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Foundation Design in Offshore Carbonate Sediments – Building on Knowledge to Address Future Challenges

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Abstract. Carbonate sediments are prevalent in many major offshore oil and gas basins, as well as a growing number of regions assigned to offshore wind development. Identified as difficult from an engineering perspective, the failure to properly characterize and design for these sediments has adversely influenced several projects. This paper provides a brief geological perspective, and identifies broad trends and characteristics to be considered when defining the engineering properties of such materials. An overview of the challenges faced when founding offshore structures in such sediments is provided, drawing on experience gained over the last 30 years, and with an emphasis on current and emerging issues.

Keywords. Carbonate, site investigation, sensitivity, foundation

1. Introduction

Carbonate sediments are found across the world, influencing offshore development from the oil and gas sector to the offshore renewable industry. When thinking about carbonate sediments, what features might a geotechnical engineer identify – grain structure, cementation, high variability, crushability, extreme sensitivity? These are all valid attributes, and highlight the complex behavior of such sediments – and the care needed in dealing with them.

The nature of carbonate sediments can influence the design process from concept stage through to operation, and ultimately to decommissioning. Challenges associated with the recovery of intact (high quality) sample, and difficulty developing design lines for a site lead to uncertainty; while high sensitivity and variability, as well as other engineering features, drive a need for bespoke design methods.

This paper briefly reviews the geology underlying the formation of carbonate sediments and where they are encountered, identifies and discusses aspects of their interpretation, and provides an overview of select foundation solutions that overcome the design challenges posed by these sediments.

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1.1. Context

The challenges associated with foundation design in carbonate sediments have been appreciated for many years, and there have been two international conferences on this topic. The first conference [1] was held in Perth in 1988 and focused both on the broader topic, but also included papers dedicated to the lessons learned from design and installation of the North Rankin A Platform. The second conference [2] was held in Bahrain in 1999 and introduced more recent engineering experiences. The period between the two events saw the release of a book dedicated to foundation design in carbonate sediments [3]. Since the late 1990s there have been numerous research studies and industry projects aimed at better understanding specific issues.

The current paper has been prepared by practicing engineers who work routinely on offshore projects encountering carbonate sediments – and the focus is on identifying practical aspects relevant for design.

2. A brief overview of carbonate sediments

2.1. What are carbonate sediments?

The term 'carbonate sediment' holistically defines both the origin and transportation/deposition processes that control individual grains, and the sedimentary package as a whole. In this context, 'carbonate' generally relates to the mineral polymorphs of calcium carbonate ($CaCO_3$). For sediments encountered offshore these are principally calcite and aragonite. Other polymorphs, such as dolomite, are typically less abundant offshore, as are non-calcium carbonates (magnesite, ankerite, siderite). In this paper, the term 'sediment' generally correspond to the very broad range of whole and detrital fragments of the skeletons and conglomerations generated by biogenic and authigenic carbonate production. Importantly in an offshore context, the term sediment also implies that individual grains have been subject to reworking, transportation and/or deposition, densifying and consolidation.

In classification terms, 'pure' carbonate sediments are defined as comprising greater than 90% $CaCO_3$ [4]. However, the term carbonate is also applied when the sediments include greater than 50% $CaCO_3$ (i.e. siliceous or clayey carbonate [4]). In contrast, calcareous sediments (or soils) are generally considered to contain between 10 and 50% $CaCO_3$ and can be considered 'transitional'. Such sediments generally do not exhibit the unique engineering properties attributed to carbonate sediments. This paper focuses on sediments with high $CaCO_3$ – but with a cautionary note that there is no fixed percentage at which such sediments should be treated as carbonate for engineering purposes.

Carbonate sediments are distinctive from other sediments in several ways. Perhaps most pertinent from an engineering perspective is the intragranular porosity inherent in some 'fresh' carbonate sediments, where the fragile grains have not collapsed. Combined with an open structure, this attribute explains the extreme sensitivity of some fine-grained carbonate soils and, for example, explains the very low pile shaft friction that can be mobilized in such soils during installation. To put this in perspective, carbonate sediments are frequently composed of more void space than solids.

Carbonate sediments can also extend into the rock realm – reflecting the fact that diagenesis of these sediments can occur independent of deep burial. Near-surface diagenetic processes are covered in more detail in the section below but it is important to note that the end product is that carbonate geology can be considered to present a sediment-rock continuum rather than a discrete divide.

The appropriate description of carbonate sediments can be problematic, and existing engineering logging standards often note the need for supplementary references. For example, the definition of grain shape, angularity and sorting/grading may give rise to misleading inferences about sedimentary processes, and subsequent engineering behavior. Reference to supplementary published geological standards can allow for greater flexibility, but this is hampered by key conflicts such as the definition of grain-size boundaries and the possibility that the added complexity detracts from the key message(s) relating to parameters for engineering consideration. To this end, there remains a need for a globally accepted classification system that acts as a bridge from geological observation to engineering parameterization.

2.2. How are they formed?

Carbonate sediments mainly originate either through biogenic primary production or authigenic precipitation. Both forms of production are intrinsically linked to the marine environment – biogenic through fauna habitats, and authigenic by the migration of hydrocarbons and bicarbonate ions of hydrothermal fluids [5]. Deposition in the marine environment means sediments are typically subject to multiple phases of degradation from wave, tidal, and current action, bioturbation and biodegradation (eg. borers, digestion), and/or mass transport processes. At any given time much, if not most, of the world's carbonate sediments are reworked – often to a state that has become unrecognizable from their original form.

Calcareous skeletons (see Figure 1) are produced by a wide variety of organisms, ranging from bacteria to a wide variety of marine plants and animals. Diversity in organisms is reflected in diversity of habitat, and carbonate sediments are accordingly produced in most marine environments – although the greatest abundance is noted in warm, clear, shallow water environments with sufficient nutrients and exposure to sunlight. Biogenic production takes place on the sea floor (benthic organisms) as well as in the water column (planktonic organisms). Unsurprisingly, the resulting sediments exhibit highly variable morphology – ranging from delicate balloon-like planktonic foraminifera to solid ooids. Biogenic production can also form carbonate rocks through coral reefs and cyanobacteria communities, such as stromatolites.

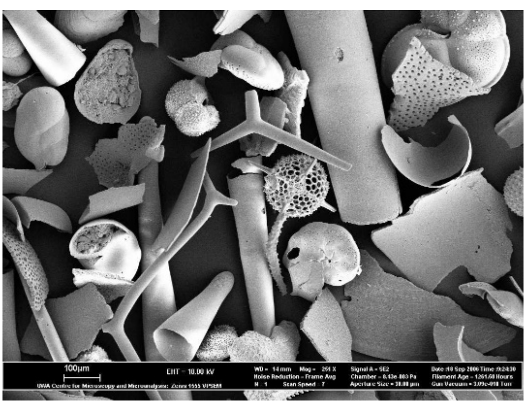

Figure 1. Example microscopic image of a carbonate sediment.

Authigenic carbonate sediments are less common or, perhaps more accurately, are more restricted in their distribution. Such sediments occur where a sulfate-methane interface intersects the seabed. At and above this interface, venting gases can react with the interstitial, near-surface pore water in shallow sediments to produce carbon dioxide and bicarbonates [6]. This anaerobic oxidation of methane catalyzes the production of calcium and magnesium carbonates. The result is the generation of cemented, boulder-scale hard-rock outcrops, which can also act as large caps or seals over vented areas. Biogenic carbonate production in the form of hard-shell chemosynthetic communities may be found proximal to authigenic carbonate mounds, illustrated in Figure 2.

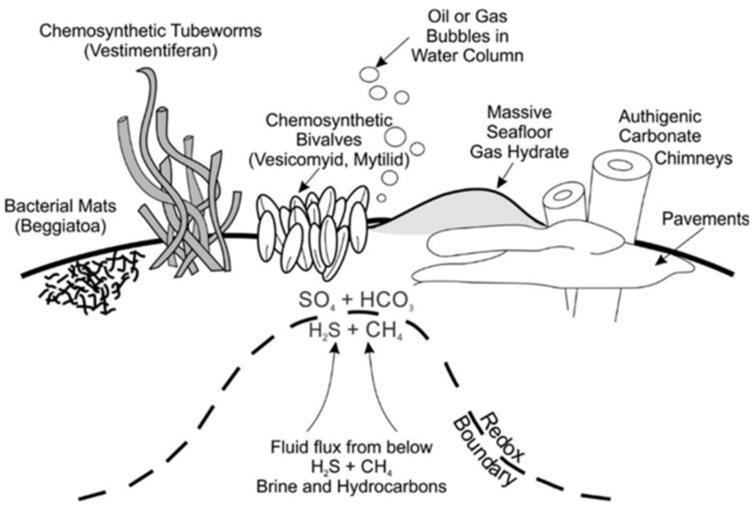

Figure 2. Illustration of authigenic carbonate production and associated biogenic communities (after [7]).

Lithification of carbonate sediments does not depend on deep burial and the associated increases in temperature and pressure – although limestone, chalk and marble can be derived from such processes. At shallow burial depths, diagenesis of carbonate sediments, and the inverse dissolution of carbonate rocks, is primarily influenced by the chemical composition of the surrounding water. This reflects the fact that calcite and aragonite may be either soluble or insoluble depending on water chemistry. The precipitation/dissolution balance is controlled by factors including water temperature, acidity and the prevalence of ions. These factors themselves vary through time in response to climate driven eustatic sea-level change. Sea-level fluctuations therefore exhibit significant control on the geology of the carbonate platforms noted on modern day continental shelves – both in terms of biogenic production and subsequent diagenesis and/or weathering of the sediment package.

