods reasonably predict the spudcan tip depth in the cases of shallow penetration. However, for punch-through locations with a sand-over-clay profile, using a calibrated method for peak load prediction and accounting for the sand plug post-peak are crucial for a more realistic prediction of spudcan penetration behavior. A continuous improvement of the prediction model is expected to reduce the risk of restricted installation due to limited leg length availability.

WTI jack-ups may occasionally need to revisit wind turbines for maintenance, repair or retrofitting purposes. With access to past installation data, calibrated soil profiles and any lessons-learned from specific WTG locations, these operations can be carried out with minimised downtime during jack-up installation at the same WTG locations. Typically, this existing jack-up data is provided by the wind farm developer, ensuring that subsequent operations benefit from prior knowledge and experience.

For locations where punch-through behaviour is predicted, an additional bearing capacity margin is often necessary which limits the optimisation of preload level. However, in many cases with relatively thin underlying clay layers, the actual spudcan penetration tends to resemble squeezing mechanism than a sudden leg run. Due to limited leg length available, the preload optimisation become increasingly importance in deepwater locations. The calibration of predictive methods with actual jacking data, ideally combined with advanced numerical simulations, is thus essential to avoid costly modifications to the WTI jack-up or seabed remediation at the WTG locations.

5 CONCLUSIONS

A paradigm shift is crucial to achieving more efficient geotechnical risk assessments and enhanced risk mitigation in response to the projected increase in WTI jack-up deployments. This can be achieved by leveraging digital tools, data integration, and advanced analysis framework. Similar initiatives have already been implemented across various engineering sectors and are adaptable for the offshore wind industry.

The implementation of geo-automation, geo-integration and geo-repository has proven to provide a robust and efficient framework for WTI jack-up foundation assessment. Despite this semi-automation, the role of geotechnical engineers remains essential in reviewing input information, exercising judgement, addressing gaps and performing QAQC on the output. This new framework not only enhances decision-making for risk mitigation but also facilitates continuous improvement of the engineering process.

AUTHOR CONTRIBUTION STATEMENT

First Author: Data Curation, Project Administration, Writing- Reviewing and Editing. **Other Author**.: Data Curation, Software, Formal Analysis. **Last Author**: Conceptualization, Methodology, Writing-Original draft.

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