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Monopile foundation behaviour in carbonate soils - existing knowledge gaps

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ABSTRACT: Carbonate sediments are found across the globe and have been a hazard for offshore geotechnical engineers for many years. Due to their nature and open structure, carbonate soils are highly compressible and prone to crushing, posing a significant risk for foundation design and installation.
Although significant experience has been gained over the years from the oil and gas industry through numerous projects, especially on the Australian continental shelf, there is still a lot of uncertainty regarding monopile foundation design in carbonate sediments. Existing design standards by the offshore wind industry, such as DNV-RP-C212 and API-RP2GEO, only provide limited guidance regarding carbonate sediments.
The current paper outlines the existing experience as documented in the literature, maps existing gaps in monopile foundation design, and highlights the required steps for ensuring feasible and economic monopile foundation design for offshore wind farm developments.

Keywords: carbonate sediments; monopiles; offshore wind

1 INTRODUCTION

Carbonate sediments are found worldwide but are most dominant as geotechnical hazards at many of Australia's proposed offshore wind zones. While monopiles are the preferred offshore wind turbine support structures globally, their performance in carbonate sediments is uncertain.

Carbonate sediments are highly variable, from soft, uncemented silts and clays to dense, well-cemented calcarenites and limestones. Uncemented carbonate sediments are highly compressible and susceptible to crushing. Under cyclic loading, this could result in significant movement and tilt of an offshore wind turbine, leading to serviceability and safety concerns. The mix of uncemented and cemented carbonate sediments poses construction challenges such as pile run and pile drivability issues (including pile buckling). In severe cases, a monopile can be lost during installation due to uncontrollable movement (pile run), posing a significant risk to the foundation and the installation vessel.

Engineers face significant challenges in ensuring the satisfactory performance of large-diameter monopiles and jacket piles in carbonate sediments due to limited guidance on axial and lateral capacity and stiffness. Existing industry standards, such as API-RP-2GEO and DNV-RP-C212, are not specifically tailored to the unique properties of these sediments and are, therefore, inadequate. A key limitation is the lack of full-scale lateral pile load test data for carbonate materials, which hampers the development of improved methodologies. While some experimental studies using centrifuge models have been conducted, large-scale testing remains absent, particularly for cyclic lateral loading of monopiles in carbonate sediments. Existing experience from jacket piles is predominantly based on oil and gas applications and does not sufficiently cover the loading cases and behaviour of offshore wind monopiles.

2 CARBONATE SEDIMENTS

2.1 Nature of soils

Carbonate sediments are defined by the presence of calcium carbonate ($CaCO_3$) minerals within the sediment, with calcite and aragonite being the

dominant forms found in offshore environments. The $CaCO_3$ can form the individual grain or the sedimentary matrix depending on the origin, transportation, and deposition processes as well as densification and consolidation processes. The carbonate source can come from a wide spectrum of biogenic and authigenic carbonate materials, including both whole and fragmented skeletal remains and aggregated particles. The variability in the formation processes leads to high variability in the sediment's geotechnical characteristics governed by the individual grains and/or the matrix.

Carbonate sediments exhibit several distinct characteristics that set them apart from other sediment types. Of particular relevance to engineering applications is intragranular porosity within some "fresh" carbonate sediments, where fragile grains have yet to collapse. This, combined with an open structure, accounts for the extreme sensitivity of certain fine-grained carbonate soils. For instance, this property can lead to challenges such as mobilising very low pile shaft friction during foundation installation. To provide context, carbonate sediments often have more void space relative to solid material. Additionally, cemented layers are commonly present, which contrast this behaviour. Cemented carbonate sediments are notoriously hard, causing issues with pile drivability.

It is essential to distinguish the carbonate sediments investigated in this study from chalk (a weak limestone), which forms through a specific process and is not addressed in the current paper.

2.2 Geographic Extent

Carbonate sediments are encountered across the globe, from the Gulf of Mexico and Brazil to the Arabic Gulf, the North Sea, East Africa, India, and, of course, Australia, as indicated in Figure 1 (Watson et al., 2019). Carbonate sediments can have a significant influence in offshore developments, encompassing both the oil and gas sector and the offshore renewable energy industry.