2.3. The importance of geology

Carbonate geology – the nature of the sediments and any diagenetic alteration – results from the complex interplay of a range of factors: water depth, temperature, salinity and clarity, metocean conditions, climate, distance from land, and pore water chemistry. Importantly, these factors themselves change over geological time, particularly in response to climate-driven eustatic sea level change. Assessment of any carbonate dominated region requires the development of a geological ground model to establish a framework for the relevant geological processes and to predict how those processes have impacted the region. Ideally, the model will evolve with the project and will be a useful tool to aid planning related to field layout, site surveys, geohazard avoidance and/or mitigation, and engineering design and installation.

The focus of this paper is on carbonate sediments formed in (open) continental shelfs, and a simplified schematic is shown in Figure 3. This schematic is essentially a generic ground model and facilitates assessment of how factors such as biogenic production, chemical alteration, physical and biogenic reworking may change both spatially and temporally. In general, carbonate dominated seabeds in less than 120 m water depth exhibit the highest degree of variability as this isopach roughly delineates the maximum extent of subaerial exposure during the last glacial maxima [8]. Variability is typically inversely proportional to water depths with notable exceptions relating to mass transport processes and authigenic carbonate production.

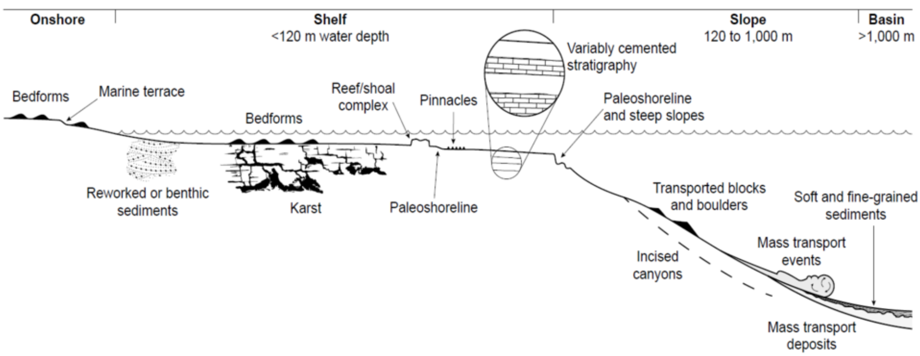

Figure 3. Illustrative shelf cross section, highlighting key geological processes.

Although not the principal focus of this paper, it is valuable to provide a brief discussion on chalk, as this group of carbonate sediment plays an important role in design of offshore structures in the North Sea and other regions. Chalk forms an extensive deposit, generally between about 200 m and 800 m in thickness, and is present over large areas (offshore) Northern Europe. Chalk was formed by the sedimentation of microscopic coccolithophores through the water column and consists of a very weak to moderately weak fine-grained limestone with coccolith bioclasts, in a matrix of coarser calcite components with localized concentrations of gravel to boulder-sized flint nodules. The $CaCO_3$ content of chalk is high, while its porosity is highly variable due to bioturbation, large-scale slumping and recrystallisation soon after deposition. In addition, zones of hard grounds consisting of gravel, nodules, horizons of hardened chalk and increased fossil content are present locally within the strata.

2.4. A comment on geohazards

Typical offshore geohazards, such as slope instability and debris flows, also occur in carbonate sediment profiles. The discussion below identifies geohazards that are more closely associated with carbonate sediments, with a more complete discussion (relative to carbonate sediments on the North West Shelf of Australia) provided in [9].

Carbonate sediments are different from silica sediments, and not all carbonate grains are the same. Arguably the most significant engineering geohazard relating to carbonate sediments is also the most widely acknowledged – that being the contrast in engineering behavior of carbonate sediments when compared to silica equivalents. For example, the impacts of this contrast are well documented in literature pertaining to foundation installation of the earliest offshore infrastructure on the North West Shelf of Australia [10]. While it is now well understood that carbonate sediments are not the same as silica sediments, it should also be noted that not all carbonate sediments are the same. For example, the engineering behavior of well sorted, solid ooid carbonate grains will significantly differ to that of planktonic foraminfera assemblages. Detailed geological inspection coupled with specialized geotechnical laboratory testing can mitigate against the potential risks posed by this geohazard.

Carbonate geology is highly variable, both laterally and vertically. Discussed previously, carbonate geology on continental shelves is inherently variable, particularly in water depths less than 120 m. Reliable site characterization can be problematic, and experience is needed in selecting both the types and quantities of data collected to support engineering analysis. A famous example of this variability is the (limestone) pinnacle formations in Cervantes, Western Australia (Figure 4). Related to geological variability but worth specific mention are karst features. Dissolution of calcium carbonate has the potential to result in the formation of voids – in the marine environment such features appear generally (but not always) filled with uncemented sediment, presenting a stark contract to the surrounding rock.

Figure 4. Local variability observed at the Pinnacles, Western Australia (photo from [11]).

Sample recovery requires bespoke equipment and methods. Engineering analysis of cemented carbonate sediments is often hampered by uncertainty stemming from data acquisition – or more specifically a lack thereof. Weakly cemented and dense sediments can exhibit similar in situ testing properties, while being fundamentally different with respect to certain key engineering parameters. Both types of sediment may result in refusal using standard push sampling techniques. Further, standard rotary coring can lead to little or no recovery when the degree of cementation is low. Specialized coring equipment and drilling parameters are needed to maximize the chance of successful recovery. The absence of high quality samples can lead to additional uncertainty being carried through to engineering design and installation, potentially leading to unconservative or excessively conservative outcomes.

Steep slopes may reflect sediment interlocking and may be aided by biogenic silicas. Steep slopes are noted at the shelf break of many carbonate dominated continental shelves. These slopes are often over-steepened relative to the apparent strength of the sediments – and in some case, overhanging sections have been observed despite the lack of any apparent cementation in the sediment. In such cases over-steepening may be explained by granular interlocking of the varied and irregular grain shapes often associated with carbonate sediments. Particulate interlocking may also contribute to the often very high peak friction angles typically noted in carbonate sediments. However, such interlocking is not unique to the carbonate component of these sediments – biogenic silicas such as spicules, diatoms and radiolaria almost certainly contribute as well.

3. Interaction with offshore development

In this section we identify regions where carbonate sediments are either known or expected to influence offshore development. Commentary is divided by region and is based on the experience of the authors – and is not intended to be exhaustive. While focus is on the oil and gas sector, the behavior of carbonate sediments can influence all offshore development. Examples of this are the recent expansion of offshore wind in the North Sea and the Baltic Sea, where chalk (and in some cases limestone) may be encountered, and potential wind farm projects offshore southeast US and southeast Australia where carbonates sediments are prevalent.

Figure 5 identifies many areas with carbonate sediment, taken initially after [12] which specifically identified areas of carbonate sand. In the current paper other known regions with carbonate sediment are also considered, particularly including locations were such materials might be found to impact offshore developments. These are also highlighted on Figure 5.

3.1. Known regions where carbonate sediments are encountered

Regions where carbonate sediments are encountered include:

- Central and North America – carbonates are found on the Yucatan Shelf in the Gulf of Mexico, the Belize Shelf in the Caribbean Sea, extending further south to Nicaragua and Columbia; and on the South Florida Shelf between the Gulf of Mexico and the Atlantic Ocean (extending out to the Bahamas). Carbonates are (often) encountered as silty sand in layers of variable thickness, typically interbedded with sediments of (significantly) lower carbonate content.
- South America – the Campos Basin in Brazil is an area where carbonates are found in relatively shallow water, occurring in layers of silty sand to sand, and often with sand at the seabed [13]. As exploration pushes further into deep water, it is possible that regions of finer grained carbonate sediment will also be encountered – although this is not currently documented in the literature.
- Europe – extensive regions of variably weathered chalk are found throughout the southern North Sea, English Channel and the southern Baltic Sea, typically of significant thickness for engineering purposes and sometimes overlain by

younger (non-carbonate) sediments. Limestone and calcarenite are also prevalent in some areas, particularly off the west and northwest coasts of France.

- Middle East – the Arabian Sea is a well-known region where high carbonate content sediment is encountered, in particular offshore Qatar and the UAE. In shallow waters the stratigraphy is dominated by variable strength calcarenite, whereas carbonate sands (sometimes lightly cemented) are encountered as water depth increases (and may be interbedded with calcareous silts and clays).
- Africa – activities off the east coast have identified cemented carbonate reefs and uncemented carbonate sediments in shallow waters associated with shelf breaks and lagoonal areas, particularly offshore Mozambique. Mass transport processes have carried some of these sediments, including extremely large boulders (> 1 km in diameter, or olistoliths, [14], [15]) through the numerous canyons which line the Mozambique coast and onto the continental slope near locations associated with well sites. Authigenic carbonate mounds have also been observed on the continental slope, related to fluid seeps and/or bioherm communities. Carbonate sediments have also been encountered to the north of Africa, in Mediterranean waters offshore Libya.
- Asia – oil and gas activities offshore India have encountered carbonate sediments, although these are more common off the west coast (with the east coast heavily impacted by terrestrial outflow). Carbonates are also encountered offshore the Philippines, where carbonate sediment is found as sand in modest water depth, becoming finer grained with increasing depth.
- Australia – north west Australia is another well-known region for carbonate sediments, extending from the North West Shelf to Browse Basin, and into the Timor Sea. Carbonates occur over the full depth profile, with shallow waters dominated by coarser grained particles, transitioning to mixed material (silty sand / sand silt) with depth, and to silt and mud in deeper waters. Carbonates are also prevalent in the Bass Strait off the southeast coast, comprising predominantly sandy sediment in shallow waters, becoming silty sand (to silt) with increasing water depth. Varying degrees of cementation are prevalent throughout these areas, particularly in shallow water and at shallow depths (i.e. within the depth range of subaerial exposure during the last glacial maximum) – although significant cementation is also often encountered at greater depths in shallow water sediment profiles and, more rarely, in deep water.

