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Streamlined workflows for offshore wind farm soil design parameter derivation and foundation concept screening

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ABSTRACT: The development of offshore wind requires an efficient and reliable assessment of foundation concepts to ensure project feasibility and risk mitigation. This study introduces a semi-automated, streamlined geotechnical workflow – from soil design parameter derivation to foundation concept screening – designed to equip wind farm developers with the necessary information to make rapid and quantifiable assessments of project foundation concept feasibility and associated uncertainty at different phases of the project. The workflow utilises a geological ground model, available Cone Penetration Test and laboratory data, alongside load estimates for various structure types and Wind Turbine Generator sizes. These inputs serve as the basis for the workflow, which comprises the: (i) generation of location specific characteristic soil parameter design lines; (ii) derivation of cyclic soil strength parameters; and (iii) capacity screening for various foundation types including the Gravity-Based Structure, Suction Bucket Jacket, Pile Jacket, and Monopile. Furthermore, installation assessments that evaluate pile driveability and suction bucket installation are also performed. The combined capacity and installation results are then post-analysed and presented in a visually informative format, such as spatial heat maps, which can be tailored to visualise many user-definable analysis outputs. These include concept feasibility and/or sizing requirement. The results allow developers to make quantifiable, risk-based decisions at various stages of the project timeline: from initial concept studies, through optimisation of the site investigation, to Front-End Engineering Design (FEED) and beyond. By automating these processes, the workflow enhances the efficiency and value of foundation screening and design, ultimately supporting the successful development of offshore wind projects.

Keywords: Offshore Foundations; Monopile; Jacket; Gravity Based Structures; Streamlined workflow

1 INTRODUCTION

The rapid expansion of offshore wind energy is critical in meeting global renewable energy targets. With increasing project scales, reducing project timelines, the movement toward deeper waters and more challenging seabed conditions, the importance of efficient and reliable foundation design is ever increasing. The foundation systems must therefore be carefully assessed to ensure structural integrity of the wind turbine structure above, as the system is subject to significant environmental loading from waves, currents, and wind. According to Gourvenec (2024), improved efficiency in geotechnical design parameter derivation, design outcomes and time spent to complete design are all key challenges to support the energy transition.

The foundation design process involves complex analyses to determine concept feasibility, sizing and associated risk. This requires accurate soil data, robust design models and assessments of installation conditions. Given the expedited demands on project timeline, offshore wind developments have seen these complexities in design and ground conditions introduced much earlier in the project, with location-by-location rapid foundation screening often required at early feasibility stages. This differs from simpler traditional approaches, such as the use of wind farm zonations, where several locations of similar ground conditions are batched together into one design. This is now considered to lack the adaptability needed for more complex project requirements, where large possible spatial variations in the ground conditions and evolving technological demands throughout the project, are faced.

To address these challenges, this study presents a streamlined, semi-automated workflow to facilitate not only early-stage feasibility, but on-going assessments throughout the project, of different foundation concepts. The workflow leverages geological ground models, Cone Penetration Test (CPT) data, laboratory test results and load estimates across various structure types and turbine sizes. By interconnecting a series of semi-automated tasks, such as: (i) deriving soil design parameters; (ii) generating location specific design lines; and (iii) screening of foundation capacities and installation, the workflow provides the opportunity to batch-process many hundreds of locations and provide a rapid and comprehensive spatial evaluation of potential foundation types. These include Gravity-Based Structures (GBS), Suction Bucket Jackets (SBJ), Pile Jackets (PJ), and Monopiles.

Most state-of-the-art research focuses on one foundation type, and/or homogenous soil conditions (like Klinkvort et al. (2020)). This paper highlights the benefits of combining simpler but more efficient calculation methods (like the rule-based PISA model, as proposed by Burd et al. (2020)), with a semi-automated approach to cover several foundation types for a large number of locations. The approach is focusing on efficiency, allowing for multiple comprehensive assessments throughout the project, which constantly can be up to date with the newest data.

Results from the analyses are provided in both tabular and visual formats, such as feasibility and/or sizing heat maps, and offer the developers not only insights into the technical feasibility of foundation options but also a clearer understanding of the uncertainties and risks. The workflow should be integrated throughout the progression of the project, as significant value can be added during site investigation as well as at Front-End Engineering Design (FEED) phases.

