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Optimising back analyses of offshore pile driving in weak rocks with a data-driven approach

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ABSTRACT: The driveability of foundation piles for offshore wind turbines through weak rock formations is subject to significant uncertainties, which often manifest into project risks associated with pile runs or pile refusals. While an improved understanding of the Soil Resistance to Driving (SRD) can be obtained by back analysing historic driving data to manage these installation risks, such back analysis is not straightforward and is in fact a highly non-linear problem governed by a large number of factors. Signal matching analyses provide valuable insights into the SRD, but it is often only possible to perform on a small subset of instrumented piles. On the other hand, extensive collections of blow count records exist which can be harnessed to enhance and inform SRD predictions. This paper investigates the case study of the Wikinger Offshore Wind Farm (OWF) in the German Baltic Sea with piles driven through glacial till and chalk. An optimisation methodology is proposed, utilising blow count records in chalk stratigraphy to assess and enhance the performance of existing SRD methods. The methodologies for back analysing the blow count records and optimising the SRD parameters across all pile locations are discussed and demonstrated through an example. Attention is drawn to potential pitfalls in performing such analyses, as well as more practical aspects including data cleaning and pre-processing.

Keywords: Pile driveability; Offshore wind farm; Weak rock; Chalk; Back analysis

1 INTRODUCTION

An increasing number of pile foundations are being installed to support offshore Wind Turbine Generators (WTGs) in areas where weak rocks are present at shallow depths. There is currently limited guidance on assessing pile driveability in such formations. The uncertainty associated with the selection of appropriate hammers and need to avoid pile runs or refusals often leads to significant costs. These concerns have led to a growing interest in back analysing historic driving records covering weak rock formations to improve the certainty of site-specific Soil Resistance to Driving (SRD) predictions.

Such back analyses must address a highly non-linear problem whose results are influenced by numerous factors including the quality and availability of the input data, the data 'cleaning' and pre-processing procedures applied, the assumed soil resistance model, the treatment of any overburden overlying the rock formations, and the optimisation approach. This paper proposes a data-driven approach, and illustrates this with example site investigation (SI) and pile driving data from the German Baltic Wikinger Offshore Wind Farm (OWF), where trial and production piles were driven through glacial till and chalk (Barbosa *et al.*, 2017).

Chalk occurs as a weak, lightly cemented limestone that underlies many OWF development areas in Northern Europe. Uncertainties in the behaviour of driven piles in chalk led to the ALPACA and ALPACA Plus Joint Industry Projects (JIPs) (Jardine *et al.*, 2024). This and earlier research by Buckley *et al.* (2020; 2021) enabled the development and verification of a CPT-based method for predicting the chalk's resistance to driving. This method, which follows an effective stress-based approach, was established through signal matching analyses of instrumented dynamic field tests at offshore and onshore sites, including the Wikinger OWF.

While signal matching analyses offer valuable insights into the SRD, it is often only possible to consider a few blows recorded at selected depths on a generally small subset of appropriately instrumented piles. On the other hand, it is common to have blow count and hammer energy records from many more piles over their full penetration depths. Ideally, these could also be employed to inform SRD predictions. This paper proposes an optimisation methodology that utilises blow counts to assess and enhance the performance of existing SRD methods. The essential 'cleaning' and pre-processing of the input data are discussed, employing Wikinger data examples, along with methodologies for back analysing blow count records and optimising SRD parameters.

2 THE WIKINGER OWF

The Wikinger OWF site geology is characterised by Pleistocene glacial and fluvioglacial tills over mainly low-to-medium density chalk (and in places dense chalk or Danian Limestone). Buckley *et al.* (2020) reported that the glacial tills exhibited total cone tip resistance, q_t, values between 3 and 30MPa, with peaks up to 50MPa in thin, dense sand bands, and generally negative excess pore pressures measured at the u_2 position. In comparison, the fluvioglacial tills showed generally lower q_t values and positive u_2 measurements. Buckley *et al.* (2020) classified the glacial tills as silty sands to sandy silts, and the fluvioglacial tills as sandy silts to silty clays.