3.2. Potential areas where carbonate sediments may be influential

This section highlights areas of current and future development, which may encounter carbonate sediments and require particular attention:

- North America – it is understood that the southeast coast is proposed for future wind farms. Carbonates are anticipated in this region, as indicated in [16].
- Central America – deep water areas of the Caribbean Sea, including offshore Venezuela and Guyana have potential to encounter soft carbonate sediments, as indicated in [17].
- Middle East – new areas of the Red Sea are currently being explored. Shallower depths are expected to comprise calcarenite with some uncemented layers, while deeper waters may contain finer grained carbonate sediments.

- Africa – additional areas along the east coast of Africa, are being developing by the oil and gas industry. Experience to date suggests that carbonate silts and sands, possible with variable cementation, may be found offshore Tanzania – potentially similar to the northern parts of Western Australia. Off the west coast of Africa, carbonates have been encountered offshore Mauritania and Senegal, although generally in deeper water and with $CaCO_3 < 50\%$ and so may not be 'true' carbonates.
- Asia – oil and gas exploration offshore Vietnam has potential to encounter carbonate sediments, which (depending on water depth) may also be the case for proposed offshore renewables projects.
- Australia – ongoing development along the northwest and northern coasts will largely occur in seabeds that mostly comprise carbonate sediments. The southern Australian coast is also anticipated to see an increase in offshore exploration with carbonate sediments similar to those found in the Bass Strait region likely to be encountered, although generally reflecting a higher energy environment.

Figure 5. Map showing where carbonate sediments are important for offshore development.

4. Select aspects of carbonate sediment behavior

This section highlights a selected range of key engineering properties of carbonate sediments, based on the experience of the authors. General trends describing the range of observed behavior are provided to avoid focusing on individual data and to facilitate a broader discussion. Noted above, a key characteristic of carbonate sediments is their high spatial variability and accordingly, care should always be used (and experience valued) when evaluating engineering parameters.

In Section 4.1 to Section 4.6 below, the presented parameters originate (primarily) from testing of normally to moderately overconsolidated samples, with and without cementation. In contrast, Section 4.7 provides commentary on the heavily overconsolidated chalks found in the southern North Sea.

4.1. CPT based interpretation

The cone penetrometer test (CPT) is widely used to characterize offshore sediments, and Figure 6 presents example CPT data from testing in water depths between 100 m and 130 m on the North West Shelf of Australia. All four profiles come from an area roughly 10 x 15 km. The profile comprises a sequence of interbedded carbonate silt and carbonate sand, with (relatively thin) layers of variably cemented material.

A comparison with traditional CPT correlations (after [18]) is provided in Figure 7, using the same CPT profiles (and color scheme), where it is seen that the data plots at the low end of the normally consolidated range. While the silts overlap with zones characterized by high sensitivity, the high sensitivity of the sands (in particular) is not immediately apparent.

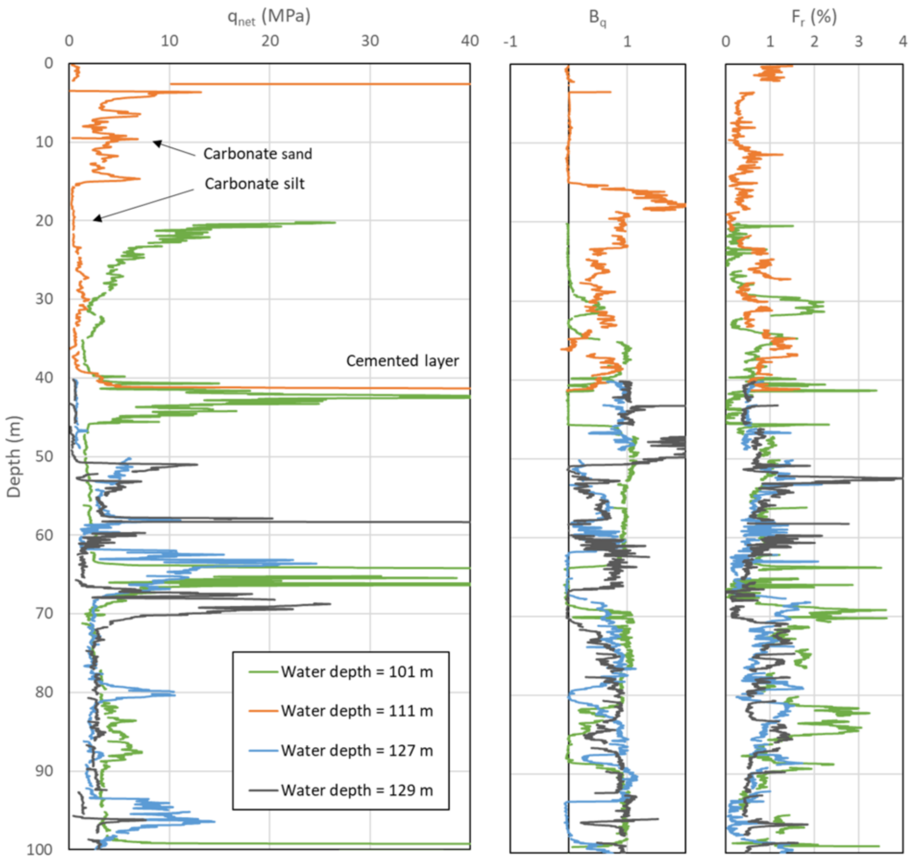

Figure 6. Example CPT data from the North West Shelf, Australia.

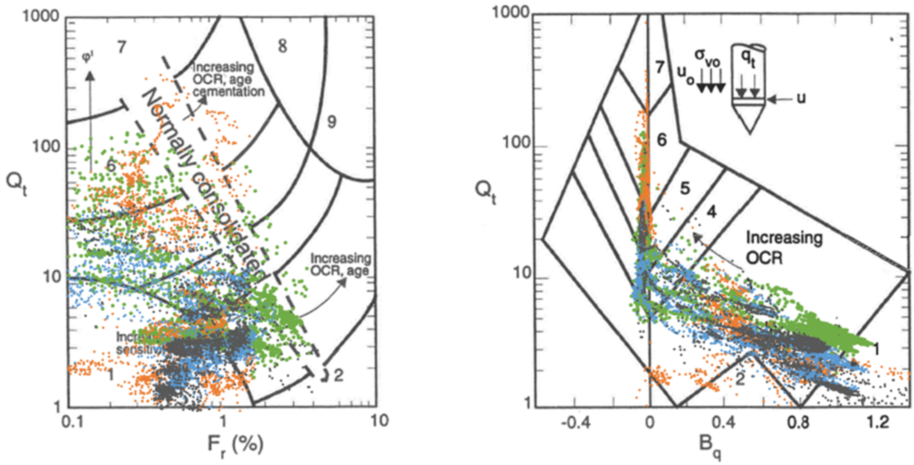

Figure 7. Comparison with CPT correlations after [18].

4.2. Shear strength (uncemented sediments)

The monotonic undrained shear strength ($s_{u\ mono}$) of uncemented carbonate sediments is a critical parameter for many aspects of engineering design. However, the high degree of variability in fines content often associated with many carbonate sediment profiles makes correlation of the undrained strength with CPT data a challenging task.

However, in general terms, $s_{u\ mono}$ can be determined from q_{net} using N_{kt} values that vary with fines content, ranging from around 10 to 15 where the profile is strongly influenced by clay/silt sized particles, to over 40 (and sometimes much higher) where the profile comprises predominantly carbonate sand. In the latter case, the high N_{kt} values reflect the effect of partial drainage and also generally vary with density. Typical strength ratios ($s_{u\ mono}/\sigma'_{vo}$), which serve as a type of state parameter, range from around 0.3 for normally consolidated fine grained strata (such as on the outer shelf and in deep water) to well over 2 where dense carbonate sand is encountered – although these should be considered broad guidelines only.

Sensitivity (S_t) is a measure of the reduction in undrained shear strength due to remoulding. High S_t is generally associated with carbonate sediments, and can be investigated through both field and laboratory testing. Figure 8 shows a typical result from insitu cyclic T-bar testing (as discussed in [19]), for a sediment with S_t in the range 25, which is reached after 10-15 cycles. Alternatively, either the fall cone test or minivane may be used in the laboratory; with the former more common outside the United States. The high sensitivity of many carbonate sediments is associated with the fragile nature of the particles, which can break during shearing; and may also result from hollow particles being filled with water, which is released on breaking leading to an apparent increase in free water content.

A useful 'rule of thumb' to determine whether a carbonate sediment will exhibit high sensitivity is where the Liquidity Index (LI) exceeds 1. When LI > 1, the remolded strength of carbonate sediments (over the depth ranges of interest to most design) often tends towards an absolute value of 1-2 kPa, regardless of the initial stress ratio – which leads to higher sensitivity being observed for samples with high undrained shear strength ratio or from significant depth. Sensitivities well over 100 have been observed in some cases. Relatively high ‘apparent’ sensitivities can also be observed due to water entrainment effects, which are relevant to subsea pipelines due to the seabed disturbance during the installation process.

