The potential use of press-in methods in the offshore renewables industry

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ABSTRACT

Currently, the offshore renewables industry uses a range of foundation systems originally developed for the oil and gas sector. However, innovative foundation measures still need to be developed for offshore renewables because of key differences in scale, loading conditions and the geographical areas in which renewable developments are deployed. Furthermore, the large-scale of offshore wind developments means there is often significant uncertainty regarding the ground conditions between site investigation points. With this in mind, this paper explores the potential use of press-in pile technology for offshore renewable development. Firstly the paper looks at how press-in piling data can be used to inform and ground-truth soil models during pile installation, as well as informing the in-service behaviour of a structure. The paper then describes a number of innovations that may allow for reduced costs and environmental impacts of offshore foundations.

Key words: *Offshore foundations, Renewables, Piles, Ground Modelling, Risk*

1. Introduction

Across the globe governments are setting very ambitious targets for energy generation from offshore renewable sources. Fixed bottom and floating offshore wind farms are seen as key to achieving this aim. Siting turbines offshore provide several benefits including: (i) the availability of high unrestricted wind speeds, (ii) the ability to use larger turbines, (iii) the ability to develop combined wind and wave/solar energy installations and (iv) the potential for offshore hydrogen production.

To date many of the foundation systems deployed (Figure 1) have built on experience in the oil and gas sectors. When water depths are shallow and strong soils are present near the seabed, gravity base foundations are often used. However, this type of foundation requires significant port infrastructure to be available close to the development site. For water depths in the range of 30 to 75m—so for most offshore developments at present—piled foundation systems give an economical solution as they have the advantage over gravity base systems in mobilising soil resistance to withstand loads. Monopiles and many jacket structures use large diameter open-ended piles to resist loads. Alternative systems for jacket foundations include suction caissons as well as novel systems such as screw piles. For waters deeper than 75m, floating platforms are preferable, tethered to support systems like piles, suction anchors or drag anchors. Whilst these foundation systems are well-known and have been deployed successfully, these foundations also face several challenges with the transition to renewable offshore energy, including the different operational loads, the geographical extent of wind farm developments and location of resources across the globe. In this paper we first look at some of these challenges. We will then consider some foundation systems in common use and see how they are being adapted to address key concerns.

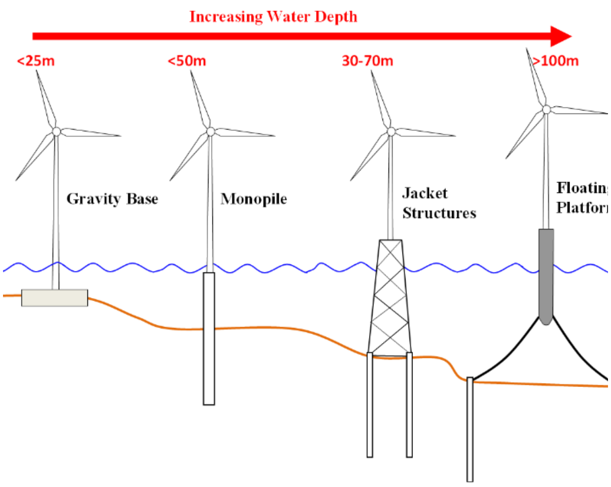

Figure 1: Typical offshore foundation systems

2. Offshore challenges

2.1. Loading conditions

Pile supported platforms used for oil and gas extraction typically have a large self-weight load, V, with relatively low horizontal environmental loads, $H \approx 0.1V$. In contrast, offshore wind turbines are relatively light, flexible structures where the horizontal loads are greater than the vertical self-weight. Open-ended tubular piles are widely used offshore, either to support multiple legs of a jacket structure or else a single monopile. To resist the large horizontal and moment loads, monopile diameters of 10m are common. Doherty and Gavin (2011), Byrne et al (2015) and others have noted that pile geometries used in offshore wind are significantly different to those used for oil and gas platforms. This has necessitated updated design methods to estimate the lateral (Burd et al. 2020, Byrne et al. 2020) and axial (Lehane et al. 2020) capacity of offshore piles. Because of the variable nature of the dominant environment loading, cyclic loading impacts are critical and are not fully considered in design codes as of yet.

2.2. Pile size

With increasingly larger pile diameters comes increasingly heavier pile weights. Whilst some self-weight penetration is expected when the pile is first placed on the seabed, a number of recent cases of pile run have been recorded. In such cases uncontrolled displacement of the pile can result in pile loss and damage to equipment including vessels, cranes etc.