The multiple stages of the workflow that are in turn iteratively processed, location-by-location, are presented below.

2 STAGE 1: DERIVATION OF DESIGN PARAMETERS

2.1 Geotechnical design profiles

The workflow begins with the derivation of geotechnical design profiles, utilising the geological ground model, CPT data and available laboratory test results. Since the number of Boreholes (BH) with sample data is typically limited, engineering design parameters (e.g. s_u, D_r, φ' etc.) are calibrated against CPT response to give soil unit specific engineering translation parameters (e.g. N_{kt}, for q_{net} translation to s_u). With this, design profiles can be derived at all locations, whether collected data is from CPT only or CPT+BH. These profiles are linearised and linked to interpreted units within the ground model. To ensure key CPT data trends are captured, sub-layers are added within units where changes in trend are identified.

Statistical analyses are incorporated in the derivation procedure, which allows for five different characteristic design profiles per location to be calculated. These are defined in Table 1 and follow the recommendations in DNV-RP-C207 (2021).

2.2 Cyclic strengths

Cyclic strengths adopted in this study are based on published cyclic soil databases for sands and clays presented in Andersen et al. (2022). For sands, the database for cyclic shear strengths is given as a function of equivalent number of cycles to failure (N_{eq}), the cyclic to average ratio of the loading (τ_{cy}/τ_a), relative density (D_r), fines content (FC) and stress path (i.e., triaxial compression (TXC), triaxial extension (TXE) and direct simple shear (DSS)). For clays, the cyclic shear strength is typically taken as a constant ratio of the static (e.g. $s_{u,cyc} = 0.9 s_{u,static}$). Location specific cyclic shear strength profiles with depth can therefore be derived for sands and clays alike, based on the calculated D_r profile and the corresponding fines content per soil unit, and undrained shear strength profile respectively. An equivalent number of cycles, $N_{eq} = 10$, and cyclic to average ratio, $\tau_{cy}/\tau_a = 2$ is assumed for all soil layers in this study. These are typical values to assume when no site- and/or foundation-specific load time histories are available.

3 STAGE 2: APPLIED LOADS

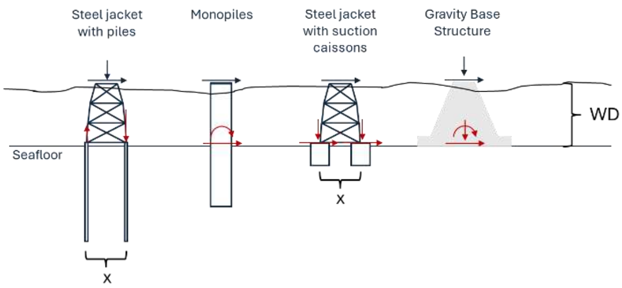

Figure 1 - Governing loads for different foundation types

The calculations in this section are based on assumed, typical loading combinations (Figure 1). It should be noted that a site-specific load simulation has not been performed, which may affect the comparability of the loads acting on the different foundation types. The horizontal load is assumed to be the main load component for all foundations, and location specific loads are derived based on water depth.

For Pile Jackets (PJ), only axial capacity is considered here. The axial loads are derived assuming moment equilibrium and that the tension force is 40% of the compression:

$$V_{compression} = \frac{H \cdot WD}{0.7 \cdot x} \quad (1)$$

Table 1 - Characteristic geotechnical parameter design conditions. Referred to as A, B C D and E profiles in text.

Condition	Name	Description
A	Low estimate	Characteristic value of lower tail of the distribution
B	Cautious low best estimate	Characteristic value of the lower tail of the mean distribution
C	Best estimate	Central unbiased estimate with lowest possible standard errors.
D	Cautious high best estimate	Characteristic value of the upper tail of the mean distribution
E	High estimate	Characteristic value of the upper tail

where x is the distance between the piles, WD is the water depth at the given location and H the assumed horizontal force acting on top of the jacket. The tension load is given as follows:

$$V_{tension} = -0.4 \cdot V_{compression} \tag{2}$$

The prolonged tension force considered is $V_{pro} = -0.25 \cdot V_{comporssion}$. Identical functions as for the PJ are assumed for Suction Bucket Jacket (SBJ). Monopile ULS moment (M) load is calculated based on Equation 3 below:

$$M = H \cdot WD \tag{3}$$

The vertical load component is not considered in the monopile capacity calculation at this stage. For the Gravity-Based Structure (GBS), the magnitude of horizontal load varies with respect to water depth.