The site comprises 70 WTG jacket structures, each supported by four open-ended steel piles with a 2.7m Outer Diameter (OD) and a 40.5mm tip wall thickness. The piles were driven to penetrations between ≈ 20 and 40m, using a Menck MHU 1200S hammer (see Table 1 for its characteristics). The blow counts and the averaged applied hammer energies were recorded at 1m intervals that are sparser than the typical 0.25m. As a result, some local variations in driving resistance were likely averaged or smoothened.

Table 1. MHU1200S hammer characteristics

Characteristics	Values
Max. rated hammer energy	1200kJ
Hammer efficiency (under water)	90%
Ram weight	648kN
Anvil weight	305kN

The site investigations included at least 1 seabed Cone Penetration Test (CPT) at each WTG location. However, fully continuous CPT profiles to pile target penetration depths were not available at all locations, as seabed CPT penetration can be difficult when encountering layers of flint, dense chalk or weak limestones. For a small subset of locations, additional downhole CPTs were performed.

Laboratory interface ring-shear tests performed on Wikinger chalk samples indicated that the operational effective stress interface shear angles, δ′, fall around 32 to 34° (Buckley *et al.*, 2020), consistent with those reported by other studies.

3 FRAMEWORK FOR BACK ANALYSIS

3.1 Data cleaning and pre-processing

Cleaning, filtering and pre-processing input data are essential, albeit often overlooked, components of back analysis and optimisation exercises. The practical aspects are discussed and illustrated below using data from the Wikinger project.

Prior to performing any pre-processing, it is useful to define criteria to filter the cases considered for back analysis. The rules applied here were:

1. Pile penetrations of at least 5m into the chalk to ensure at least five data points in the chalk.
2. CPT profiling being available in the overlying glacial till and in at least 5m of chalk.
3. Continuous pile driving to depth (no pauses).

Reviewing the stratigraphic and blow count profiles, 25 out of 70 WTG cases met these three criteria. Figure 1 shows a typical CPT profile from one location. Careful processing of the raw CPT data was performed to remove artificial minima related to the start of pushes in downhole CPTs and unrepresentative local maxima associated with thin flint bands.

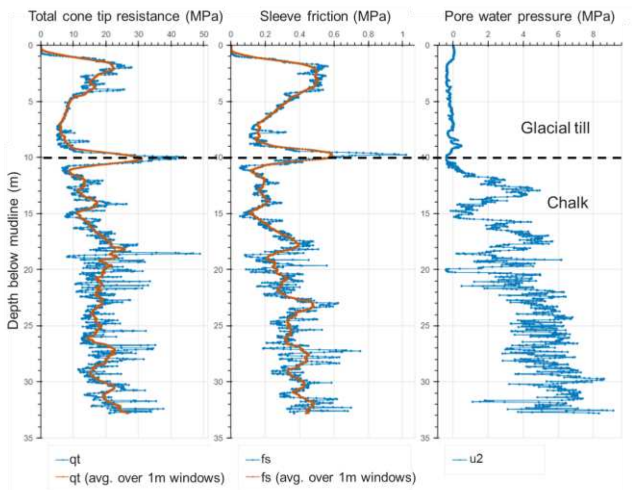

Figure 1 Examples of CPT q_t, f_s and u_2 profiles at Wikinger OWF through glacial till and chalk

Averaging techniques were subsequently applied to the cleaned CPT profiles for SRD calculations. In cases where more than one CPT was available per

WTG location, an average was taken from all CPTs within the jacket footprint. Additionally, the CPT traces were averaged over a certain depth interval. It is important to note that the approach taken to select appropriate q_t values from often variable CPT traces can have a significant influence on the calculations (Jardine *et al.*, 2005).