As indicated by Watson et al. (2019), carbonate sediments are dominant in the Bass Strait, the location of the Gippsland offshore wind area, where a surficial carbonate content of 100% can be encountered. These are predominantly sandy sediment in shallow waters, becoming silty sand (to silt) with increasing water depth (Watson et al., 2019) with varying degrees of cementation.

According to Heap et al. (2006), carbonate sediments are also likely to be encountered in all the other offshore wind areas identified in Australia, as shown in Figure 2.

Figure 1. Global map showing carbonate sediment locations (after Watson et al., 2019).

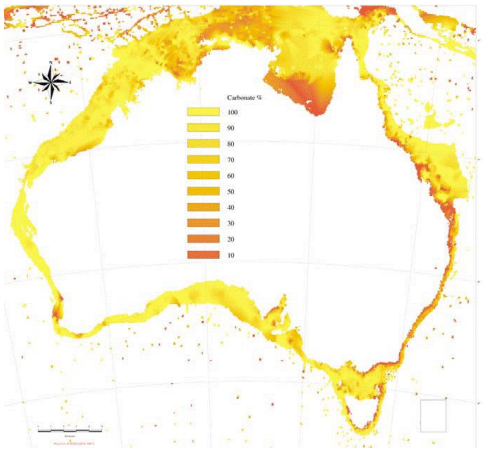

Figure 2. Carbonate content of surficial sediment around Australia (after Heap et al. 2006).

3 PREVIOUS WORK DONE

Existing knowledge and design methods for pile foundation behaviour mainly rely on experience from offshore oil and gas projects on the continental shelf of Australia. This work was predominately undertaken by the University of Western Australia Centre for Offshore Foundation Systems (COFS UWA) and the industry in order to address the challenges encountered in several high-profile projects in Bass Strait and off the Northwest Shelf of Australia (including North Rankin A, Goodwyn A and Yolla A and Trefoil) which necessitated costly retrofit programs (Randolph, et al., 2005). The following sections outline some key publications for pile foundations in carbonate sediments.

3.1 Site investigations

A major problem of carbonate sediments in site investigation is the large spatial variability of soil strength and characteristics, as they can significantly vary both vertically and horizontally over small distances. This makes site investigation (both geophysical and geotechnical) more complex and

costly, as an intensive site investigation program and an integrated ground model are required to characterise the potential site correctly. In the case of offshore wind, where site investigations constitute 5-20% of Development Expenditure (DEVEX) (Department for Energy Security and Net Zero. 2023), this can significantly impact the project development.

As White et al. (2013) mentioned, sampling carbonate sands can be very challenging, and specialised techniques are required depending on the soil type and degree of cementation. In addition, in-situ testing with devices other than the traditional CPT cone, such as the T-bar or ball penetrometers, can provide more reliable information due to the high sensitivity of the soil matrix. However, complete CPT profiles can be challenging to obtain in the case of cemented sediments.

The challenges in sample recovery can have a major impact on laboratory testing. Joer et al. (2013) demonstrated that a significant variance in lab testing results can be expected between laboratories.

An elaborative discussion of the behaviour of carbonate soils can be found in Randolph and Gourvenec (2011).

3.2 Axial and lateral in-place pile behaviour

Randolph and Jewell (1989) presented a model for calculating the axial pile capacity, emphasising the cyclic degradation of carbonate soil.

Wesseling et al. (1988) and Williams et al. (1988) established the p-y formulations for uncemented carbonate sands based on centrifuge and model pile tests, while Novello (1999) provided a simplified method for static and cyclic p-y curves for slender piles, as a function of the CPT cone tip resistance, q_c, the effective overburden stress, pile diameter and a material constant. Moreover, Dyson and Randolph (2001) also proposed a power law p-y formulation based on q_c.

Furthermore, Guo and Zhu (2005) have proposed a closed-form solution for static and cyclic p-y curves, which were compared to the onshore test results performed as part of the Kingfish B platform development.

In their keynote lecture, Erbrich et al. (2011) introduced two tools for pile analysis and design in carbonate soils: CYCLOPS for axial loading and pCyCOS for lateral loading. Both methodologies combine strong theoretical foundations with empirical calibrations to address observed soil behaviour. Both models have been used in the foundation design of offshore oil and gas projects. CYCLOPS relies on the constant normal stiffness (CNS) calibration approach for cyclically loaded piles in cemented carbonate soils, though its applicability requires caution due to site variability. pCyCOS uses p-y curves derived from cyclic and monotonic testing but lacks comprehensive full-scale lateral load tests for uncemented carbonate soils.