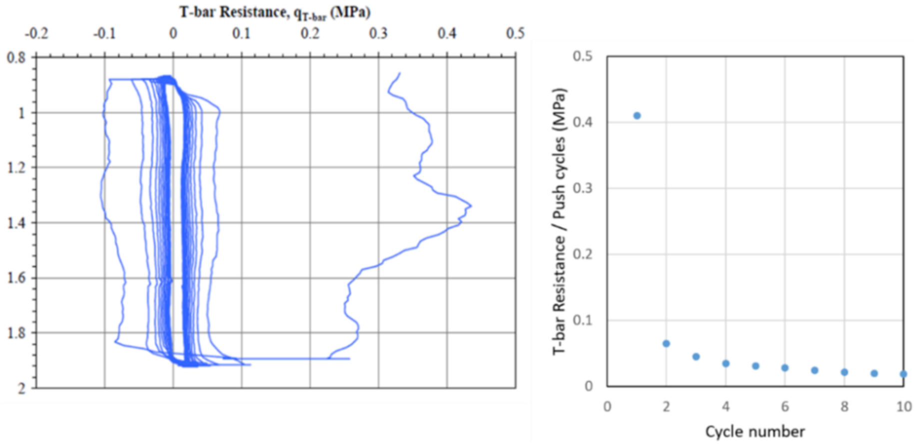

Figure 8. Typical cyclic T-bar test.

While high sensitivity is a manifestation of highly destructive processes at very large shears strains, uncemented carbonate sediments also typically exhibit significant strength degradation during cyclic loading at relatively small strains. This is due to classical softening as a result of compaction induced excess pore pressure generation, as the samples attempt to densify under cyclic loading. Most carbonate sediments are prone to reaching a state of cyclic mobility (initial liquefaction) under sufficiently intense cyclic loading, although this tendency reduces with an increasing component of clay minerals. Cyclic degradation can be explored through cyclic simple shear tests, allowing the impact of number of cycles (N) and load bias (1-way or 2-way) to be investigated. Figure 9a presents typical results from testing of carbonate silt / sandy silt / silty sand across a range of locations offshore Australia, and shows the ratio of cyclic to monotonic soil strength plotted against normalized monotonic soil strength. In this case a reference of N = 10 was adopted, and all results are shown for a maximum strain γ = 10%. Consistent with the nature of carbonate sediments, considerable spread is observed in the data. However, the potential for cyclic loading to lead to significant strength reduction is clear – and is greatest for 2-way testing and generally increases for higher initial soil strength.

Two further characteristics related to undrained shear strength merit further comment:

- Carbonate sediments typically display only modest response to strain rate changes. Typically explored through simple shear testing at different rates, experience suggests that (while local variations may occur) strength increases of less than 5% per log cycle of shear strain rate may be expected in most cases (albeit once again, an increasing clay mineral fraction may enhance the rate effect).
- When designing foundations in carbonate sediments, especially shallow foundations, the potential for strength increase with application of additional

vertical stress can be useful for optimizing design. Again, simple shear tests can be used to explore this – typically using samples from the same depth, and performing tests at varying vertical stress. Figure 9b shows (illustrative) relationships typically observed from testing of carbonate sediments ranging from silt to sand. The stress ratio decreases with increasing levels of applied stress – with larger decreases observed for samples with higher initial stress ratio. For design purposes, undrained strength increases in the range 25-50% of the applied increase in vertical stress are common.

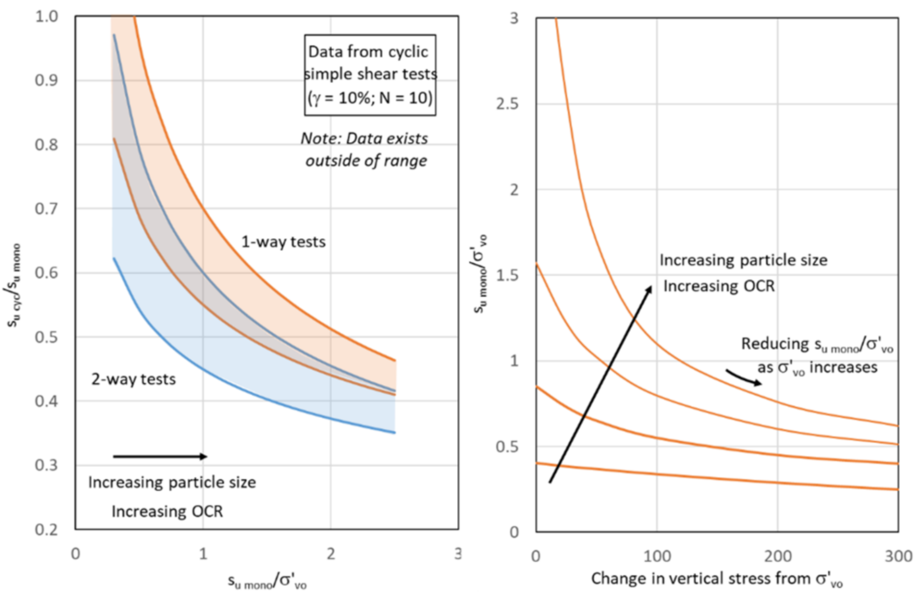

Figure 9. Undrained shear strength (a) degradation of soil strength due to cyclic loading; (b) changes in stress ratio for (applied) increases in vertical stress.

Aside from undrained shear strength, cohesion (c′) and friction angle (ϕ′) are other important engineering properties, use to explain (for instance) the steep slope angles often observed in uncemented carbonate sediments (Section 2.4). Methodology has been developed to combine results from UCS testing with stress path testing (trixial and simple shear) to evaluate both of these parameters. In the case of simple shear, an important consideration in the interpretation of stress path is device type, with studies showing that the ‘Berkeley’ type apparatus leads to a diagonal failure plane, and shear stress mobilized on this plane considered more representative of the true stress path (noting that the shear stress on the diagonal plane tends to be slightly higher than on the applied horizontal plane). Tests performed on a range of uncemented carbonate sediment supports the presence of cohesion caused (presumably) by particle interlocking, which also explains the (high) peak friction angles often observed. Peak friction angles greater than 50º are often observed, which reduce (post-peak) to closer to 40º as the interlocking is broken.

4.3. Shear strength (cemented sediments)

Many cemented carbonate sediments demonstrate a brittle response, with significant post-peak softening, which requires careful consideration in design. The discussion below focuses on defining the shaft friction response for design of drilled and grouted piles, although this can be extended to other foundation types.

A critical challenge in dealing with cemented material relates to variability over the zone of interest. As noted previously, high geological variability may be experienced in such materials. Further, interpreters often face incomplete data sets – with complete CPT profiles often difficult to achieve (even with small diameter cones), and high quality sample recovery often challenging. Correlations are needed, with one example illustrated in Figure 10a, comparing q_{net} to unconfined compressive strength (UCS) – showing that in this case UCS ~ q_{net}/20 (but note that this is not a general rule).

The peak interface strength (τ_{peak}) can be explored via constant normal stiffness (CNS) testing in a direct shear device, with the adopted normal stiffness (K) determined as a function of small strain shear stiffness (G_{max}) and pile diameter. Testing is usually performed for a soil-soil interface, as it is anticipated this will generally govern design; although testing can also be performed to examine soil-grout and grout-steel interfaces in a similar manner. Figure 10b shows a typical monotonic (soil-soil) response, highlighting the brittle nature of these materials. Historical correlations exist to link τ_{peak} to q_{net}, including those in [20] and [21], and noting that other factors (grout pressure, borehole roughness and pile diameter) are also important and can influence τ_{peak} [22]. These suggest τ_{peak} typically in the range 2-2.5% of q_{net}, thereby implying N_k ~ 40-50 (which, coincidentally, is consistent with the above example UCS relationship). While the authors have experience indicating that higher ratios of τ_{peak}/q_{net} may be observed in some cases, the stated range is generally considered reasonable for design – especially where highly brittle behavior is observed.

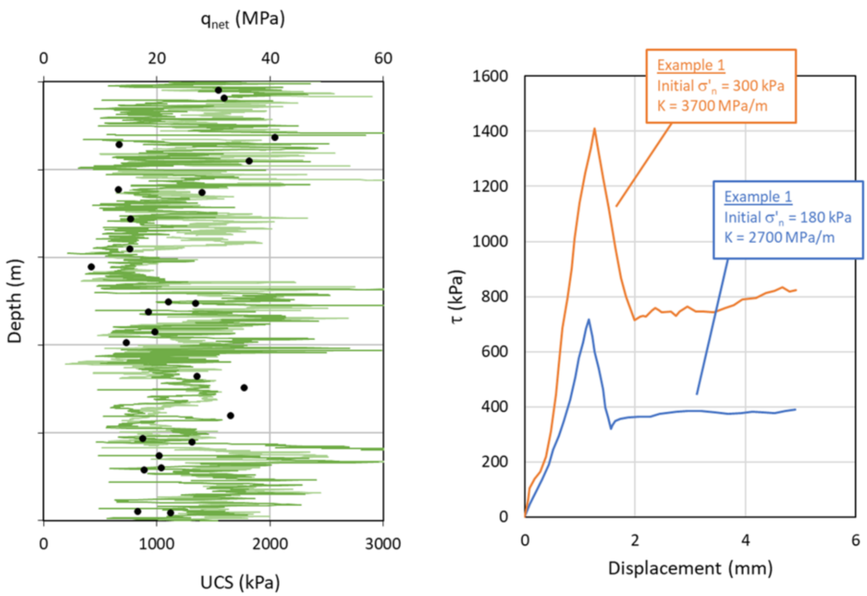

Figure 10. Strength of cemented sediments (a) q_{net} versus UCS; and (b) brittle response from CNS testing.