Another challenge with the increasingly large dimensions of offshore piles is noise effects during installation. Conventional installation is by dynamic driving. As pile diameters increase, the sound pressure increases (Bellmann et al. 2020), potentially causing harm to marine mammals nearby.

2.3. Challenging soils

Another critical difference between renewables and oil and gas projects is the geographical extent of the entire development. While oil and gas platforms are usually large stand-alone structures, offshore wind farms consist of multiple turbines spread over relatively large development sites, not to mention the substations and interconnector cables that are required. Finding areas near-shore to place such large developments becomes more and more difficult as the number of wind farms begins to grow and so development is expanding to deeper water depths and areas with problematic soil conditions.

An example of a problem soil is sand containing glauconite: an iron-rich potassium phyllosilicate mineral. This soil type has been identified at a number of offshore wind development sites. Glauconite particles tend to crush during Cone Penetration Testing (CPT) and pile installation, transforming itself into a high plasticity clay. CPT measurements in glauconite measure very high cone tip resistances q_c and high friction sleeve resistances f_s, corresponding to large friction ratios, F_r (%). The concerns is that the combination of high shaft and base resistance could lead to premature refusal of piles during installation.

Westgate et al. (2024) describe field tests on closed and open-ended piles installed in glauconitic sand at a site in New Jersey. Five small (0.324m) diameter piles were installed. Four were closed-ended and one was an open-ended pile. Four large diameter (1.52m) open-ended piles were also installed at the test site. Driveability analyses were performed with GRLWEAP implementing the Alm and Hamre model formulation using (i) the shaft and base resistance predicted using the sand formulation, (ii) the shaft and base resistance predicted using the clay formulation and (iii) a hybrid method using the clay method for the shaft resistance and the sand method for the base. The clay method and hybrid method gave predictions that were in close agreement with dynamic analysis of the installation data.

Other problem soils include rock deposits encountered at many development sites. In weak rocks (typically those with Unconfined Compressive Strength, UCS < 5 MPa), driving of piles is possible with large capacity hammers. However, in such rock deposits occasional high-strength bands are often present, necessitating occasional drilling and significantly increasing installation time and costs. In harder rocks, drilling is possible. In a recent project offshore France, large diameter piles were drilled in competent bedrock using a modified tunnel boring machine (TBM) developed by DEME and Herrenknecht.

3. Ground modelling

3.1. Offshore site investigations

Offshore wind developments often span across vast, expansive areas, hundreds of square kilometres in size. For geotechnical site investigations, sampling and testing programmes need to be efficiently designed to cover these large areas and identify key risks and geohazards associated with each and every turbine location.

IJmuiden Ver in the Dutch North Sea sector is an example of one of these site investigations (**Figure 2**). Covering an area of 400 km^2 and with an anticipated capacity of 4 GW, foundation installation and turbine construction is expected to commence in the coming years. The initial site investigation comprised 381 CPTs and 151 boreholes, corresponding to a spatial density of roughly 1 CPT per km^2 and 0.4 boreholes per km^2. Data sparsity, therefore, is quite high with the geotechnical data.

To compliment this data, seismic surveys (sub-bottom profiling and multi-channel seismics) were conducted along survey lines 70 m apart, amounting to almost 12,000 km of survey lines in total. Seismic surveys give high spatial resolution in the horizontal direction, making it easier to map out layer boundaries and to infer the stratigraphy between geotechnical testing locations.

3.2. Data-driven ground modelling

Integrating these large, multivariate datasets is the primary objective of ground model development. Ground models aim to capture the geological, geomorphological and geotechnical features that may influence short-term offshore activities, such as drilling and rig anchoring, as well as the long-term reliability of offshore foundations (ISO, 2023). Ground models for very small and simple projects can consist of one single characteristic soil profile, where the elevation and properties of each soil layer are assumed to be constant across the entire site. However, as sites increase in size, the complexity of the ground model must also increase so that the ground conditions are accurately portrayed.

