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Back analysis of suction pile installations in intermediate soils

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ABSTRACT: Suction piles, also known as suction caissons or suction anchors, have been used extensively in the offshore industry since the 1980s. Existing design methods, such as the DNV-GL method, were primarily developed from installations in dense sands or clays. However, with the continued growth in offshore wind energy, suction piles are being installed more and more in intermediate soils, such as silt, sand and clay mixtures. However, problems can arise when using current design methods for forecasting installation response in these soils. Furthermore, it's also challenging to classify the soil based on CPT measurements, as well as selecting the appropriate design factors for the suction pile's shaft and base resistance. To evaluate how design methods perform in intermediate soils, a database has been compiled of installation records across 126 piles at three different sites. This paper focuses on the suction installation phase, comparing the performance of different design methods and soil classification methods in predicting the required suction pressures. The performance of three different design methods have been compared, in addition to a sensitivity analysis on the design factors—indicating the likely range of these factors for intermediate soils.

Keywords: Suction piles; intermediate soils; cone penetration test; back-analysis

1 INTRODUCTION

The installation of a suction pile consists of two phases: self-weight penetration and suction assisted penetration. Forecasting the installation response during both phases is often done using CPT-based methods, whereby:

$$R_{tip}(z) = k_p(z) * q_c(z) * A_{tip} \quad (1)$$

$$R_{shaft}(z) = \int_0^z k_f(z) * q_c(z)\, dz * A_{wall}(z) \quad (2)$$

where R_{tip} and R_{shaft} are the shaft and base resistances respectively at a depth z, q_c is the CPT cone tip resistance, A_{wall} is the surface area of the pile shaft, A_{tip} is the area of the annular ring at the pile base, and k_p and k_f are empirical factors relating the measured cone resistance to the base and shaft resistance respectively.

The factors for k_p and k_f are chosen based on soil type and have been extensively studied in homogeneous clays and sands. For example, the DNV-GL design method (DNV, 1992), prescribes a k_p of k_f of 0.4 and 0.3 respectively in clay and 0.3 and 0.001 in sand. Based on previous experience, the SPT Offshore design method uses the same factors, albeit with a reduction in shaft resistance to account for the clay sensitivity S_t by multiplying the shaft resistance by $1/S_t$. S_t is obtained by using equations 3, 4 and 5 by calculating the pore pressure parameter B_q from the CPT, the cone factor N_{kt} and the undrained shear strength s_u.

$$S_t = \frac{s_u}{f_s} \quad (3)$$

$$s_u = \frac{q_t - \sigma_{v0}}{N_{kt}} \quad (4)$$

$$N_{kt} = 10.5 - 4.6 * \log(B_q + 0.1) \quad (5)$$

Nevertheless, there are uncertainties regarding what factors to use in intermediate soils. Design methods do not explicitly prescribe a corresponding k_p and k_f, both of which are dependent on the drainage condition and the rate of penetration (DNV, 1992; Offshore Wind Accelerator, 2019). Additional complications arise at sites with interlayered soils of different permeabilities because of the effect they have on the suction path (Klinkvort et al., 2019; Offshore Wind Accelerator, 2019).

Using an extensive database of installation records, this paper compares the efficacy of three design methods during suction-assisted penetration in intermediate soils. The work forms part of a wider project that has analysed installation records during both self-weight penetration and suction assisted penetration in both intermediate and layered soils.

2 METHODOLOGY

Installation data from three different wind park locations (WP1, WP2 and WP3) was processed and compiled into the database, for a total of 126 suction pile installations (Table 1). The suction piles at WP1 were part of a three-legged jacket structure, where only one CPT was performed per jacket location. For WP2 and WP3, shorter suction anchors were used and CPTs were performed at each location.

The classification system by Schneider et al. (2008) was used to classify the soil, based on recommendations for intermediate soils by Bilici et al. (2023). An example of one of the sites is given in Figure 1. The top layer consists of clay, followed by an intermediate soil layer with a mixture of sand and intermediate soils at the bottom. At this site, a three-legged jacket was installed, a jacket integrated with suction piles 10 m in diameter and 25.7 m in length. Self-weight penetration was around 15 m for the three suction piles. From this point, suction was applied (Figure 2), resulting in a constant increase in suction pressure to a maximum of 300 kPa.