The cyclic response of cemented materials is also of interest, especially in cases where the design loading could lead to progressive failure. Given the brittle behavior of such materials, two types of CNS test may be used to explore the cyclic behavior:

- Displacement controlled cyclic CNS testing – where the displacement of each cycle is fixed, and the (changing) shear stress is measured. This type of test can be used to explore the 'post peak' behavior on the interface.
- Stress controlled cyclic CNS testing – where the sample is sheared between preset stress limits, typically a fraction of the peak shear strength. This type of test can be used to evaluate the 'pre-peak' behavior of the interface, in a similar manner to cyclic simple shear testing in uncemented sediment.

Figure 11 presents examples of the different test types. As the results are heavily influenced by site specific conditions, it is difficult to draw broad conclusions. However, experience suggests that when cycling 'pre-peak' (generally stress controlled) it is normally possible to apply stress levels > 50% of τ_{peak} without rapid failure; whereas cycling 'post peak' (generally strain controlled) leads to residual cyclic strengths as low as 10% of τ_{peak} after a moderate number of cycles.

As a final comment, given the conditions under which cemented layers form, high variability should be anticipated in these materials. A range of stress-controlled conditions is needed during testing to bound the likely range in response, and appropriate engineering judgement employed in design.

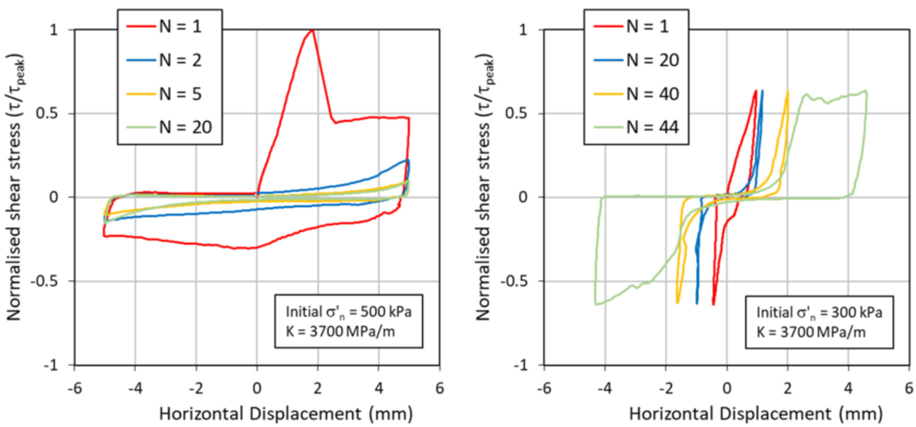

Figure 11. Response from (a) strain controlled; and (b) stress controlled cyclic CNS tests.

4.3.1. Chalk

Presenting design challenges broadly similar to cemented materials found on open carbonate shelfs, chalk is a highly variable engineering material that is generally characterized in terms of intact dry density and fracture state. The latter is based on the classification system proposed in [23] and designates chalk from structureless through various grades of structured chalk. Figure 12 illustrates typical variations of cone resistance and UCS values with dry density and grade, as measured in the southern North Sea. CPT refusals are common in high density chalk especially where flint bands are present – and the latter can be problematic for driven pile installation.

A specific challenge when defining the mechanical response of chalk for foundation design is understanding the transition from strongly dilatant to highly contractive response, which can result from the large strains induced during foundation installation (remolding during pile driving) or under severe environmental loading – and this aspect typically governs the design capacity of deep foundations in chalk.

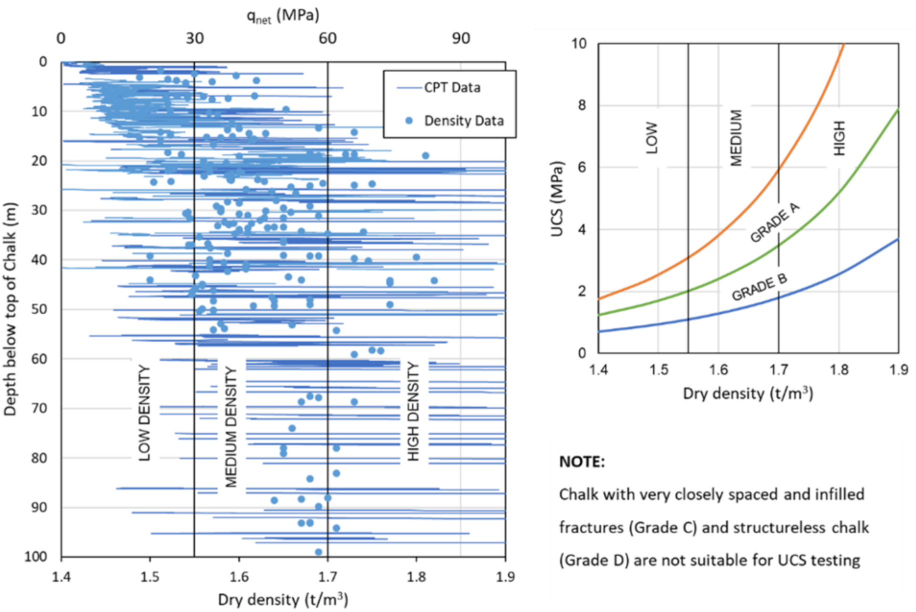

Figure 12. Typical CPT and UCS variations by chalk dry density and grade.

4.4. Interface strength

A brief comment is warranted on the importance of direct shear testing to evaluate, for example, the friction characteristics of pipeline-soil interfaces. Testing is generally performed using representative interfaces manufactured from the appropriate material (e.g. polypropylene or concrete) and with the appropriate roughness, selected in collaboration with the client based on the expected pipeline coating and surface finish. At the stage when this testing is conducted (e.g. as part of a geotechnical interpretative report) these pipeline details are often unknown and so it may be necessary to test a range of interface roughness, or supplement the testing later in a project when these interface properties are known. Tests may be conducted on either intact or reconstituted soil samples (depending on the expected amount of soil disturbance during pipe lay), normally with multiple tests required per soil zone/type to estimate the range of interface properties for that zone.

Shearing is performed under conditions of constant (total) normal stress and can be performed at rates (or for durations) to measure undrained, drained, or partially drained shearing conditions. Slow monotonic tests are generally performed to measure drained interface shear resistance with tests performed at different normal stress levels to quantify how the interface shear resistance changes with normal stress. Faster tests are performed to measured undrained shearing behavior and these may include cyclic events to explore the transition of shear resistance with increasing number of cycles (or drainage time).

There is general understanding on how qualitatively the interface shear resistance varies with interface roughness, soil stress history, normal stress and drainage conditions. However, pipeline and zone specific testing is required to quantify the range of interface properties for a particular pipeline and soil zone combination.

4.5. Shear stiffness

Small strain stiffness (G_{max}) is typically measured via resonant column testing, or from bender element tests performed on (for example) triaxial samples. As tests are typically performed on a modest number of samples, correlations are used to develop profiles of G_{max} with depth. One such approach is outlined in [18], based on q_{net} and σ'_{vo} giving:

$$\frac{G_{max}}{q_{net}} = A\left(\frac{\frac{q_{net}}{P_a}}{\sqrt{\frac{\sigma'_{vo}}{P_a}}}\right)^n \tag{1}$$

where p_a is atmospheric pressure (100 kPa). From experience with a wide range of uncemented silt to sand samples, indicative values for A in the range 200 – 800 are observed, with n = -0.75, although site-specific values should be determined. In contrast, for cemented carbonate materials the stiffness ratio (G_{max}/q_{net}) may be 2-3 times higher.

For dynamic analysis in soft soil sites, resonant column tests may be used to examine both the degradation of shear stiffness (G) with strain, and the associated damping ratio. A recent study reported in [24] developed relationships for G/G_{max} and damping ratio for a range of soils types encountered in the Bay of Campeche, including carbonate sediments. The relationships proposed in this study are compared on Figure 13 with select data obtained from testing uncemented carbonate sediments (varying from sandy silt to sand) from the North West Shelf of Australia. It is seen that the Australian data compares reasonably well with that reported in [24], although tends towards the upper bound for low strain levels, but with more rapid degradation as strain level increases.

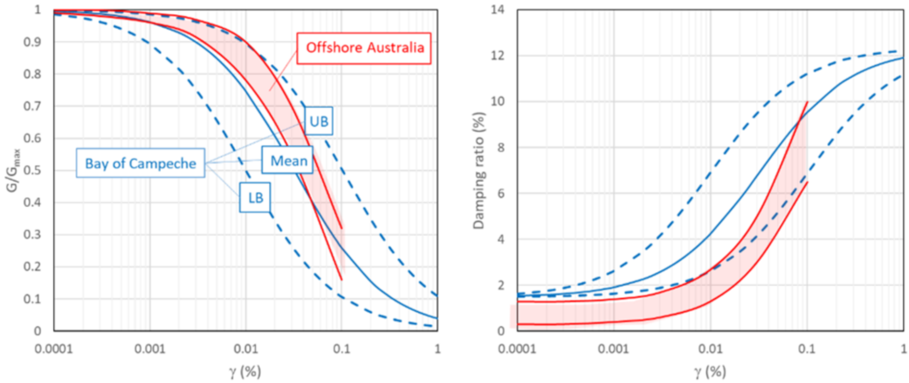

Figure 13. Stiffness degradation and damping ratio, Bay of Campeche vs offshore Australia.