4 STAGE 3: FOUNDATION SCREENING

4.1 Pile Jackets

Pile sizing is based on a constant diameter and thickness. The total vertical pile capacity, Q_t, is calculated at increasing pile lengths, for both cored and plugged scenarios, until its magnitude is greater than or equal to the required design load. The Q_t calculations are based on the unified CPT method for sands (Lehanne et al. 2020) and API main text method for clays (API, 2011). Pile lengths are calculated with shaft and tip capacity for both A and B profile (Table 1).

Pile driveability is checked using a modified version of VibPile, outlined in Kaynia et al., (2022). This development simulates the non-linear dynamic response of piles under impact driving. Pile refusal is considered to occur when the pile driving resistance exceeds one of the three criteria: (i) 250 blows per 0.25 m over 1.5 m consecutive penetration; (ii) 1600 blows for an interval of 1.0 m; or (iii) 650 blows per 0.25 m over on 1.25 m increment. The analyses in this paper are performed with a MHU1900 hammer.

Pile driveability is checked for both pile lengths, and driving resistance is calculated based on both D and E profiles (Table 1).

4.2 Monopiles

Monopile sizing is based on a constant diameter and pile thickness with depth. The rule-based PISA model, as proposed by Burd et al. (2020), is adopted with a maximum lateral displacement equal to 10% of the diameter applied as the design criteria.

Monopile driveability is calculated with the same procedure and refusal criteria as described in Section 4.1. The analyses is this paper are performed with a MHU4400 hammer.

4.3 Suction Bucket Jackets

Initial sizing of the buckets is performed using in-house developed 2D limit equilibrium slip surface software (NGI, 1985abc). The program analyses three different shapes of slip surface (at progressive depths below the skirt tip) to identify the minimum safety factor (SF) for a given input soil profile, foundation geometry and embedment, and design vertical, horizontal and moment load combination. Failure mechanisms analysed are typical pure vertical failure, rotational moment governed failure and combined horizontal sliding and rotational moment failure. A counter moment of $M = -0.7 \cdot H \cdot z$, where H is the horizontal force and z the skirt length, has been applied to restrain the bucket as expected from the connection to the jacket leg. This calculation is repeated with increased bucket diameter or skirt length until a sufficient SF is reached. A constant bucket thickness is assumed for all buckets. Only the B characteristic profile has been adopted in bucket sizing.

Prolonged tension loading differs from the peak tension loading in terms of soil drainage. For the peak tension load, the soil response is expected to be fully undrained and a larger soil volume around the buckets is mobilised at failure. The resistance to withstand the drained tension load is derived mainly from the side friction along the inside and outside skirt wall of the bucket. Especially for sands, this capacity is often significantly lower that the tension capacity for peak loading. The drained pull-out resistance for sand was calculated based on the active earth pressure coefficient with a negative roughness and the B characteristic drained friction angle. For clay, calculations were done in accordance with the methods outlined in Andersen & Jostad (2002) and Andersen & Jostad (2004)

4.3.1 Suction bucket installation

The assessment of penetration resistance and suction pressure required to install the caissons to their target penetration depths is performed using the CPT-based method (Senders & Randolph, 2009):

$$Q_{tot} = Q_{side} + Q_{tip} \tag{4}$$

$$Q_{side}(z) = A_{side} \int_0^z k_f(z) \cdot q_c(z) dz \tag{5}$$

$$Q_{tip}(z) = k_p(z) \cdot A_{tip} \cdot q_c(z) \tag{6}$$

where Q_{tot} refers to the total penetration resistance, Q_{tip} the resistance at the skirt tip and Q_{side} the resistance along the skirt walls. Further, z refers to the penetration depth measured at skirt tip, q_c the cone resistance, A_{tip} the tip area of the skirts and A_{side} the side area of the penetrated skirts. k_p and k_f are empirical constants relating cone resistance to respectively the skirt tip resistance and the skirt wall friction.

