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Pile end bearing resistance in rock and potential influence of pilot holes

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ABSTRACT: As offshore developments continue to expand worldwide, rock is often encountered at relatively shallow depth below seafloor. Driven piles are commonly used offshore and considered a reliable foundation option, with internal drill outs (Drive-Drill-Drive, DDD) considered an important mitigation option. However, the existing guidance with respect to estimating 'intact' pile driving resistance and in-place pile capacity for driven piles in rock is limited with even less information regarding the effects of internal drilling.
The initial pile end bearing resistance is a function of pile dimension, rock strength, weathering profile and in-situ stresses with the internal drilling reducing internal pile friction and pilot hole potentially altering the rock fracturing mechanism and/or stress relaxation. The aim of this paper is to summarise existing industry best practice, supplement it with inhouse knowledge including numerical modelling, small scale testing and field data to provide refined recommendations with respect to the intact end bearing resistance and the effect of internal pilot holes for reducing the end bearing resistance.

Keywords: Piles, Rock, End bearing

1 INTRODUCTION

Rock within likely foundation depths is often encountered as offshore developments, especially offshore wind projects, continue to expand worldwide.

Driven piles are commonly used offshore and are considered a reliable and economical foundation option. However, rock can provide a significant challenge to driving with a high potential for early refusal and/or causing pile tip damage. If rock/hard driving is anticipated, then internal drill out of the pile (to the pile toe or below) is a mitigation option to allow driving to continue. This method is called Drive-Drill-Drive (DDD) and is discussed in more detail in the following section.

The existing guidance with respect to estimating 'intact' (i.e. 'non drilled') pile driving resistance and in-place pile capacity for driven piles in rock is limited with even less information regarding the effects of internal drilling.

The aim of this paper is to summarise current best practice and provide recommendations as to how end bearing resistance in rock should be considered and evaluation of potential effectiveness of DDD.

2 DRIVE-DRILL-DRIVE

Drive-Drill-Drive (DDD) can be an effective mitigation technique in the event of early pile driving refusal or in case pile tip buckling risk is anticipated. Installation methods including DDD are discussed in more detail in Cardoso et al. (2024) and is summarised below.

There are generally three main DDD phases:

- Phase 1 – Normal driving until refusal (or before if tip buckling is a risk)
- Phase 2 - Internal drill out to the refusal depth (or above) to remove/reduce internal shaft friction then redrive till refusal/target depth
- Phase 3 - Drill pilot hole out to a depth below refusal to reduce internal shaft resistance and the end bearing resistance then drive to target

These phases are illustrated in Figure 1 below:

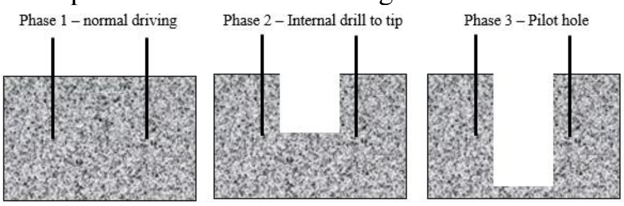

Figure 1: Drive-Drill-Drive Phase Illustration

DDD has been successfully used as a mitigation option on several offshore wind developments including monopiles for Teesside and Gwynt Y Mor and the Courseulles OSS jacket piles.

3 CURRENT PRACTICE

3.1 Phase 1 - No-drill End Bearing Resistance

The end bearing resistance can be calculated using the bearing factor method and the rock strength (UCS) as recommended by several publications including Stevens et al. (1982):

$$q_u = N_k * \sigma_c \qquad (1)$$

where:

q_u - End bearing resistance (MPa),
N_k - bearing resistance factor (-),
σ_c - Uniaxial Compressive Strength (MPa).

There is limited public domain information available regarding tip bearing factors for tubular driven piles in rock; Table 1 summarises existing references.