In contrast, cemented carbonate sediments tend to show limited degradation in shear stiffness until approaching the peak response.

4.6. Compression behavior

By the nature of their deposition, uncemented carbonate sediments are highly compressible. Typical ranges of compression index (C_c) are shown on Figure 14(a), plotted against in situ voids ratio (e_o) – where low voids ratio typically reflects coarser grained materials or higher OCR, and high void ratios are typical of (very) soft soil profiles. As is evident, both voids ratio and compressibility are significantly higher than typical ranges for siliceous sands and silts at practical stress levels. An alternative perspective is that the yield stress ratio (YSR) for carbonate sediments is generally low, so that high compressibility is encountered at stress levels relevant for foundation design. The coefficient of consolidation (c_v) controls the rate of settlement. It is a function of stress level, stress history (loading vs unloading) and soil type – and for carbonate sediments may vary from less than 1 m^2/yr for mud/silt to over 10^6 m^2/yr for carbonate sands, with a wide range in data often observed.

Under cyclic loading, carbonate sediments will exhibit an increase in pore pressure, consistent with their compressible nature. Subsequent dissipation of the excess pore pressure results in further settlement, which can be explored by measuring the compression in simple shear tests after cyclic loading. This is discussed in [25] for a selected carbonate silt / sand, where the response in that case was shown to be comparable to recompression behavior under 1D conditions – as highlighted on Figure 14(b).

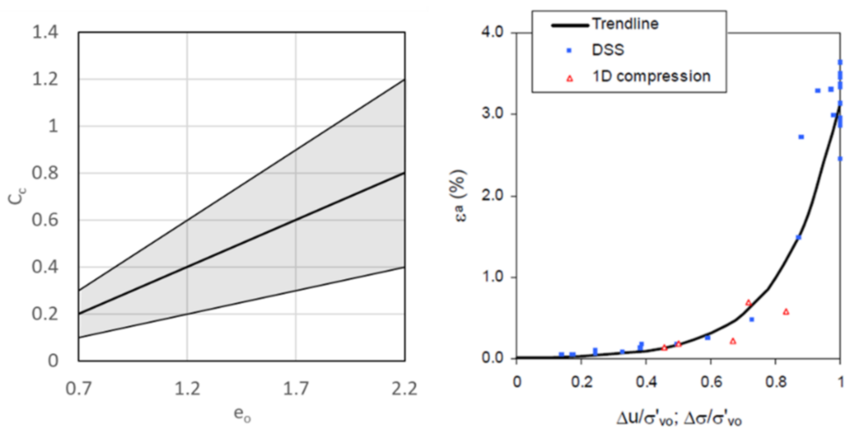

Figure 14. Compression behavior (a) typical C_c vs e_o and (b) post cyclic recompression, after [25].

4.7. Resistance to scour

The resistance to scour governs both the magnitude and rate at which erosion will occur around subsea structures, as highlighted in Section 6.2. Recent testing reported in [26], [27] have shown some differences in the erosion response of carbonate sediments relative to silica sand and silt. In general, similar threshold velocity to initiative erosion is observed for sand sized particles, while considerably higher resistance to scour is observed for silts. This is illustrated in Figure 15, where the critical shear stress of undisturbed carbonate sediments is compared to siliceous soils as reported in [28].

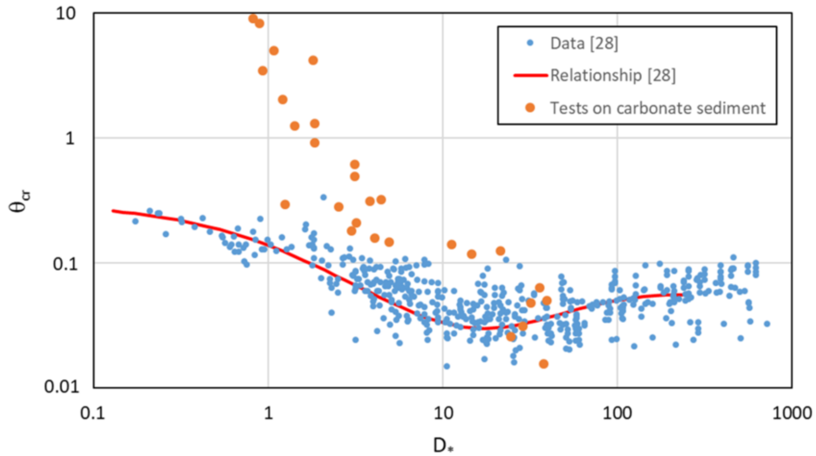

Figure 15. Erosion resistance of carbonate sediments.

5. On the importance of sample quality and interpretation

Section 4 highlighted the high sensitivity of many carbonate sediments, while Section 2 noted that the difficulty in sampling these materials – both uncemented and cemented – represents a geohazard, owing to the potential impact on engineering studies. Careful 'management' of sample quality is therefore of paramount importance.

Such management starts with the development of specialist drilling/sample techniques to minimize disturbance during recovery, continuing to sample storage and transportation to the laboratory. The effect of the latter can be tracked via accelerometers, and the data used as a semi quantitative tool to understand quality issues and potential variability between samples. Close inspection of each sample, including any observed settlement in sample tubes before and after transport, can also provide insights into sample disturbance – and is undertaken routinely in our practice prior to laboratory testing.

Once in the laboratory, non-destructive approaches are available to enhance our understanding of the material, as well as to aid selection of sub-samples for testing. The use of x-ray or CT scanning are common means to inspect samples prior to extrusion, while more advanced techniques (such as the use of a Multi-Sensor Core Logger) can provide valuable early information to characterize an offshore site.

Selection of an appropriately experienced soil laboratory and specification of test standards is critical. As highlighted in [29], results from different laboratories can vary significantly – especially in regards to characterization testing, although this is also true for advanced testing.

Owing to the wide variability of carbonate sediments, it is important to take advantage of existing data from past projects wherever possible. As well as being a valuable in assessing sample quality, such databases can be used to increase confidence in the relatively modest amount of testing often performed to characterize individual offshore sites, while also allowing trends to be developed. With sufficient data, it also becomes possible to adopt data science based approaches, allowing uncertainty from characterization to be captured explicitly in the design process.

6. Foundation design in carbonate deposits

The previous sections have focused on the physical and engineering properties of carbonate sediments. In this section, we outline aspects of foundation design that have been adapted to address the challenges posed by these sediments.

6.1. Deep foundations

As for all soil types, the vast majority of offshore pile foundations comprise steel tubular piles, with the two most common pile types being (i) driven and (ii) drilled and grouted. The latter is relatively rare in non-carbonate sediments but common in many sediments with high carbonate content because of the potential for low shaft capacity, although driven piles are often used in chalk. Excluded from this list are the so-called suction piles (or buckets) which, for most applications, do not rely on axial shaft friction as the principal support mechanism, instead mobilizing direct bearing on the baseplate and/ or skirts to resist vertical and lateral loads respectively. In any case, applications for deep pile foundations are numerous, ranging from supporting jacket platforms and wind turbines to tethering tension-leg platforms or anchoring floating production vessels. Over the last two decades, typical offshore pile diameters have increased substantially – from less than 2.5 m historically, to extremes of over 8 m for monopiles supporting offshore wind turbines, and 3 to 6 m diameter for jackets and anchoring systems.

6.1.1. Driven piles

While driven piles are generally installed open-ended, a limitation of in carbonate materials is the potentially low shaft resistance that is mobilized during installation, especially in carbonate silt and sand. This is attributed to the tendency for carbonate materials to either be crushed (coarse-grained) or remolded (fine-grained) during the large strain shearing induced during penetration at the soil/pile interface. In addition, cyclic loads applied during dynamic pile driving will also tend to cause liquefaction in the surrounding soils, further reducing available shaft friction.

This behavior can result in uncontrolled pile penetration, i.e. 'pile runs' or free-falls, if appropriate mitigation measures are not taken, for example as per ([30] and [31]). In many carbonate soils, particularly the more compressible varieties that also exhibit high friction angles or may have a modest degree of cementation, the shaft resistance is expected to remain at very low levels when the piles are later subject to operational loads, with only modest set-up (i.e. increase in shaft friction) expected over time. Even where driving can be controlled by an arrestor device, for example using a hydraulic brake to limit free-fall velocities ([31] and [32]), use of driven piles as bearing piles in such sediments is generally limited to cases where loads are predominantly compressive and a hard layer exists that can provide significant end-bearing support.

Driven open-ended piles are used widely in carbonate sediments where there is either somewhat lower carbonate content or where carbonates are interbedded between

significant non-carbonate layers. However, even in these conditions piles often exhibit relatively high embedment ratios in order to achieve the required capacity.
Pile monitoring data has been widely used worldwide to justify and improve axial pile design in carbonate soils, and this has resulted in site specific methods where sufficient geotechnical and pile monitoring data are available. Site specific methods combine both geotechnical and pile monitoring data and have significantly improved the pile design methods, especially where partially drained carbonate silts (which are difficult to characterize) are encountered.

While chalk is also a carbonate sediment that often exhibits low shaft friction during driving, significant set-up is commonly observed shortly after installation. This allows driven piles to be used more successfully in chalk than in more common carbonate materials, as discussed further in Section 6.1.3.