3.3 Pile installation

Pile installation in carbonate sediments can be a significant risk for offshore wind farm developments due to the nature of the soil and the resulting requirements for larger foundations.

Soil resistance to driving (SRD) of carbonate sediments can be significantly lower than that of typical silica grain soils, as predicted by standard industry SRD methods such as Alm & Hamre (2001). This can be attributed to the soil matrix's open structure and the soil grains' crushability when subjected to the continued cyclic loading from the hammer impact forces. Furthermore, most SRD methods require the use of reliable CPT data that are challenging to obtain in carbonate soils.

SRD predictions in carbonate sediments are typically performed using the Stevens et al. (1982) method, which uses the unconfined compressive strength UCS of the soil (Brunning and Ishak, 2012). However, again, this value depends on obtaining high-quality samples, which, as explained in the previous section, can be challenging. Boylan et al. (2017) discussed the installation of 5.5m diameter (OD) piles in the Ichthys development and compared the predicted SRD, based on a modified Alm & Hamre (2001) method, with the back-analysed SRD. The paper shows that the recoded resistance is aligned with the lower bound predictions. Schneider et al. 2007, discuss the behaviour of piles driven in calcareous sands and demonstrate the rapid development of friction fatigue compared to silica sands.

Most of the experience with pile installation in carbonate sediments is based on the installation of Oil and Gas piles in the Arabian Gulf and offshore Australia, but as presented by Perikleous et al. (2020), the installation behaviour of monopiles can be significantly different from that of slender piles. As such, it is questionable whether existing prediction methods will provide reliable results for big monopiles used by the offshore wind industry.

4 DESIGN CONSIDERATIONS FOR OWT

4.1 Slender pile vs monopile (PISA)

The pile foundations of oil and gas projects are typically long slender piles with a ratio of length to diameter (L/D)>60. In contrast, typical monopile pile

foundations used in the offshore wind industry have a significantly lower L/D ratio (typically 2 to 6). Consequently, the behaviour of these piles differs significantly, especially concerning lateral loading, as documented by the PISA project (Byrne et al., 2017). p-y springs typically used for analysing the lateral response of slender piles do not sufficiently capture the much stiffer monopile behaviour, where in addition to the p-y springs, distributed moment springs and base moment and shear force should also be used, as shown in Figure 3.

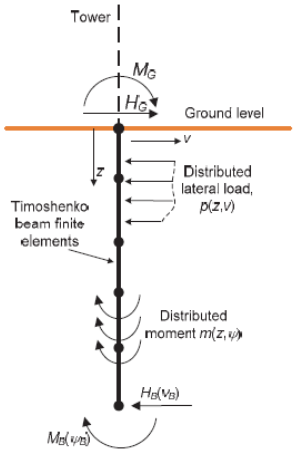

Figure 3. Soil reaction components of monopile (after Byrne et al. 2017)

As such the suitability of existing models as the ones outlined in Section 3.2 needs to be validated when it comes to monopile foundation design.

Furthermore, existing monopile design methodologies are based on point information (e.g. CPT reading) which inherently assumes that soil conditions are relatively uniform across the area of influence of the monopile, typically considered as 3-5 times the diameter (OD). Given the current monopile diameters (OD >10m) the validity of this assumption will need to be evaluated.

An additional complication for monopiles installed in cemented carbonate sediments, either by impact driving or drill and grout, can be crack propagation in cemented layers to the seabed and its influence on the foundation stiffness, which is a critical parameter for wind turbine generators. This kind of stiffness degradation can significantly complicate the foundation design as it can affect different design limit states.

4.2 Constitutive models for carbonate soils

State-of-the-art design methods used in offshore wind, such as PISA, heavily rely on finite element analysis (FEA). Correct constitutive models that capture carbonate soils' behaviour, including high porosity, crushability, cementation and stress path dependency, is critical for correctly modelling the monopile behaviour. Although some relevant models can be found in literature, such as Berenguer Todo Bom, L., & Modaressi-Farahmand-Razavi, A. (2014), Liu et al. (1997) and Islam et al. (1997), those models are not currently implemented in any of the widely used FEA codes. Their suitability for monopile foundation design requires further validation.