The performance of three design methods is presented in this paper: the CPT-based SPT Offshore and DNV-GL methods, along with the undrained strength DNV-GL / DNV s_uu method (DNV, 2021). Since the CPT-based methods do not prescribe a k_p and k_f factor for intermediate soils, the factor was linearly interpolated between the factors prescribed for sand and clay based on the soil behaviour type index.

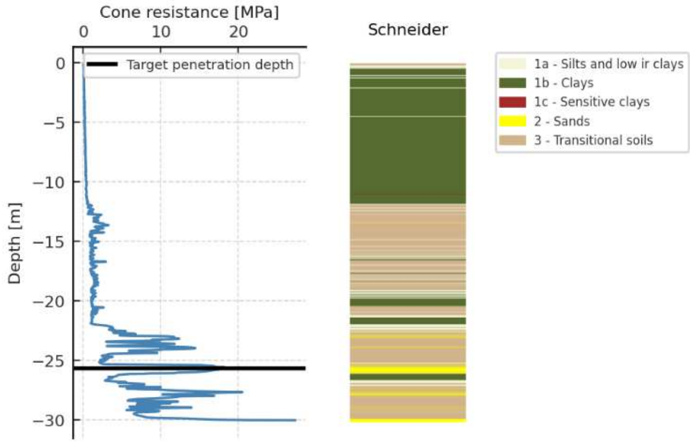

Figure 1: CPT profile from WP1

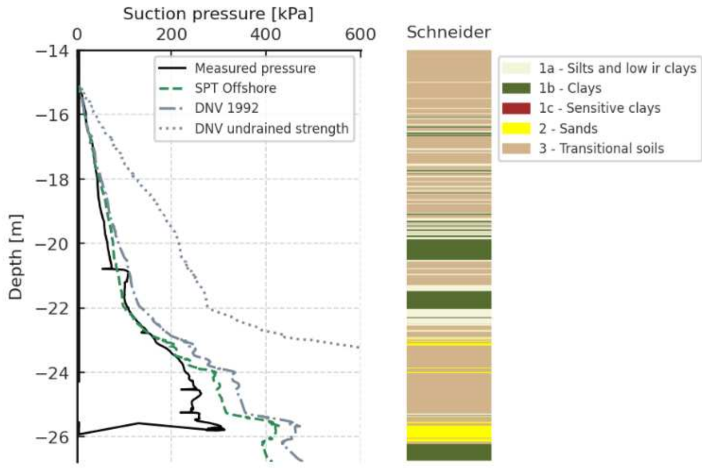

Figure 2: Suction-assisted penetration at WP1, comparing the measured suction pressure to predictions

Table 1: Overview of suction pile database in intermediate soils

Site	# of piles	Diameter [m]	Length [m]	Ground conditions
WP1	105 piles in 35 jacket installations	10 − 12	19.5 − 26	Profiles consisting of intermediate soils over sands and clays over intermediate soil / sand mixtures
WP2	8 single pile installations	9 − 12	10 − 17.5	Layered profiles consisting of combinations of clays, silts and intermediate soils
WP3	13 single pile installations	9.45	7.8	Large variety in encountered soil profiles

3 RESULTS

Figure 3 provides an overview of the best performing design method per installation for the three different sites. The best performing design method was chosen based on a visual inspection, for example, in figure 2 the suction pressures predicted with the SPT Offshore method are closest to the measured pressures. In some cases the single best design method could not be picked and multiple methods were designated as the best method. For WP3 in particular, where almost no clay layers were found, the SPT Offshore and DNV method resulted in similar predictions. Overall, the SPT Offshore method turned out to work best for predicting required suction pressures in the encountered intermediate soil profiles.

The difference between the measured and predicted suction pressures within each soil layer (as defined in the Schneider (2008) classification chart) was also quantified using the Root Mean Squared Error (RMSE) between the predicted and measured pressure at a certain depth. As shown by Figure 4, most of the prediction error arose in transitional soils, whereas silts in comparison had a much lower prediction error.