Driving through cemented carbonate layers can lead to installation difficulties. This may include early refusal on such hard layers, pile damage and/or uncontrolled pile runs. While the pile may pass through a hard layer, it may undergo what is referred to as 'extrusion buckling' whereby the pile tip is distorted from its original circular shape. As the pile is driven further, the magnitude and extent of the distortion increases, leading to increased driving resistance and enhanced risk of premature refusal. Such failure modes have been known to occur when open ended piles are driven into variably cemented materials [33]. In general, extrusion buckling refers to the potential for initial imperfections in the structural geometry of the primary pile, either pre-existing or initiated by heterogeneities in the sediments (such as boulders, [34]), to propagate upwards as the pile is driven into the seabed. This phenomenon occurs in sediments that have a much higher stiffness than the elastic hoop stiffness of the pile itself, causing pile deformations to propagate at an accelerating rate [35]. Where such risks are identified, analyses should be conducted to eliminate the risk of extrusion buckling.

6.1.2. Drilled and grouted piles

In contrast to driving, drilled and grouted piles generally provide superior axial support by mobilizing shaft resistance along the grout-soil interface. This is because the drilling out process does not generally impart significant damage to sediment at the grout-soil interface, hence eliminating the main problem with driven piles in these soil types.

Drilling and grouting is essential where driving is not possible, for example through strata of medium to strong cementation (including calcarenites and limestones) – where the design objective is to take advantage of these hard (cemented) strata to provide the required axial capacity.

The depth at which a suitably thick hard stratum is found, and the competence of the shallower sediments, determines whether a drilled and grouted pile can be installed as a single-stage pile, or whether a multi-stage construction process is required. For example, multi-stage piles are only occasionally used in the Middle East, but are common in Australia where considerable depths of overlying unstable silts and sands preclude drilling of an unsupported hole. In these cases, an open-ended primary pile is driven first to the top of the hard stratum in order to restrain the overlying sediments. This section of pile also provides the lateral resistance, which can be assessed using appropriate methods [36].

Following installation of the primary pile, a rotary drill is lowered through the primary pile to remove the internal soil plug, then advanced to sufficient depth to accommodate an insert pile. The insert pile is then grouted in the drilled hole and to the primary pile. The drilled and grouted section of the pile generally provides most of the required axial capacity. The process is illustrated in Figure 16.

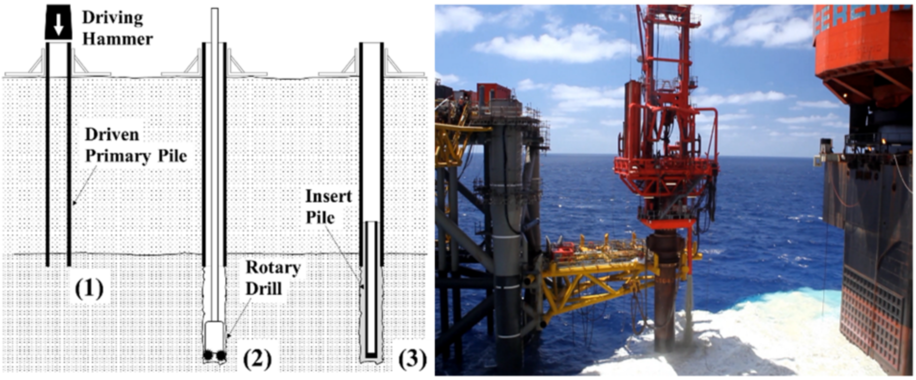

Figure 16. Installation of a drilled and grouted pile in carbonate soil.

For drilled and grouted piles, the following installation aspects should be considered as appropriate:

- Where a primary pile is used to provide support in the upper soil, it is essential to consider any risks of extrusion buckling, which may lead to excessive pile deformation. The resulting enhanced driving resistance may cause premature refusal and the distorted shape may preclude subsequent passage of a drill bit to allow further construction (as was the case for the Goodwyn A Platform on the North West Shelf).
- To maximize shaft friction capacity, insert pile holes are generally drilled offshore without any active stabilization such as drilling muds. This can lead to a risk of hole collapse if there is insufficient cementation. While open holes may be stable where there is sufficiently high cementation, or where undrained conditions prevail in the soil for a sufficient duration, holes drilled in insufficiently cemented carbonate sediments that exhibit drained or partly drained responses are at high risk of collapse. To mitigate this risk, a technique that has been used with high success for projects in Australia’s Bass Strait involves using an elevated drill riser and the application of a positive water head (i.e. above hydrostatic) to enhance the effective stresses acting at the hole wall, though seepage induced drag. With an appropriate head and ensuring a sealed riser (particular care being required to avoid breaching at the tip of the primary pile) this has proven to provide sufficient hole stabilization to allow the drilling, pile lowering and grouting operations to be completed successfully.
- In most weakly cemented carbonate sediments a ‘rough’ interface is expected to arise naturally as a result of drilling operations. However, in some cases where there is potential to realize particularly high shaft friction, reliance on natural roughening may be insufficient. This was the case for the Pluto Platform on the North West Shelf offshore Australia where the grouted piles were installed within high quality limestone. In this case a reaming tool was used to ‘roughen’ the hole wall by gouging circumferential ‘grooves’ in the hole wall at regular intervals [37].

With regard to pile performance, geotechnical models with a strong theoretical basis have been developed and utilised over the last 15 years for modelling pile interaction with carbonate materials. Models such as CYCLOPS and pCyCOS, both described in [36], define complex t-z and p-y load transfer algorithms that simulate both the non-linear and cyclic (softening) aspects observed in specialized laboratory element strength tests on carbonate materials. CYCLOPS can be applied in both cemented and uncemented soil, with parameters calibrated from CNS direct shear or simple shear tests, respectively. Conversely, pCyCOS only applies for uncemented soil, with static and cyclic simple shear tests defining the required input information. Where cemented materials are found near the surface, p-y models that can address potential brittle failure should be adopted instead. The 'CHIPPER' model [38] was developed for this purpose and accounts explicitly for wedges of 'chipped' material forming in the upper meters of the seabed below which 'full-flow' failure occurs. The p-y curves in this model incorporate both the brittle nature and the high compressibility that is typically found in many cemented carbonate sediments. Such models have been applied with great success to the design of piles offshore Australia and can be readily applied in other regions where carbonate sediments are prevalent or more generally for laterally loaded piles in weak rock.

6.1.3. Specific considerations related to axial capacity of piles in chalk

During driving of small-displacement piles in structured chalk, crushing occurs leading to the formation of an annulus of chalk 'putty' around the pile, which has significantly lower strength than the structured chalk. This is somewhat analogous to, but less extreme, than the processes that result in high sensitivity seen in many other types of carbonate soil, as discussed earlier. A similar local de-structured zone of width comparable to the pile wall thickness also occurs when driving piles into weak limestone. Allowing for this, common offshore design practice for axial capacity in chalk is to apply the recommendations of CIRIA [23]. These are based on a cautious interpretation of a small number of short-term static pile load tests, which lead to the adoption of unit shaft resistance values of 20 kPa in low to medium density chalk and 120 kPa in high density chalk, the lower value being particularly challenging for piles in the southern North Sea – and does not take account of the potentially highly significant magnitude of set-up that occurs in the chalk putty following pile installation.

Site-specific variations to the CIRIA limits have been proposed previously in [39], but still do not account for set-up. An approach outlined in [40] provides a framework for evaluating long-term pile shaft capacities in chalk, including set-up for the chalk putty annulus, and were calibrated to full-scale field testing from [41]. The procedures provide a more fundamental (and less cautious) approach to design than the CIRIA limits.

While the above relates to driven piles, drilled and grouted piles may also be used in chalk. Design requires the use of analysis calibrated to the (local) shear response of chalk as measured under CNS conditions – similar to that proposed in [22].

6.1.4. Other technologies

An approach to overcome the risk of premature refusal during driving is the 'drive-drill-drive' method, which has been successfully used for many years ([42], [43]). This technique was recently employed in carbonate sediments for a project on the North West Shelf of Australia [44], in this case utilizing a newly developed riserless drilling system. In this project, anchor piles were initially driven towards target penetration but with a pre-determined limiting acceptable blow count. Where the limiting acceptable blow count was reached prior to target penetration, relief drilling was performed through the pile centre, after which driving was recommenced. The main risk with this approach is that if the piles are driven excessively hard before commencing drill-out, extrusion buckling of the pile may occur, which could then preclude a successful drilling operation. For this project extensive analysis was conducted to ensure that this risk was minimal for the prescribed acceptable blow count.

A less conventional approach, which may be viable where shallow strata contain only thin or weakly cemented layers, is the use of tubular piles that are driven closed-ended. This concept was proven and adopted successfully in calcareous sediments in the Campos Basin offshore Brazil [45], using a strengthened conical tip to close the tubular piles. Field data demonstrated improved axial shaft friction and also a significant increase in the end-bearing resistance that could be relied upon. Where such piles are driven through highly sensitive surficial sediments, consideration needs to be given to the more extensive zone of remolded soil that would form around the pile compared with an open-ended pile, which might compromise any required lateral resistance.

As an alternative to both driven and drilled and grouted piles, offshore versions based on onshore continuous flight auger piles are starting to be developed per [46], avoiding creation of an open hole and allowing a grouted pile to be constructed from seabed level.

6.2. Shallow foundations

Shallow foundations support a wide range in offshore structures – from large gravity structures to small subsea structures, and also including mudmats of piled jacket structures. Designs in carbonate soil tend to be bespoke, and are tailored to the specific challenges for each structure. This section build (in part) on previous discussion in [47].