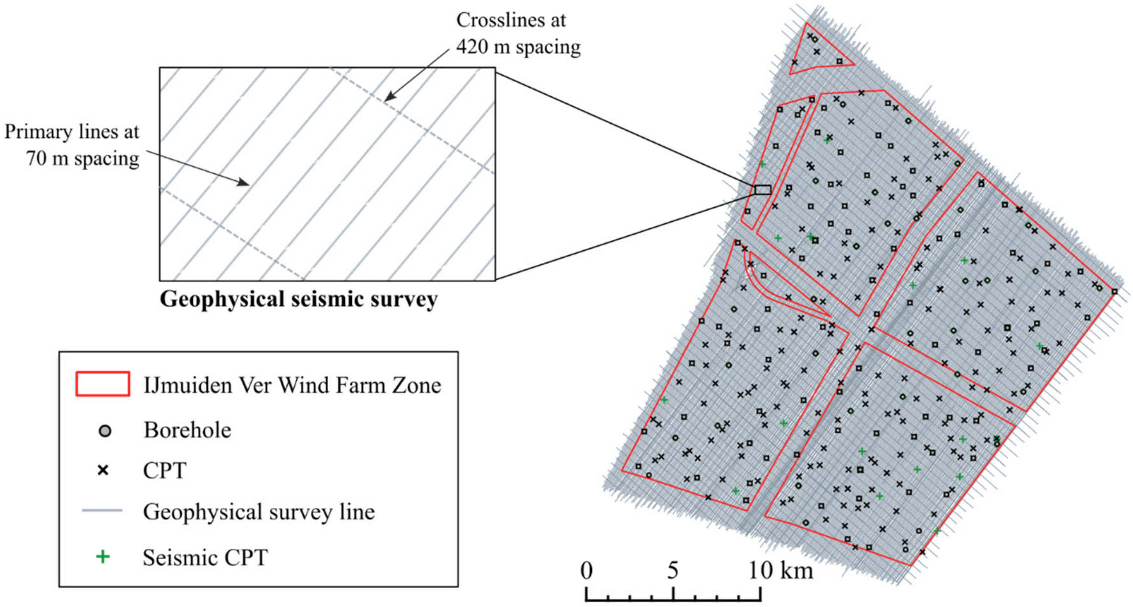

Figure 2: Site investigation data collected at IJmuiden Ver (offshorewind.rvo.nl)

Ground modelling has traditionally been a manual task. At each relevant location, such as a monopile foundation, a soil profile is devised and each layer is assigned geotechnical properties based on in-situ and laboratory tests. For offshore wind farms, this process can become laborious and time-consuming, particularly in cases like IJmuiden Ver where hundreds of wind turbine locations may be planned across a vast area.

Geostatistical techniques, such as kriging and random field modelling, are often the first port-of-call for interpolating between site investigation points (e.g. Vessia et al., 2020; Vanneste et al., 2022), and have been used for many years to model and characterise reservoirs in the oil and gas industry. However, data sparsity across offshore wind farms often makes it difficult to estimate the parameters required for geostatistical techniques, particularly with respect to the spatial variability in the horizontal direction.

To remediate this, research into data-driven, semi-automated site characterisation tools is rapidly growing (**Table 1**). Data-driven tools rely solely on measured data, including data collected from the current project and data collected from previous projects at the same site, neighbouring site or further afield (Phoon and Zhang, 2022). These techniques are frequently machine learning-based, using algorithms such as neural networks, random forests or clustering techniques. Once given a high quality, labelled dataset, these algorithms can learn the relationships and interdependencies between different site investigation techniques and different sampling points. A huge benefit of these approach is that they often remove the for apriori parameter estimation, whilst being able to efficiently integrate multivariate data at different stages during a site investigation.

The outputs of these models can be both qualitative and quantitative. Qualitative models usually provide stratigraphical information, schematising the site into a certain number of layers depending on the requirements of the project. Quantitative models, which are often an extension to the qualitative models, attribute soil parameters to these layers, or to all locations within a site. These soil parameters can include CPT-based parameters such as cone tip resistance q_c, or other geotechnical parameters, such as the soil stiffness or soil strength.

Table 1: Recent data-driven ground modelling approaches learning based approaches for ground modelling

Reference	Model	Output
Gan et al. (2020)	Random forest Support vector machine ScatteredInterpolant	Formation drillability
Kim and Ji (2022)	Neural network	Stratigraphic
Peuchen et al. (2022)	Convolutional neural network	CPT q_c value
Samui and Sitharam (2010)	Neural network	SPT N-value
Shi and Wang (2021)	XGBoost with convolution	Stratigraphic
Vanneste et al. (2022)	Random forest	CPT q_c value
Wu et al. (2021)	Random forest	Stratigraphic
Xie et al. (2022)	Neural network Random forest Gradient boosting	CPT q_c value

3.3. Press-in piling and ground modelling

Nevertheless, ground models based solely on site investigation data are still constrained by uncertainty between sampling points. Translating information from a 4 cm diameter CPT cone to an 8 m diameter monopile, for example, may introduce unwanted scaling effects relating to large differences in CPT/pile tip sensing distances, in addition to uncertainties relating to soil spatial variation.