3.1 Optimization of empirical factors

To reduce the RMSE in intermediate soils, a back-calculation of the empirical k_p and k_f factors was performed using a Monte Carlo simulation. Five hundred combinations of k_p and k_f factors were sampled from uniform distributions with intervals as suggested by DNV (1992) (k_p from 0.3–0.4 and k_f from 0.001–0.03). Each combination was used to make a prediction with the SPT Offshore method for the required suction pressures in an intermediate soil layer. By comparing the measured pressures and each of the 500 new predictions, the RMSE between the measured and predicted pressures was calculated. Figure 5 provides an example of such an analysis for an installation at WP1, considering just the installation response of the first intermediate soil layer. Overall, the simulation suggests that a k_p factor of 0.30 to 0.40 gives a relatively low RMSE when using in combination with a k_f of 0.010 to 0.015. This same analysis was performed for six more profiles (Table 2) to give an idea of the representative k_p and k_f factors. Overall, the analysis suggests that a k_p factor of around 0.35 and a k_s factor of 0.012 fit well across the dataset. Nevertheless, some clear deviations are shown with the normalised pore pressures $\Delta u_2/\sigma'_{v0}$ and normalised cone resistance Q_t and there is no clear relation between the CPTu measurements and k_p and k_f factors. For clarity, the SPT method as shown in Figures 3 and 4 was used as in the original formulation with interpolated parameters and without optimized parameters.

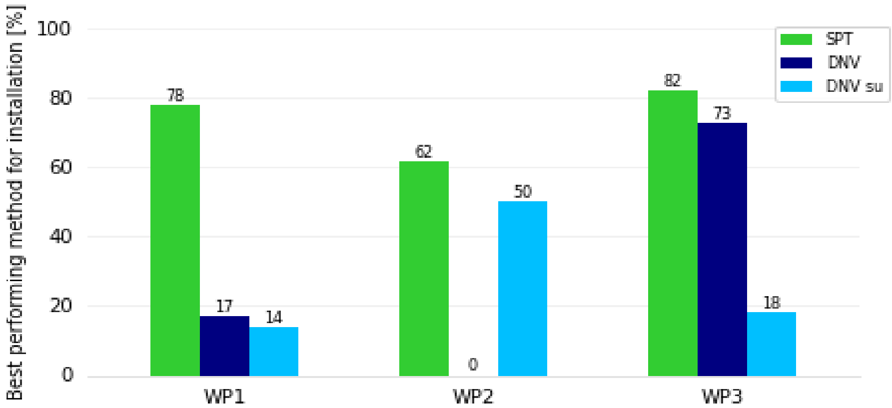

Figure 3. Overview performance design methods for different wind park locations

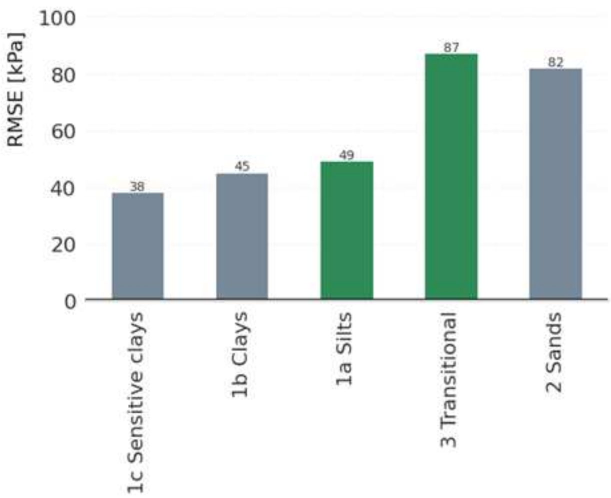

Figure 4. Error in each soil zone when comparing the measured to predicted suction pressure

4 CONCLUSION

Comparing the predicted suction pressures of three design methods to the measured pressures across 126 different installations, the SPT Offshore method provided the most accurate predictions in intermediate soils for the required suction pressures, compared to

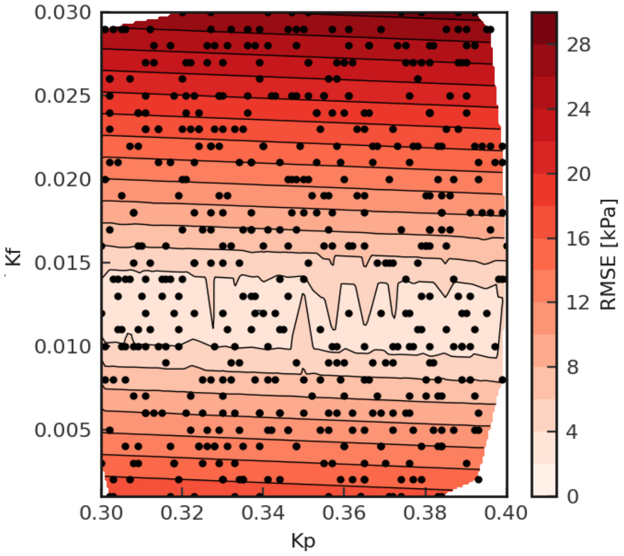

Figure 5. Monte-Carlo simulation of potential design factors for an installation at WP1