Two sets of CPT factors have been used in the prediction, high estimate (HE) and best estimate (BE) (see Table 2). If the required suction pressure exceeds the cavitation limit or the assumed buckling limit, the location is assumed unfeasible for installation.

Table 2. CPT factors for SBJ installation predictions.

Soil type	**High estimate**		**Best estimate**	
	k_p	k_f	k_p	k_f
Clay	0.4	0.03	0.4	0.03
Sand	0.3	0.001	0.15	0.0002

4.4 Gravity Based Structures

The bearing capacity analysis for the GBS is performed using the same 2D limit equilibrium slip surface software in Section 4.3. An initial round of calculations is performed to find an optimal GBS diameter given the assumed loading. For GBS stability, there are three fundamental ways to reach a target factor of safety: (i) increase diameter; (ii) increase mass; and/or (iii) dredge soft seabed sediments and replace with gravel infill. Diameters are analysed in 2 m increments from 30 m to 42 m for all locations. For each diameter an optimisation loop is used to test different dredge and replace depths varying from 0 m to 6 m below seafloor. An arbitrary optimisation criterion is set such that the GBS diameter is selected when more than 80% of the locations meet the capacity requirement with less than 3 m of dredge and replace required.

In practice these requirements could be set within limits of what is technically possible – with respect to transport, installation and/or seabed preparation – and to minimise cost. In this study, restraints on the GBS diameter and mass are adopted, with varying dredge depths per location the varying factor.

4.5 Workflow

Figure 2 illustrates the flow chart of the streamlined design process. Each step is tailored for batch processing, with all tools standardised to read the same soil input format and generate structured output to be seamlessly compatible with subsequent design steps. This integration is achieved through a combination of: (i) *python* wrappers around existing executables; and (ii) fully *python*-based scripts, ensuring efficient data handling and interoperability between tools. The computational methods used have been carefully selected to balance efficiency and accuracy, allowing rapid calculations while maintaining the reliability needed for critical design decisions. To maximise efficiency, manual interventions have been minimised throughout the workflow, streamlining the overall analysis. This systematic approach enhances both the speed and adaptability of the design process, supporting robust assessments of various foundation options with minimal processing time.

5 STAGE 4: DISSEMINATION

The example presented herein is derived from a publicly available dataset (Rijksdienst voor Ondernemend Nederland, n.d., NGI, 2022), with hypothetical load cases applied to various foundation types.

Table 3 presents the loads and geometries adopted in this study. As mentioned in Section 3, GBS loads vary with the water depth and therefore only an average value is presented herein. A vertical load of 162 MN is assumed. Figure 3 to Figure 6 present tailored foundation feasibility maps for all investigated foundation types. Since all PJ were proven installable, Figure 3 focuses on the difference between the A and B line pile lengths. Figure 4 and Figure 5 show feasible locations for both a BE (B/D) line design and a HE (A/E) line approach. Figure 6 gives a feasibility map showing the dredge and refill requirement using cautious best estimate (B) soil profiles. A scale indicating the equivalent of 1500 m is included in the lower right corner of all plots.

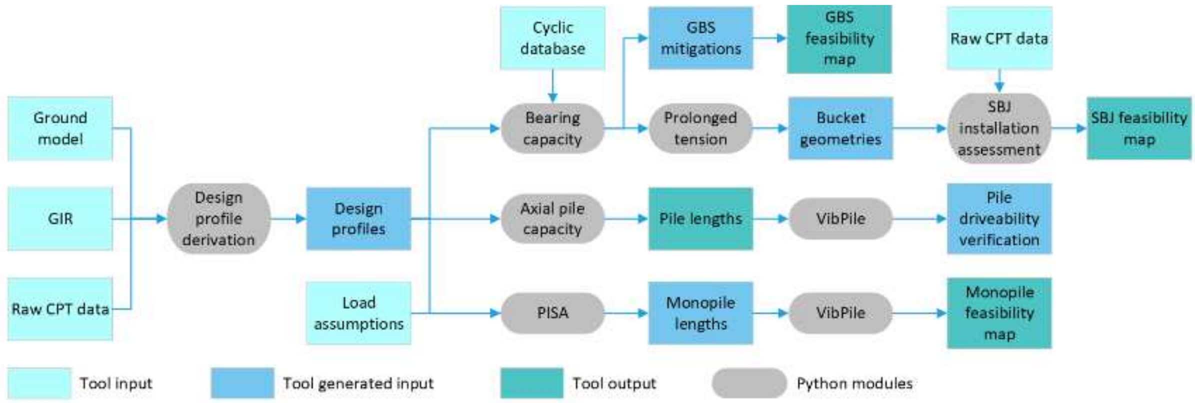

Figure 2 - Flowchart illustrating the streamlined workflow. GIR refers to Geotechnical Interpretation Report.