Leveraging pile installation to improve ground models can help identify the true soil conditions around the foundation. Similar to a CPT, the installation effort of a press-in pile is directly correlated to the soil conditions. Efforts have been made (Brown and Ishihara, 2021; Ishihara and Kusakabe, 2021; Ishihara, 2023) to translate site investigation data directly into installation data and vice-versa. However, some uncertainties still need to be resolved. With most of the press-in piling market based in eastern Asia, research (Ishihara and Haigh, 2018; Ishihara and Kusakabe, 2021) has inevitably focused on correlations with the Standard Penetration Test. Fully instrumented, full-scale tests on press-in piles, paired with an adjacent CPT, are relatively limited in comparison. Furthermore, correlating CPT data to the installation records of more complex press-in pile types, such as rotary press-in piles, becomes challenging given the interdependencies between press-in force, torque and fluidization rate, if applicable. For offshore construction, understanding the relationship between these piles and

CPTs becomes particularly crucial because of the need for flexibility and redundancy when installing in remote offshore locations.

4. Potential developments in offshore piling technology

4.1. Background

In Section 2 we identified some geotechnical challenges with installing piles offshore, including the need for larger piles, challenging soils and the environmental impact of pile installation. One topic not addressed is the increasingly larger ship sizes required to install the very large diameter monopiles typically used in offshore construction. In this section we present some simple solutions that will be explored in the coming years in the International Press-In Association (IPA) technical committee on offshore foundations.

4.2. Increasing pile size

Very large diameter monopiles are difficult to construct, transport and install. Composite foundations where smaller tubes are arranged in efficient shapes have been developed by researchers including Yetginer et. al. (2006).

Ongoing development in submersible seabed rigs have help with facilitating offshore site investigation, particularly with CPT testing. These machines have the advantage in that they can be controlled remotely and require much smaller offshore vessels. It is envisaged that similar developments could allow piling rigs to work. Such rigs (Figure 3) could install numerous pipe or sheet piles as a pile group or as modular systems, all acting in unison to support an applied load.

Figure 3 Seabed piling rig (www.giken.com)

4.3. Difficult soil conditions

There are a number of risks with installing piles using conventional driving methods. These can be mitigated using a range of techniques including (i) water jetting, (ii) soil removal at the pile tip using an auger (iii) and combining rotation and axial force in order to reduce installation resistance (**Figure 4**). Not only would such techniques mitigate installation risks, but they also have the combined benefit of reducing vessel costs and environmental impacts from logistics and noise/vibration.

Figure 4: The GYROPRESS: a method of facilitating pile installation in difficult soil conditions (www.giken.com)

5. Conclusions

Offshore wind is an environmentally friendly solution for our future energy needs and governments across the globe have set ambitious development targets. To achieve these targets, various technical challenges need to be overcome. This paper has considered some solutions to address the following aspects:

(i) Decreasing pile sizes through the use of modular systems.
(ii) Reducing vessel size through the use of remotely operated sea bed pile installation equipment.
(iii) Reducing noise and vibration by avoiding pile hammering.
(iv) Eliminating pile run problems by using lighter piles that are connected to the piling rig.
(v) Developing solutions that overcome resistances in difficult soils and achieve target penetrations.

References

Bellmann, Michael A., et al. (2020) "Underwater noise during percussive pile driving: Influencing factors on pile-driving noise and technical possibilities to comply with noise mitigation values." *ERa Report: Experience report on piling-driving noise with and without technical noise mitigation measures*.

Brown, M.J. and Ishihara, Y. (2021) ‘Predicting the capacity of push and rotate piles using offshore design techniques and CPT tests’, in *Proceedings of the Second International Conference on Press-in Engineering*. Kochi, Japan: Taylor & Francis.

Burd, H.J. et al. (2020) PISA design model for monopiles for offshore wind turbines: application to a marine sand, *Geotechnique*. Vol. 70. No. 11, pp 1048-1066, https://doi.org/10.1680/jgeot.18.P.277

BW Byrne, R McAdam, HJ Burd, GT Houlsby, CM Martin, L Zdravković, DMG Taborda, DM Potts, RJ Jardine, M Sideri, FC Schroeder, K Gavin, P Doherty, D Igoe, A Muir Wood, D Kallehave, J Skov Gretlund (2015) New design methods for large diameter piles under lateral loading for offshore wind applications International Symposium on Frontiers in Offshore Geotechnics, Olso, June

Byrne, B. et al. (2020) PISA design model for monopiles for offshore wind turbines: Application to a stiff glacial clay till. *Geotechnique*, Vol. 70. No. 11, pp 1030-1047 https://doi.org/10.1680/jgeot.18.P.255

DeGroot, D., Westgate, Z., & Yetginer-Tjelta, T. (2023). Geological and geotechnical challenges of the East Coast United States for offshore energy transition. Invited Keynote Paper, *Proc. SUT Offshore Site Investigations and Geotechnics Conference*, London.