the DNV (1992) and DNV undrained strength (2021) methods. A back calculation of empirical factors was also performed, indicating best-fit k_p and k_f factors of 0.35 and 0.012 respectively. The analysis indicated that most of the uncertainty was in the appropriate k_f factor, likely due to variations in the drainage conditions across different types of intermediate soils. The work presented in this paper formed part of a wider study into self-weight and suction-assisted penetration in layered, intermediate soils along with CPT-based classification of intermediate soils. The results of the study suggested that more research is needed into the effect of seepage flow on the reduction of soil resistance, particularly with respect to the uncertainties regarding the effect of drainage conditions on both the CPT and pile.

AUTHOR CONTRIBUTION STATEMENT

T.P. Berg: Investigation, Methodology, Programming, Visualization, Writing – original draft **K.J. Duffy**: Conceptualization, Methodology, Supervision, Writing – review & editing **K.G. Gavin**: Conceptualization, Writing – review & editing **S. Raymackers:** Conceptualization, Resources, Writing – review & editing **G. Peeters**: Conceptualization, Supervision, Resources, Writing – review & editing **O. Aziz**: Writing – review & editing, supervision

REFERENCES

Bilici, C., Carotenuto, P., Lunne, T., Augustesen, A., Krogh, L., Dias, H., Burbury, D. (2023). Offshore geotechnical site characterization of silty soils. *Offshore Site Investigation and Geotechnics 2023 Conference Proceedings*. London, United Kingdom, pp. 178-183.

Det Norske Veritas. (1992). *DNV CN 30-4 Foundations.* Det Norske Veritas, Hovik, Norway.

Det Norske Veritas. (2021). *DNV recommended practice: Offshore soil mechanics and geotechnical engineering*. Det Norske Veritas, Hovik, Norway.

Klinkvort, R. T., Sturm, H., & Andersen, K.H. (2019). Penetration model for installation of skirted foundations in layered soils. *Journal of Geotechnical and Geoenvironmental engineering,* 145(10), 04019085, http://doi.org/ 10.1061/(ASCE)GT.1943-5606.0002106.

Offshore Wind Accelerator. (2019). *Suction installed caisson foundations for offshore wind: Design guidelines.* Offshore Wind Accelerator.

Robertson, P. K. (1990). Soil classification using the cone penetration test. *Canadian Geotechnical Journal*, pp. 151-158, http://doi.org/10.1139/t90-014.

Schneider, J. A., Randolph, M. F., Mayne, P. W., & Ramsey, N. R. (2008). Analysis of factors influencing soil classification using normalized piezocone tip resistance and pore pressure parameters. *Journal of Geotechnical and Geoenvironmental Engineering*, pp. 1569-1586, http://doi.org/10.1061/(ASCE)1090-0241(2008)134:11(1569).

Table 2. Overview of back calculated empirical factors

Installation	Q_t Normalized cone resistance	$\Delta u_2/\sigma'_{v0}$	k_p	k_f
01*	7 – 20	-1 – 4	0.3 – 0.4	0.010 – 0.015
02*	8 – 50	-5 – 4	0.3 – 0.4	0.010 – 0.015
03*	40 – 50	0 – 10	0.3 – 0.36	0.025 – 0.030
04	5 – 60	-5 – 3	0.3 – 0.4	0.003 – 0.009
05**	10 – 200	-4 – 5	0.3 – 0.4	0.007 – 0.010
06 **	7 – 400	-30 – 0	0.3 – 0.4	0.007 – 0.015
07**	50 – 700	-30 – 0	0.3 – 0.34	0.006 – 0.012

**Thin clay inclusions were found in the intermediate soil layers which might have influenced the back calculation.*
*** Higher permeability layers were found in which a possible seepage flow might have reduced the soil resistance and back calculated factors.*