Various averaging approaches are suggested in the literature. Smith (2001) recommended averaging q_t over 0.3m intervals for chalk, while others suggested averaging q_t over a distance of 1.5D (D being the pile outer diameter) above and below the tip for base resistance calculations. However, the q_t processing should also consider the form of the CPT traces. Marked local variations were seen in the CPT traces recorded at Wikinger and the production piles had 2.7m ODs. Averaging q_t over a distance of 1.5D was considered to be overly crude and obscured most of the marked local q_t variations. However, the blow count records were recorded at 1m intervals, making any finer treatment of the CPT profiles inappropriate. The records were therefore averaged over 1m windows (i.e. ±0.5m around each point, see Figure 1) for input into the subsequent shaft and base SRD calculations.

3.2 Soil resistance to driving (SRD)

Following the cleaning and pre-processing of the input data, appropriate empirical methods need to be selected for the calculation of SRD. While the chalk forms the focus of this paper, the pile driving behaviour is also influenced by the tills which overlie the chalk in most of the selected WTG locations. For the examples presented herein, the piles penetrated through glacial tills which were treated as sands as per Buckley *et al.* (2020). Commonly adopted CPT-based methods to predict SRD during pile installation in sands include Alm and Hamre (2001), which was developed empirically from back analyses of 186 driving records of jacket piles, with diameters ranging from 1.83 to 2.74m, in typical North Sea sands and clays. The Alm and Hamre (2001) formulation for shaft resistance (τ_{rzi}) in sands is described by Equations 1 to 3. This method assumes that friction only occurs on the outside of the pile wall. The formulation for base resistance (q_b) in sands, applying on the pile steel annulus, is presented in Equation 4.

$$\tau_{rzi} = f_{sres} + (f_{si} - f_{sres})\mathrm{e}^{-\frac{\sqrt{q_t/\sigma'_{v0}}}{80}h} \quad (1)$$

$$f_{si} = S1 \cdot q_t \left(\frac{\sigma'_{v0}}{p_a}\right)^{S2} \tan\delta'_{ult} \quad (2)$$

$$f_{sres} = S3 \cdot f_{si} \quad (3)$$

$$q_b = S4 \cdot q_t \left(\frac{q_t}{\sigma'_{v0}}\right)^{S5} \quad (4)$$

where q_t (kPa) is the cone tip resistance, h (m) is the relative pile tip depth, δ'_{ult} (°) is the ultimate interface shearing angle, σ'_{v0} (kPa) is the effective overburden, and p_a (kPa) is the atmospheric pressure. $S1$, $S2$, $S3$, $S4$ and $S5$ are fitting parameters with values given in Table 2.

For the chalk, the updated SRD formulation from Jardine *et al.* (2024) was used, which has the benefit that it follows established physical mechanisms supported by field test observations. The overall shear resistances are calculated by Equations 5 and 6. Consistent with the method, the unit shaft resistance is applied on the outside of pile wall only. The base resistance values, applied over the open piles' steel annuli, are calculated from Equation 7.

$$\tau_{rzi} = \sigma'_{ri}\tan\delta'_{ult} \quad (5)$$

$$\sigma'_{ri} = C1 \cdot q_t \left(\frac{h}{R^*}\right)^{-C2(D/t_w)^{C3}} \quad (6)$$

$$(h/R^* \geq 6)$$

$$q_b = q_t(D/t_w)^{-C4} \quad (7)$$

where D (m) is pile outer diameter, t_w (m) is pile tip wall thickness, and R^*(m) is the equivalent radius for open piles, $R^* = \left(R^2 - R_i^2\right)^{0.5}$. $C1$, $C2$, $C3$ and $C4$ are fitting parameters with values given in Table 2.