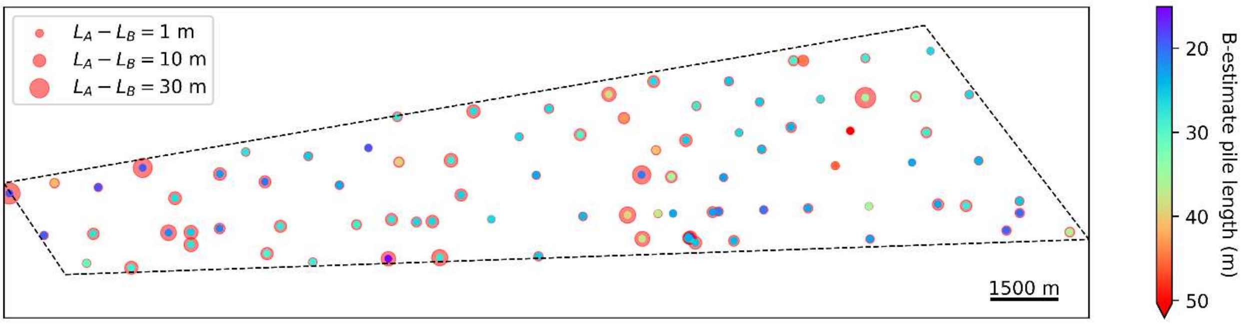

Figure 3 - Feasibility map of the PJ. Colour scale indicates the cautious best estimate (B) of the pile length, while the size of the red circles represents the difference between the pile lengths of the A and B profiles

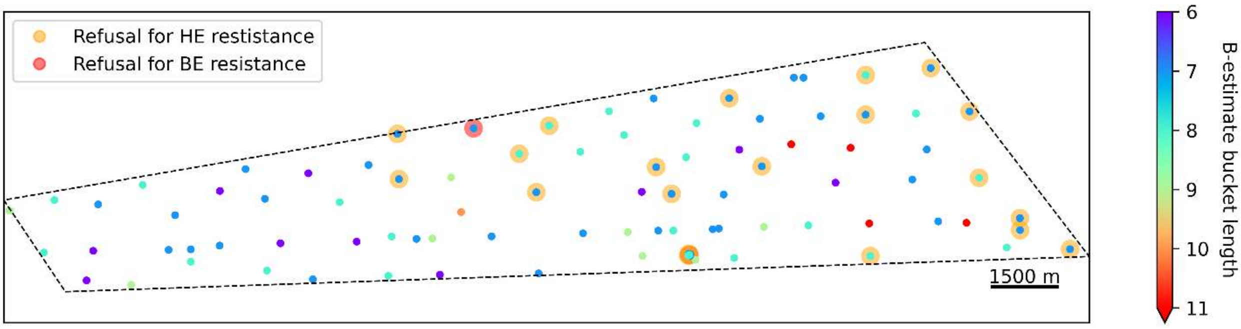

Figure 4 - Feasibility map for SBJ. Colour scale represents the cautious best estimate (B) of bucket length. Red circles indicate sites where installation is not feasible under best estimate (BE) resistance. Orange circles mark locations where installation is feasible for BE resistance but not for HE resistance