Table 1: Bearing Factors from Literature

Bearing Factor	Reference
3.0 - Pile driving in (carbonate) rock	Stevens, Wiltsie, & Turton (1982)
0.3 - rock with open joints 3.0 – weak rock	Fleming (1992)
2.5 - pier sockets in weak rock	Rowe & Armitage (1987)
4 to 6 - sandstones, limestones and granites	Rehnman & Broms (1971)
5.0 - Rock socket piles in mudstone	Williams (1980)
5.4 to 6.8 for rock with widely spaced joints	Tomlinson (2014)

The value recommended by Stevens et al. (1982) is probably the most commonly used (Irvine et al. 2015) but there is a significant range in the bearing factors detailed by different authors. However, the data does appear to indicate the bearing factor is sensitive to rock strength and weathering profiles with weathered/jointed rock such as indicated by Fleming (1992) showing lower bearing factors. It is also noted rock socket end bearing factors tend to be lower (such as Rowe & Armitage, 1987).

Whilst there is limited guidance with regards to bearing factors for piles, there has been more research for larger spread footings. Kulhawy and Goodman (1980) and more recently Prakoso and Kulhawy (2006) correlated the foundation Bearing Factor with the weathering profile/discontinuity spacing (s_j) relative to foundation width (B) and rock joint / discontinuity friction angles (from 10-40°) as shown in Figure 2.

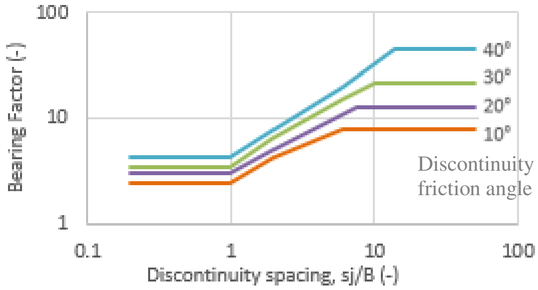

Figure 2: Prakoso and Kulhawy (2006) Factors

Merifield et al. (2006) (Figure 3) concluded that bearing capacity in rock is a function of:

- Rock UCS normalised to effective footing width
- Rock weathering (GSI)
- Rock mass Hoek & Brown constant, (m_i)

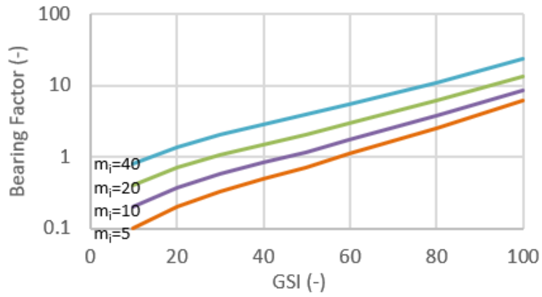

Figure 3: Merifield (2006) Bearing Factors

The available data would appear to indicate bearing factors are relatively insensitive to rock strength (and wall thickness), however, end bearing resistance is significantly sensitive to weathering (GSI/RQD) and joint condition (rock mass constant (m_i) / joint friction angle). Relatively intact rock will tend to be in the range indicated in most of the studies shown Table 1 (N_k = 3 to 6) but weathered and/or low density rock could show much lower values particularly for larger pile diameters.

3.2 Current Practice – Influence of drill

There is notable uncertainty as to the bearing factor to use for intact rock with limited guidance regarding the effect of pilot holes in rock.

Rojas (1993) undertook a limited number of small-scale models to assess the influence of pilot hole-boring (phase 3) on pile capacity in clay and recommended the following:

$$Q_{ur} = Q_u \left(1 - 0.5 * \left(\frac{A_{pp}}{A_{tp}}\right)\right) \qquad (2)$$

where:

Q_{ur} - Reduced end bearing resistance (MN),
Q_u -(Original) end bearing resistance (MN),
A_{tp} - total pile area,
A_{pp} - prebored pile area.

Inhouse experience indicates that the Rojas method for estimating bearing capacity factors tends to over-estimate the bearing factor (considered conservative for pile driving) but may provide a useful initial estimation.