Table 2 Default SRD fitting parameters from Alm and Hamre (2001) and Jardine et al. (2024)

Default Alm and Hamre (2001) parameters				
S1	**S2**	**S3**	**S4**	**S5**
0.0132	0.13	0.2	0.15	0.2
Default Jardine *et al.* (2024) parameters				
C1	**C2**	**C3**	**C4**	
0.031	0.481	0.145	0.175	

3.3 Driveability back analysis

3.3.1 WEAP analysis

In this investigation, driveability back analyses were performed using the commercial software GRLWEAP 14, a wave equation analysis program based on the 1-D elastic stress wave propagation model from Smith (1960). The pile is modelled as a series of lump masses connected by springs, while the soil resistance model consists of a linear spring and plastic slider in parallel with a viscous dashpot to represent all soil damping effects. The quake (*U*) and damping (*J*) parameters used in the analysis are based on typical values recommended by Alm and Hamre (2001), see Table 3.

Table 3. Quake and damping parameters (Alm and Hamre, 2001)

Shaft		**Toe**	
$U_{q,s}$ **(mm)**	J_s **(s/m)**	$U_{k,b}$ **(mm)**	J_b **(s/m)**
2.5	0.25	2.5	0.5

A key procedure in the back analysis involves deriving the SRD from the driving blow count and energy data using the bearing graphs generated by GRL-WEAP. Bearing graphs, which describe the relationship between SRD and required blow counts per pile penetration depth, are unique to each specific pile geometry, hammer/energy rating, adopted quake and damping parameters, assigned shaft resistance distribution and assumed split between shaft and end bearing. Figure 2 shows an example of how the bearing graph can be used to back analyse the SRD for a specific set of conditions.

It is important to note that the back analysed SRDs themselves also carry considerable uncertainties; the solutions are not unique but depend on the adopted soil resistance models, the dynamic variables (e.g. hammer performance, energy loss, damping), as well as the software and the skill of the operator.

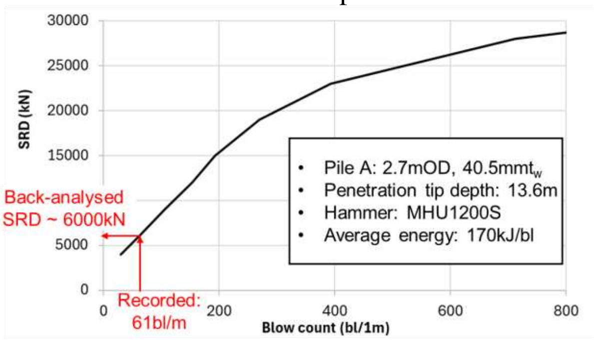

Figure 2 Example bearing graph

3.3.2 Performance evaluation

The objective of the back analyses is to develop an optimised set of SRD parameters from the driving data. The optimisation process requires a scoring measure to determine the fitness between the back analysed SRD derived from driving data and the SRD predicted from existing formulations. A scoring system adapted from the concept of Normalised Root Mean Squared Deviation (NRMSD) proposed by Perikleous *et al.* (2023) was used:

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n}\left(SRD_{derived,i}-SRD_{pred,i}\right)^2}{n}} \quad (8)$$

$$NRMSD = RMSD/SRD_{derived,avg} \quad (9)$$

where $SRD_{derived,i}$ (kN) is the SRD back analysed from driving data at depth i, $SRD_{pred,i}$ (kN) is the predicted SRD at depth i, n is the penetration increment, $SRD_{derived,avg}$ (kN) is the averaged back analysed SRD at the corresponding location.

A NRMSD of zero indicates a perfect match between the back analysed and predicted SRD. It is noted that NRMSD could be biased depending on the shape of the SRD profile and the distribution of the associated errors. For instance, if both the SRD and the associated errors increase with depth, NRMSD could be skewed toward larger values, potentially introducing a depth bias in parameter fitting. However, in the dataset examined herein, the SRD profiles for chalk typically exhibit only a modest increase with depth, likely due to the strong h/R* effect described by Buckley *et al.* (2020; 2021). Consequently, the impact of this potential bias is considered minimal.