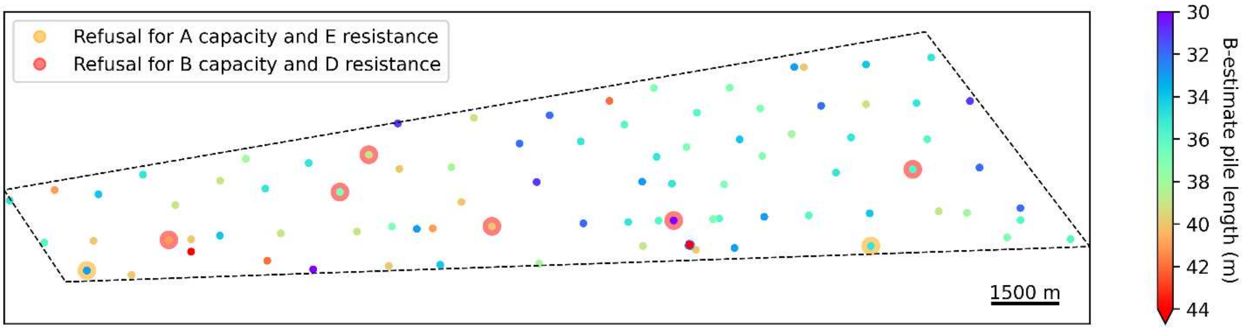

Figure 5 - Feasibility map for monopiles. The colour scale represents the cautious best estimate (B) of pile length. Red circles indicate sites where refusal occurred for best estimate conditions (B capacity and D resistance). Orange circles mark locations where installation is feasible for BE conditions but not for HE conditions (A/E)

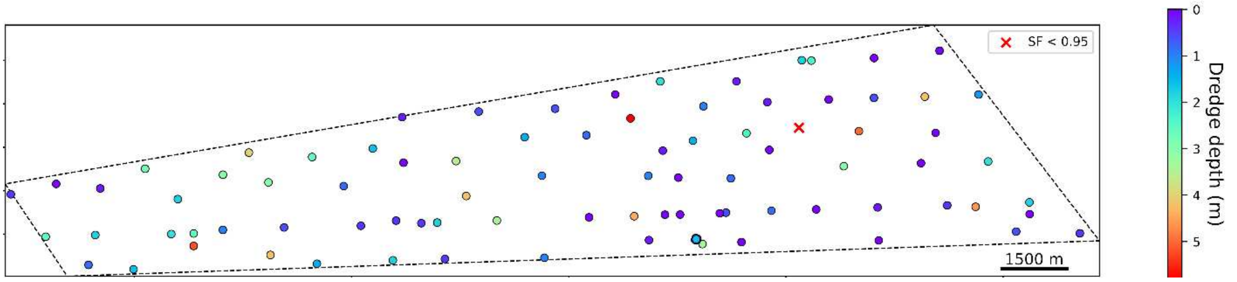

Figure 6 - Feasibility map for GBS. The colour scale gives the required dredge and refill depth for a chosen diameter of 36 m and cautious best estimate (B) soil profiles

Table 3 - Loads and geometries used for this study

Foundation type	**Horizontal load (H) (MN)**	**Jacket distance (x) (m)**	**Diameter (D) (m)**	**Thickness (t) (m)**
PJ	45	47.6	3	0.08
SBJ	45	47.6	12-15	0.08
MP	36	-	12	0.10
GBS (varies with WD, average presented)	33	-	36	-

6 CONCLUSIONS

This paper presents an efficient and streamlined approach to foundation studies for offshore wind projects. By employing computationally efficient calculation methods, the workflow delivers rapid results while maintaining a sufficient level of accuracy. The outputs provide valuable insights to support foundation concept decision-making and have broader applications at various phases of the project.

The analyses serve as a robust quality control mechanism for derived design profiles. Moreover, examining the results can help identify specific soil units or site areas where reducing uncertainties through additional data acquisition could have a significant impact. This insight is particularly valuable for planning further site investigations and laboratory testing programs.

The approach also facilitates earlier-stage decision-making for foundation concepts, potentially reducing the costs of site investigations. By efficiently processing data for individual locations, the workflow enables location-specific designs for each wind turbine, moving away from the traditional practice that may neglect ground condition variability.

AUTHOR CONTRIBUTION STATEMENT

Oda Mohus: Data curation, Formal Analysis, Visualization, Writing- Original draft. **David Moellenbeck**: Formal Analysis. Visualization. Writing- Original draft. **Rasmus Klinkvort**: Conceptualization, Methodology, Supervision, Writing- Reviewing and Editing. **Victor Bjørn Smith**: Writing- Reviewing and Editing. **Steven Bayton**: Software, Methodology, Writing- Reviewing and Editing.

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