3.3 Current practice conclusions

The initial pile end bearing resistance is a function of pile dimension, rock strength, weathering profile. Formulae detailed by Prakoso and Kulhawy (2006) and Merifield et al. (2006) are considered reasonable for an initial assessment of 'intact' end bearing but additional information would be required to confirm.

Drilling operations should reduce the internal pile friction and the pilot hole is likely to significantly reduce in-situ stresses and thus potentially alter the rock fracturing mechanism and activate strength reduction effects due to stress relaxation. The Rojas (1993) method may provide an initial estimation of the stress reduction but there is limited data to validate this. Consideration could be given to numerical modelling to better understand the potential effectiveness as discussed below.

4 NUMERICAL MODELLING

The authors have experience undertaking detailed analysis such as Limit Equilibrium (LE), Finite Element Modelling and Particle Modelling to justify and optimise the bearing factors used in detailed design.

4.1 LE Model – Phase 1 Normal Driving

Limit Equilibrium software (LimitState. 2015) was used to investigate the failure mechanism and mechanics of pile penetration into rock. The assessments used a Tresca soil model and various pile and pilot hole geometries were assumed with the pile 'wished in place' before downwards displacements were applied to investigate penetration resistance.

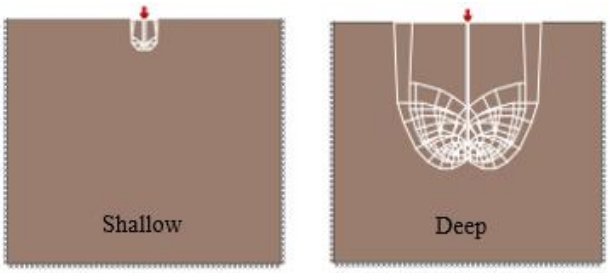

Figure 4: Normal Driving – Tip Failure Mechanism

Initial limit equilibrium modelling of pile wall penetrating intact rock as shown in Figure 4 indicates a local 'coring' mechanism as the pile penetrates into rock. The following influence was noted for intact driving, which is in line with traditional methods, validating the intact bearing factor, $N_k = 4.5$

4.2 LE Model – Phase 2 Internal Drill

An internal drill out would remove the soil/rock within the pile. Resulting in a removal of internal shaft friction. It would also result in a reduction in the internal confining stresses, allowing for a preferential internal coring mechanism as illustrated below.

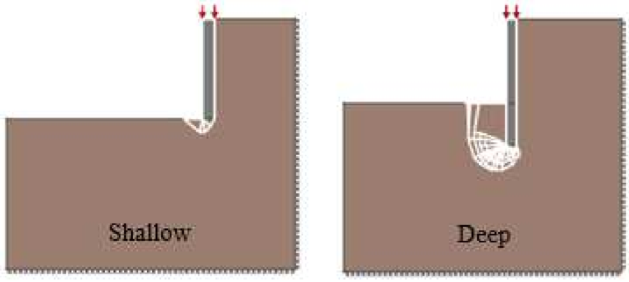

Figure 5: Internal Drill out – Tip Failure Mechanism

The results as shown in Figure 5 indicate the internal drill removes the vertical confining pressure inside the pile which results in a significant reduction in the bearing factor when driving restarts.

The following influence was noted as pile penetrates below base of drill out:

- tip at base of drill, Nk = 2.8 (i.e., -37%),
- tip at 25cm below drill, Nk = 3.7 (i.e., -18%),
- tip at 50cm below drill, $N_k = 4.0$ (i.e., -11%).

The bearing factor is indicated to increase as penetration below socket increases. However, it should be noted that the 'wished in place' mechanism is likely to result in the resistance being overestimated as it does not account for the disturbing effects of earlier driving.

4.3 LE Model – Phase 3 Pilot Hole

Pilot holes will remove internal shaft friction and further reduce end bearing resistance through a progressive 'wedge' failure as illustrated in Figure 6.