Equations 8 and 9 were formulated to assess the match between back analysed and predicted SRD for single piles. The scoring system needs to be modified when considering a large number of piles to allow the SRD parameters to be calibrated across the full set of pile records. This paper proposes the following joint optimisation score which sums the NRMSD from all piles:

$$NRMSD_{sum} = \sum_{k=1}^{m} NRMSD_k \quad (10)$$

This scoring approach implicitly assumes that all piles have equal weighting when determining the SRD parameters.

3.3.3 Optimisation algorithm

In this investigation, a Genetic Algorithm (GA) was used to optimise the SRD parameters with the objective of minimising $NRMSD_{sum}$ from all piles. This was implemented by the publicly available Python library PYGAD. GA is a heuristic search algorithm, inspired by the process of natural selection, which aims to find approximate solutions to optimisation problems (Katoch *et al.*, 2021). This optimisation method was chosen for its capability to work well in multivariate regression problems. For instance, GA performs a global search which has an advantage over gradient-based methods as it is less likely to get trapped in local minima.

In simple terms, the first step in GA is to initialise a population of candidate solutions randomly. The fitness of each solution is then evaluated using the fitness function. In this investigation, the fitness function was defined as the reciprocal of the $NRMSD_{sum}$ from all selected piles. The fittest candidates with the highest fitness scores are then selected for reproduction. Crossover is then performed to produce new offspring, during which mutation is applied to introduce variability. The old population is then replaced with a new one to create a new generation. This process is then repeated until a target fitness score or a maximum number of generations is reached (Katoch *et al.*, 2021).

3.3.4 Workflow

For each pile at each selected WTG location, the first stage of the analysis is to optimise the SRD parameters for the glacial till layer in order to minimise the errors propagated to the chalk calculations. The back analysed SRD profile of the till for each pile can be obtained using the bearing graphs. This can then be compared with that calculated using the default Alm and Hamre (2001) method and the corresponding NRMSD can be obtained. By repeating this procedure for the selected piles, the SRD parameters in the Alm and Hamre (2001) sand formulation (i.e. $S1$, $S2$, $S3$, $S4$ and $S5$ in Equations 2 to 4) can be optimised using GA such that the $NRMSD_{sum}$ is minimised.

The second stage of the analysis is to optimise the SRD parameters from Jardine *et al.* (2024) for the chalk. During this stage, the optimised Alm and Hamre SRD parameters are used for the glacial till. The back analysed chalk SRD profiles for each selected pile location are derived from the bearing graphs. These are then compared with the values predicted by Jardine *et al.* (2024). Similarly, GA can be used to optimise the chalk SRD parameters ($C1$, $C2$, $C3$ and $C4$ in Equations 6 and 7) to minimise the $NRMSD_{sum}$ from all piles.

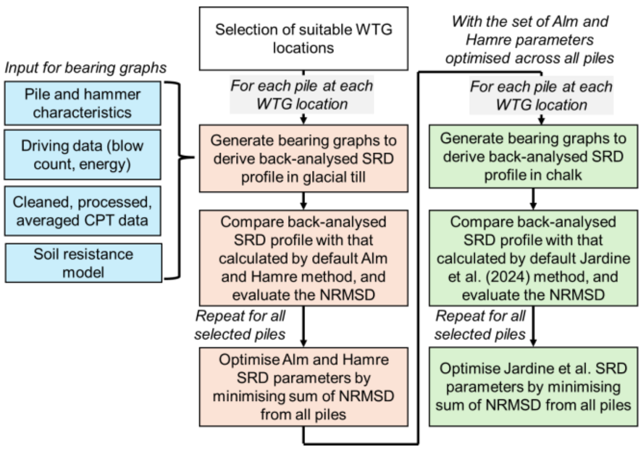

Figure 3 Proposed flowchart for driveability back analysis across all selected piles driven in a till overlying chalk stratigraphy

3.4 Discussion

As a demonstration of concept, although by no means statistically significant, two illustrative piles (Piles A and B) are considered from the Wikinger OWF database. Neither contributed to the earlier studies that established the Jardine *et al.* (2024) method, as these piles were not instrumented and so represent independent test cases.