Gan, C. *et al.* (2020) ‘Spatial estimation for 3D formation drillability field: A new modeling framework’, *Journal of Natural Gas Science and Engineering*, 84, p. 103628. Available at: https://doi.org/10.1016/j.jngse.2020.103628.

Ishihara, Y. (2023) *Use of press-in piling data for estimating subsurface information and pile performance*. PhD Thesis.

Ishihara, Y. and Haigh, S. (2018) ‘Cambridge-Giken collaborative working on pile-soil interaction mechanisms’, in *Proceedings of the First International Conference on Press-in Engineering*. Kochi, Japan, pp. 23–46.

Ishihara, Y. and Kusakabe, O. (2021) ‘State of the art report on the use of press-in piling data for estimating subsurface information’, in *Proceedings of the Second International Conference on Press-in Engineering*. Kochi, Japan: Taylor & Francis, pp. 42–66. Available at: https://doi.org/10.1201/9781003215226-65.

ISO (2023) *Oil and gas industries including lower carbon energy — Offshore structures — Part 8: Marine soil investigations*. International Organization for Standardization (ISO 19901-8:2023).

Kim, H.-S. and Ji, Y. (2022) ‘Three-dimensional geotechnical-layer mapping in Seoul using borehole database and deep neural network-based model’, *Engineering Geology*, 297, p. 106489. Available at: https://doi.org/10.1016/j.enggeo.2021.106489.

Lehane, B. Bittar, E. Liu, Z. Jardine, R. Carotenuto, P. Rattley, M. Jeanjean, P. Gilbert, R. Haavik, J. Morgan, N. Lacasse, S. and Gavin. K. (2020) A new CPT-based Axial Pile Capacity Deign method for Piles in Sand, *Proc.*

International Symposium on Frontiers in Offshore Geotechnics (ISFOG), Austin, USA.

Peuchen, J. *et al.* (2022) 'Upscaling 1 500 000 synthetic CPTs to voxel CPT models of offshore sites', in. *Cone Penetration Testing 2022*, Bologna, Italy: CRC Press, pp. 641–645.

Phoon, K.-K. and Zhang, W. (2022) 'Future of machine learning in geotechnics', *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*, 17(1), pp. 7–22.

Samui, P. and Sitharam, T.G. (2010) 'Site Characterization Model Using Artificial Neural Network and Kriging', *International Journal of Geomechanics*, 10(5), pp. 171–180. Available at: https://doi.org/10.1061/(ASCE)1532-3641(2010)10:5(171).

Shi, C. and Wang, Y. (2021) 'Development of Subsurface Geological Cross-Section from Limited Site-Specific Boreholes and Prior Geological Knowledge Using Iterative Convolution XGBoost', *Journal of Geotechnical and Geoenvironmental Engineering*, 147(9), p. 04021082. Available at: https://doi.org/10.1061/(ASCE)GT.1943-5606.0002583.

Vanneste, M. *et al.* (2022) 'Data-Driven Ground Models: The Road to Fully-Integrated Site Characterization and Design', in D.V.K. Huynh et al. (eds) *Proceedings of the 2nd Vietnam Symposium on Advances in Offshore Engineering*. Singapore: Springer, pp. 3–21. Available at: https://doi.org/10.1007/978-981-16-7735-9_1.

Vessia, G., Di Curzio, D. and Castrignanò, A. (2020) 'Modeling 3D soil lithotypes variability through geostatistical data fusion of CPT parameters', *Science of The Total Environment*, 698, p. 134340. Available at: https://doi.org/10.1016/j.scitotenv.2019.134340.

Westgate et al. (2024) The Piling in Glauconitic Sands (PIGS) JIP: Reducing Geotechnical Uncertainty for U.S. Offshore Wind Development, Offshore Technology Conference OTC035843-MS

Wu, S., Zhang, J.-M. and Wang, R. (2021) 'Machine learning method for CPTu based 3D stratification of New Zealand geotechnical database sites', *Advanced Engineering Informatics*, 50, p. 101397. Available at: https://doi.org/10.1016/j.aei.2021.101397.

Xie, J. *et al.* (2022) 'Development of two-dimensional ground models by combining geotechnical and geophysical data', *Engineering Geology*, 300, p. 106579. Available at: https://doi.org/10.1016/j.enggeo.2022.106579.

Yetginer, A. G., D. J. White, and M. D. Bolton. "Field measurements of the stiffness of jacked piles and pile groups." *Geotechnique* 56.5 (2006): 349-354.