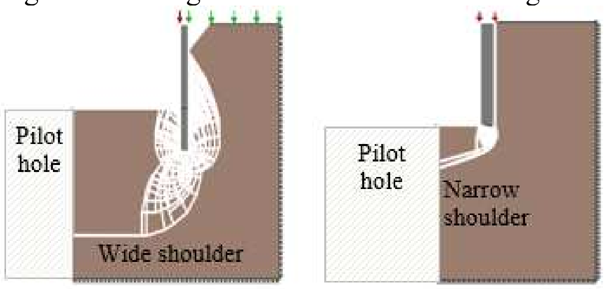

Figure 6: LE Pilot hole model.

However, it should be noted that the 'wedge' mechanism will only have a significant effect as the pilot hole diameter approaches that of pile (i.e. the shoulder width is narrow).

Author experience and LE sensitivity checks would indicate the N_k is most sensitive to pilot holes within ~5 wall thicknesses, this is consistent with pile group effects and jackup spudcan interaction effects.

Numerical Finite Element Modelling (FEM) was undertaken in Plaxis 2D which showed similar results.

4.4 PFC3D

Traditional LE and Finite Element Methods (FEM) may struggle to handle the large-scale displacements associated with pile penetration problems, as well as the brittle nature of rock failure. To overcome these limitations, PFC3D (Particle Flow Code in 3D) was used to simulate the behaviour of rock mass and the brittle breakage in individual particles after failure.

The rock model was simulated using a packed assembly of spherical particles with interparticle contact that was modelled using the built-in linear parallel bond contact model (Itasca, 2000). The contact model parameters were calibrated via simulated unconfined tests to obtain a UCS of 20MPa.

Figure 7 presents the developed pile model and the pile penetration simulation result in terms of end bearing pressure versus vertical pile penetration, resulting in an end bearing factor of approximately 4.1.

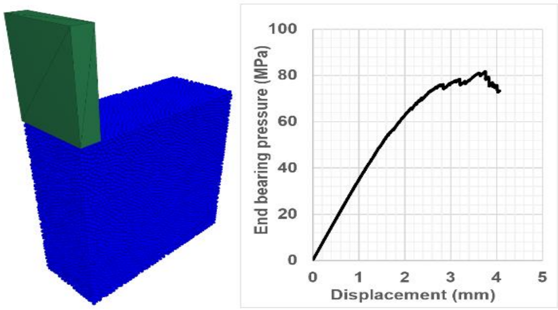

Figure 7: PFC3D model results.

5 SMALL SCALE TESTS

In the initial stages of studying pile driving in rock, a scaled test setup was developed to perform some experiments. Using an SPT hammer, concrete (intended to model sandstone) and steel test pipes, the setup replicated the challenge of driving a pile into a pilot hole. The focus of the study was to observe the reduction of end bearing relative to pilot hole diameter and pile wall thickness, examining various pilot-hole to pile diameter ratios as detailed in Table 2.

The influence of pilot holes was estimated by comparing the blow count per cm penetration. The test results indicate bearing resistance reductions vary with pilot hole diameter and correlates well with the outcome of LE model and the Rojas method tends to provide a relative high estimate as shown in Figure 8.

Table 2: Small scale test details

Ratio D_{pilot} / D_{pile} [%]	Residual End Bearing [%] Set 1	Set 2	Set3	Set 4
88	78	65	55	75
92	65	41	41	51
96	53	37	38	45

A secondary conclusion was that despite the careful preparation and the prudent installation during the test, multiple piles 'failed' due to pile tip damage / buckling, however increasing pilot hole diameter tended to reduce risk of damage.