The two piles were back analysed following the workflow summarised in Figure 3. Prior to initiating the optimisation using GA, engineering judgement had to be exercised to ensure that the bounds confining the SRD parameter search space were reasonable. Restricting the parameter space also helps decrease the computational time.

The Alm and Hamre (2001) SRD parameters optimised to fit the two analysed piles are presented in Table 4. While the results are not representative of the entire population of Wikinger piles, they suggest that a slight adjustment to the default parameters yields SRD profiles more closely aligned with the driving records in the till layer. Given that the underlying back analysed SRD values are dependent on the shaft-to-end bearing ratio, checks were made to ensure the fitted parameters lead to comparable ratios to those initially assumed. While this was the case, the bearing graphs could have been re-generated with updated shaft-to-end bearing ratios if significant differences had been noted. This process could have been repeated until the input and output values converged.

Using this optimised set of Alm and Hamre parameters for the till, the optimisation for the chalk was performed. It was found that the optimised values of parameters $C1$, $C2$, $C3$ and $C4$ fell close to the Jardine *et al.* (2024) default values (Table 4). Figure 4 compares the back analysed SRDs and the post-predictions of the two example piles after the joint optimisation.

While the demonstration considers only two piles, the full Wikinger OWF dataset is being back analysed to establish more statistically meaningful conclusions. Similar studies from other relevant chalk OWF sites should allow the development of an expanded database. A probabilistic approach can then be used to better quantify the practical impact of the earlier described input and model uncertainties.

Table 4 Summary of optimised SRD parameters across two example pile locations

Optimised Alm and Hamre (2001) parameters				
S1	**S2**	**S3**	**S4**	**S5**
0.034	0.237	0.1	0.2	0
Optimised Jardine *et al.* (2024) parameters (Same as default)				
C1	**C2**	**C3**	**C4**	
0.031	0.481	0.145	0.175	

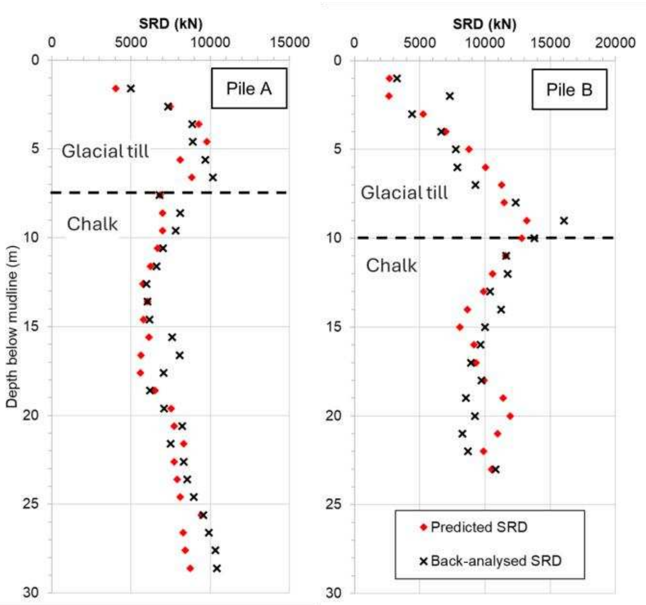

Figure 4 Comparison between back analysed SRDs and predicted SRDs for two example Wikinger piles

4 CONCLUDING REMARKS

This paper has proposed a systematic, data-based, workflow for back analysing historic driving blow count databases in weak rock formations to allow better prediction of driving behaviour at new weak rock development sites. The approach starts from existing formulations and updates these to provide best fits to the available geotechnical, pile and installation data. The approach has been illustrated employing exemplar data from the Wikinger OWF dataset of piles driven through glacial till and chalk.