4.3 Cyclic degradation

Cyclic degradation of strength and stiffness of soil can be design driving for WTG monopile foundations as it can dominate both the Serviceability Limit State (SLS) and the Ultimate Limit State (ULS). Cyclic degradation and its effect on pile foundation response is still an important research topic, even in typical soils (i.e. silica soils). Dimensions of modern offshore wind turbine monopiles are often driven by SLS criteria (monopile rotation), which is heavily affected by the cyclic degradation of soil stiffness under cyclic loading.

Carbonate sediments, being highly compressible, experience a rise in pore pressure under cyclic loading. This can lead to stiffness degradation around the monopile surface. In combination with the fragile nature of the carbonate particles, this can lead to significant accumulated displacements and, under extreme storm loads, a reduction of soil strength. As the excess pore pressure dissipates, additional settlement takes place.

Furthermore, under cyclic loading, pile foundations undergo a stress redistribution along the pile length as the stresses in the upper soil layers increase and the soil degrades. Stresses propagate to lower soil layers, causing further degradation along the pile length as the cyclic event progresses.

The pyCyCOS program by Erbrich et al. (2010) provides valuable input on assessing the effects of cyclic degradation, especially stiffness degradation. However, the method's applicability to large monopile foundations needs further investigation.

For drill-grouted piles or piles driven into cemented carbonate soils, cyclic loading can lead to crack creation and subsequent propagation, as previously mentioned, resulting in permanent stiffness degradation. This can significantly impact the Fatigue Limit State (FLS) and SLS design.

5 EXISTING TESTS

Pile testing in carbonate sediments is mainly limited to scale tests performed predominately for slender piles. Early work includes the pile model tests by McCarel

et al. (1984) and the centrifuge tests by Wesselink et al. (1988) and Dyson & Randolph (2001).

As part of the Kingfish B development medium scale tests of 0.356mm OD and 6,27m length steel piles were installed and laterally loaded Williams et al. (1988)

More recently, de Almeida et al. (2024) and Malakshah et al. (2022) reported centrifuge tests of laterally loaded monopiles in carbonate sands under static and cyclic loading.

6 WAY FORWARD

Ensuring safe and economical monopile foundation design requires further research to understand the proper response of these foundations in carbonate sediments.

Existing design methods should be reevaluated and, if necessary, be adjusted for monopile foundation design. As mentioned, existing methods have been developed for flexible piles, but they do not capture the monopile behaviour. Ideally, this development needs to be validated by large-scale field tests, such as the ones performed by the PISA (Byrne et al., 2017) and ALPACA (Jardine et al., 2019) projects, for static and cyclic testing, as well as proper instrumentation of the piles for analysing the axial capacity and soil resistance to driving. Of course, the large variability of carbonate soils can make selecting a suitable testing site challenging. Other design aspects that need to be addressed are the influence of cemented soil layers on the in-place and installation behaviour and the selected installation method (impact-driven, drill and grouted). A vigorous site selection process must be established to select a suitable testing site (or sites).

To complement the findings of the field-testing campaign, high-quality centrifuge tests from research centres with experience in carbonate soil testing can be performed. These tests can address specific topics, such as the influence of cyclic loads or installation hazards.

Furthermore, developments in the numerical modelling aspects of design, especially constitutive modelling, are also seen as necessary for fully utilising state-of-the-art FEA-based design methods. To establish confidence in these models, the capacity of existing and/or new constitutive models to capture the monopile behaviour in carbonate sediments must be evaluated based on well-documented field tests and scale tests.

7 CONCLUSIONS

Offshore pile design standards and guidance do not include methods for assessing lateral pile capacity in carbonate materials. Although some proprietary methods exist (Erbrich et al., 2011; Novello, 1999; Guo & Zhu, 2005), they are not applicable to very large-diameter monopiles and lack validation through physical-scale field testing. Moreover, widely used constitutive soil models in finite element design tools are not equipped to handle the characteristics of crushing carbonate materials or those that experience property changes over time, rendering these tools impractical for such applications.

Obtaining reliable testing data to validate and further develop existing design tools and methods for offshore wind turbines is necessary to ensure proper and safe monopile foundation design.

AUTHOR CONTRIBUTION STATEMENT

Yiorgos Perikleous: Conceptualization Writing- Original draft. **Other Authors**.: Writing- Reviewing and Editing,

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