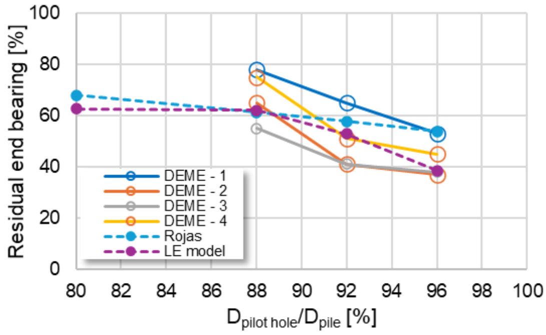

Figure 8: Small Scale Test Results

6 OFFSHORE EXPERIENCE

The authors have experience from several offshore wind farms with good quality site investigation data and Pile Drive Monitoring (PDM) data. The sites with good data include a range of pile sizes and rock types including sandstone, mudstone and limestone.

The authors also have experience from several sites with lower quality geotechnical survey data and/or limited driving information (no PDM), which indicated the potential for significant driving variability, even for locations with apparently similar rock and pile dimensions. Experience with nearby sites and or similar rocks tended to increase accuracy of predictions.

6.1 Parameter sensitivity

The available survey data usually included borehole logs, laboratory testing such as UCS and point load (Ip) and limited amount of offshore testing including pressuremeter and PS logging. Some examples are shown in Figure 9 where available data indicates the potential for laboratory tests to underestimate the in-situ (confined) rock strength, potentially due to deconfinement and/or sample disturbance in weak rocks, conversely the opposite could be true if only good quality (strong) samples are tested meaning the potential for lab testing to overestimate insitu rock mass strength. Therefore, rock mass and sample quality should be carefully assessed and strength testing planned with care.

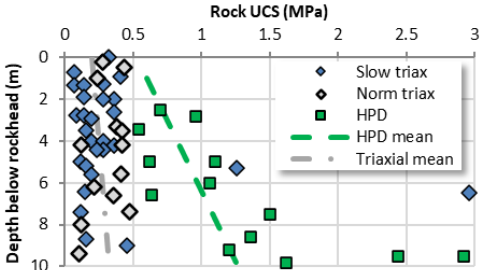

Figure 9: Site UCS Data

6.2 Normal Driving PDM Assessment

Detailed data including good quality geotechnical survey and driving data including Pile Driving Monitoring (PDM) was available for 3 sites with shallow rock. The basic information for these sites is outlined in Table 3 below. The lab testing comprised UCS and point load (I_p) tests and the indicative bearing (N_k) values were estimated from the available PDM data assuming in-situ rock strength measurements are most accurate.

Table 3: Offshore site data examples

Parameter	Site 1	Site 2	Site 3
Pile diam	1.27m	2.0m	6.1m
Rock type	Mudstone	Sandstone	Mudstone
Strength – Lab test	0.5MPa	~3.2MPa	15MPa
Strength – HPD	3MPa	~7MPa	NA
GSI	60-100	60-80	60-80
Joint friction*	10-20°	20-30°	10-20°
Intact rock, m_i*	5-10	15-20	5-10
Indicative N_k	~9	~4.5	~1.5

*Note values estimated from literature.

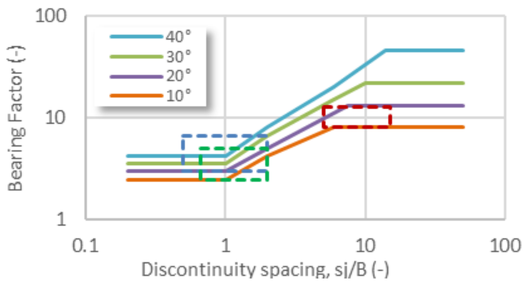

Figure 10: Offshore Data overlay with Kulhawy

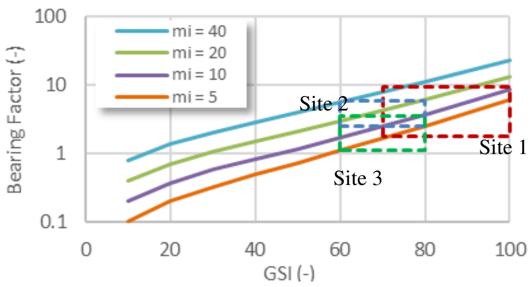

Figure 11: Offshore Data overlay with Merifield

Envelopes showing the range of bearing factors (from PDM) and weathering (from boreholes) for the sites considered are shown on the plots suggested by Kulhawy and Merifield in Figure 10 and Figure 11.