While the approach appears promising, great care is required to optimise the highly intricate process. While most attention is often paid to the set of optimised SRD parameters, it is equally, if not more, important to appreciate the decisions and assumptions made throughout the back analysis process.

In many cases, weak rock formations are overlain by some soil overburden. The characterisation and the soil resistance modelling of the overburden are often overlooked but may influence the overall pile driving modelling significantly.

The quality and the availability of the input data often dictate the scope for data-driven optimisation. In most back analyses, a significant portion of time is devoted to data cleaning and pre-processing. Establishing filtering criteria helps identify suitable datasets and reduces time spent on pre-processing irrelevant data. Applying CPT averaging is a key pre-processing step. While various averaging techniques exist in the literature, due consideration should be given to the site-specific CPT profiles and pile details.

The limited examples examined in this study showed how the SRD employed for the glacial till layers needed adjustment to fit the available data records, while the Jardine *et al.* (2024) chalk SRD method appeared satisfactory without further modification. Application of the approach to larger and more statistically meaningful datasets is currently in hand.

AUTHOR CONTRIBUTION STATEMENT

S.P.C. Che: Conceptualisation, Data curation, Methodology, Formal analysis, Visualisation, Writing- Original draft. **F.C. Schroeder, S. Kontoe, R.J. Jardine, P. Barbosa**: Review, Writing- Reviewing and editing.

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REFERENCES

Alm T. and Hamre, L. (2001). Soil model for pile driveability predictions based on CPT interpretations. Proc. 15th Intl. Conf. Soil Mech. Geotech. Eng., Istanbul, Turkey: 1297-1302.

Barbosa, P., Geduhn, M., Jardine, R.J. and Schroeder, F.C. (2017). Large Scale Off-shore Static Pile Tests – Practicality and Benefits. Proc 8th Int. Conf. on Off-shore Site Investigations and Geotechnics, SUT London. Vol. 2, p. 644-651. doi:10.3723/OSIG17.644

Buckley, R.M., Jardine, R.J., Kontoe, S., Barbosa, P. and Schroeder, F.C. (2020). Full-scale observations of dynamic and static axial responses of offshore piles driven in chalk and tills. Geotechnique. 70 (8), pp. 657-681. doi/10.1680/jgeot.19.TI.001.

Buckley, R.M., Kontoe, S., Jardine, R. J., Barbosa, P., & Schroeder, F.C. (2021). Pile driveability in low-to-medium density chalk. Canadian Geotechnical Journal. Vol. 58(5), pp. 650-665. doi:10.1139/cgj-2019-0703.

Jardine, R. J., Chow, F. C., Overy, R. F. & Standing, J. R. (2005). ICP design methods for driven piles in sands and clays. Thomas Telford Ltd. London.

Jardine, R.J., Buckley, R.M., Liu, T.F., Andolfsson, T., Byrne, B.W., Kontoe, S., J., McAdam, R. A., Schranz, F. and Vinck, K. (2024). The axial behaviour of piles driven in chalk. Geotechnique. 74 (6), 553-569. https://doi.org/10.1680/jgeot.22.00041

Katoch, S., Chauhan, S.S. and Kumar, V. (2021) A Review on Genetic Algorithm Past, Present, and Future. Multimedia Tools and Applications, 80, 8091-8126.

Perikleous, G., Stergiou, T., Hansen J.K., Meissl, S. (2023). Methodology for developing and evaluating an SRD methodology based on offshore wind monopile driving records. 9th International Offshore Site Investigation and Geotechnics (OSIG): Innovative Geotechnologies for Energy Transition, 2023.

Smith, E. A. L. (1960). Pile-driving analysis by the wave equation. J. Soil Mech Found. Eng. - ASCE, 4(86), 35-61.

Smith, A. K. C. (2001). Interpretation of cone penetration tests in chalk. Ground Engineering, 34(9), 30-35