6.3 Drive-Drill-Drive PDM Assessment

Detailed data including good quality geotechnical survey and driving data including Pile Driving Monitoring (PDM) was available for a site where pilot hole methodology was implemented to allow pile driving until penetration, and a second site where drill-out of large diameter pile was performed before resuming impact driving until target penetration. The reduction of the end bearing due to the pilot hole, or drill-out, was derived by comparing the PDM data at the end of initial driving (refusal in rock) with the PDM when driving resumed after drilling. A behaviour in line with the LE numerical modeling was observed in both cases, respectively for the pilot hole and internal drill phases.

6.3.1 Phase 2 - Drill out PDM

The drill out process on a large OD pile provided a bearing reduction of ~20%. This result fits with coring behaviour evaluated from the LE numerical modelling at 0.25m penetration. This is likely due to the shape of the internal drill out leaving some rock towards the inner diameter of the pile.

6.3.2 Phase 3 - Pilot Hole PDM

For the pilot hole case, a reduction of 73 to 85% of the total end bearing was observed which indicates greater reductions than predicted by numerical analyses. The LE numerical analyses assumed intact rock. The initial pile driving process and drilling processes are likely to result in rock fracturing and potentially in-situ stress relaxation which could result in greater reduction with the pilot hole. Therefore, the LE modelling was considered conservative, tending to underestimate the influence of the pilot hole.

It should be noted that one of the data points corresponds to a pile for which driving interruption occurred in overburden soils prior to encountering competent rock layer, here the reduction in end bearing was ~27%. This point is considered an outlier as the shaft friction is considered likely to provide the majority of the driving resistance therefore the results are not applicable to rock with high end bearing resistance.

Figure 12 illustrates the reduction of the tip bearing resistance from LE numerical models and PDM results, accounting for the dimension of the rock shoulder, pile diameter and pilot hole diameter.

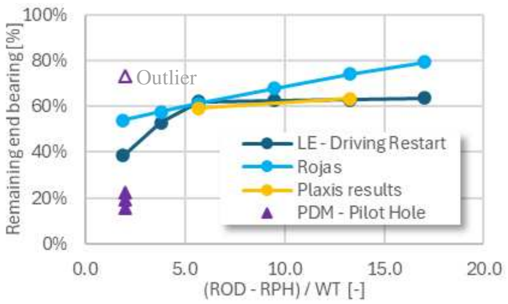

Figure 12: DDD PDM Results comparison

7 SUMMARY AND CONCLUSIONS

The paper highlights the importance of insitu rock strength, weathering and potential variability when assessing pile end bearing resistance and understanding resultant driving risk and mitigation strategy (DDD). Sampling, in-situ and laboratory testing should be carefully planned to provide a good understanding of rock conditions. Engineering experience in the region and/or similar rocks can provide significant insight into potential rock behaviour.

It also provides a framework for assessing the initial end bearing resistance. The Prakoso and Kulhawy (2006) or Merifield et al. (2006) methods are considered reasonable for an initial assessment of intact end bearing. The Rojas (1993) method may provide an initial estimation of the stress reduction. Additional information would be required to confirm both methods. Consideration could be given to numerical modelling to better understand the potential effectiveness as discussed above. Instrumented test piles may also provide a significant benefit.

The bearing resistance methods detailed above can also be used to evaluate end bearing capacity for axial pile design. It should be noted that DDD particularly using pilot holes could also result in reduced axial capacity. Therefore, the optimum DDD should be carefully considered during the design process to de-risk installation without adversely affecting capacity.

AUTHOR CONTRIBUTION STATEMENT

J Irvine: Original draft. **I Terribile**.: LE and FE modelling. **A Crochelet:** PDM interpretation. **E Nicolini:** Supervision, Review. **S Raymackers:** Editing, Review. **B Alsayegh: L**ab tests, Review

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