6.2.1. Evolving use of shallow foundations

The late 1990s saw the adoption of large gravity structures in carbonate sediments for the first time. Two key structures include the West Tuna Platform for ExxonMobil [48] and the Wandoo B Platform for the Wandoo Alliance [49]. Foundation challenges are well documented for the Wandoo B platform, which is founded on a thin layer of carbonate sand overlying cemented strata. Dominated by large (environment) lateral loads, and varying on-bottom weight in response to GBS storage needs, the sensitivity of the sand to cyclic loading was a critical consideration. To maximize the sliding resistance, the underside of the base was roughened (maximizing the interface friction), and a drainage blanket was used to minimize the build up of excess pore pressure (thereby reducing the equivalent number of cycles, and hence the degradation of strength). Scour protection, comprising placed rock, was used to mitigate the risk of undermining of the foundation.

A more recent large gravity structure is the Wheatstone Platform, which moved away from concrete to adopt a steel substructure design. In this case, the foundation design took advantage of a region of weakly cemented seabed to allow the platform to be supported on (individual) shallow foundations. The seabed required placement of a rock blanket and, similar to Wandoo B, scour protection was used to protect both the blanket and the surficial sand. In optimizing the foundation design, the effect of consolidation under the weight of the structure, cyclic loading and post-peak behavior of the cemented sediment were all addressed explicitly.

Other streel gravity platforms include the Yolla A Platform [25] and more recently the Ichthys Riser Support Structure [50]. Both of these structures are on much softer sediments than the foregoing cases and therefore utilize deep skirts penetrating into seabeds comprising uncemented carbonate muds, silts and sand through a combination of self-weight and suction. In each case, the design was undertaken through a combination of analytical and numerical approaches, with both capacity and settlement addressed. For the Ichthys RSS in particular, seismic design proved particularly challenging [51]. Although Australia is not in general a highly seismic area, there is sufficient seismic activity in northern areas under the rare ductility level events to cause a significant problem in the very soft, uncemented carbonate sediments that are generally highly susceptible to liquefaction [52]

As the offshore sector pushes into deeper water, shallow foundation design has shifted to that needed to support subsea structures. A typical development requires a large number of seabed structures, with foundations ranging from small seabed structures to support individual valves to large structures supporting complex manifold systems. Foundation design needs to address installation (including the penetration of skirts where used) and capacity issues, the latter allowing for cyclic degradation. Of particular importance is the assessment of settlement, including that resulting from self-weight consolidation as well as from design events such as earthquakes, and reliable estimates of lifetime settlement is needed in order to ensure the integrity of connectors between individual structures.

Figure 17 illustrates the evolving use of shallow foundations in carbonate sediments.

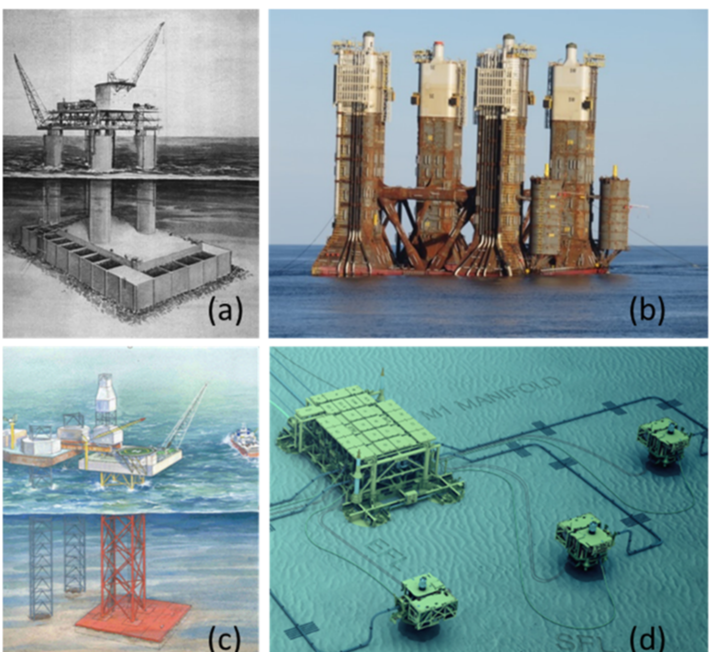

Figure 17. Shallow foundations in carbonate sediments, (a) Wandoo B CGS [49]; (b) Wheatstone Platform [53]; (c) Yolla A Platform [25]; (d) Gorgon subsea manifold [54].

6.2.2. Select aspects of design

While many of the design issues associated with shallow foundations are not unique to carbonate sediments, the properties of such materials can lead to a need for bespoke design methods. Consideration is now routinely given to the incorporation of strength increase due to consolidation, and design tools exist to capture the effects of cyclic loading in an efficient way, both of which lead to smaller foundations being acceptable. However, there are aspects that require specific attention, and are worth capturing here:

- Installation considerations are important for shallow foundations. For instance, local variability may impact the penetration of skirts, while low strength at mudline or insufficient drainage can lead to aquaplaning or higher than anticipated initial embedment.
- Noted previously, settlement is a key consideration – and is especially important when considering its impact on tie-in spools (or other stiff connections). While calculation approaches are relatively standard, it can be challenging to determine appropriate input parameters for carbonate sediments. A particular challenge is the case of settlement after seismic events – whereby excess pore pressures are generated in the seabed that, while perhaps not leading to liquefaction or flow failure, still result in large post-event settlement. This may vary significantly between structures, leading to stress on connectors.
- Subsea systems are required to accommodate large axial expansion of pipelines, associated with thermal effects. While it may be possible to accommodate this through design of the structure, another option is to allow the foundation to slide directly on the seabed. The key consideration in this case is ensuring that over the life of the development, and for the full range of thermal expansions (which may be several meters), the foundation does not penetrate excessively into the seabed. The critical design considerations for such foundations are discussed in [55] and, in accordance with these, several structures of this type have now been installed in carbonate sediments.
- While sliding foundations are required to accommodate large movements, opportunities also exist in regards the development of 'compliant foundations'. This is particularly important in the design of manifolds, or other subsea structures that include a number of tie-in spools. Loads associated with tie-in and operation can be a high proportion of the design loads – but reduce significantly in response to (small) foundation movement. Accordingly, allowing for the 'compliance' of the foundation can significantly reduce the requirements for foundation design and in turn, lead to more cost-effective outcomes.
- The potential for scour to influence the performance of shallow foundations is well understood. Traditional design approaches are based on assessing the susceptibility of the soil at seabed to scour and, where deemed necessary, the installation of scour protection – such as rock blankets or concrete mats. It was noted in Section 4.7 (Figure 15) that for specific particle size ranges, carbonate sediments demonstrate greater resistance to scour than silica materials of comparable (silt to sand) particle size. This can be assessed for individual sites, with testing extended to assess not just the threshold but also the rate at which scour will occur. In some cases, this can lead to opportunities (via adoption of probabilistic approaches) to avoid early placement of scour protection, and adopt a 'wait and see' (i.e. observational design) approach [56].

6.3. Spudcan foundations

The installation of jack up rigs on uncemented silty carbonate sediments has proven to be challenging, with key considerations being the assessment of spudcan penetration during installation and preloading, and spudcan capacity under storm loading.

6.3.1. Penetration

In regards to spudcan penetration, the key risks relate to the potential for deeper than expected penetration and unexpected punch-through events, driven by the high sensitivity and transitional drainage conditions often associated with carbonate sediments. Case histories where this has proven significant are presented in [57], from jack up rigs installed off south east Australia. For one of these cases, where the jackup was installed adjacent to the Yolla A Platform, unexpectedly large penetrations occurred as the maximum preload was approached - with punch-through involving a 'free-fall' of about 4 m for each spudcan. Significant tilt of the jack up rig occurred, with the rig itself coming to within a few meters of the Yolla A Platform topside. Following the punch through, each spudcan was successfully loaded to the maximum preload with minimal additional penetration.

In this case, it is important to note that punch-through was not predicted, despite assessments being made by multiple parties, and the presence of high quality in situ (and laboratory) test data. Based on the lessons learned, [57] proposed an approach to assess spudcan resistance to penetration based directly on in situ T-bar penetrometer data, and take account of (i) consolidation properties and drainage behavior, (ii) rate effects, and (iii) geometry effects.

A second phase of jackup operations occurred at the Yolla A Platform location, with spudcans installed through the existing crater, as described in [58]. Given the complexity of this operation, and inherent risks to the adjacent platform from further punch-through, a rigorous design approach involving both analytical and large deformation finite element analysis was adopted. These studies confirmed and highlighted the significant impact that the high sensitivity and transitional drainage conditions have on the spudcan penetration response in such soils.

The other significant case study presented in [57] was from a nearby site (Trefoil). At that location, initial static preloading led to legs at very different depths, which was deemed unacceptable. A program of cyclic preloading was therefore undertaken at the site, where the 'high' legs were cycled as rapidly as possible (albeit only about 1 or 2 cycles per hour). Eventually, all legs were lowered to an acceptable level using this approach, as a result of soil softening induced by the cyclic loads. This was considered a great success, but also an alarming surprise to the jackup owner, who had never encountered such 'unusual' soil behavior before. It should be appreciated that cyclic preloading of this type can cause significant structural distress to a jackup rig and it is recommended that appropriate geotechnical and structural studies should be conducted to confirm the safe operating limits prior to any such operation.

6.3.2. Capacity under storm loading

Similar to the design of shallow foundations, the offsetting effects of strength gain due to consolidation (under self-weight) and cyclic degradation need to be addressed when assessing the response of spudcans under the imposed loads from storms.

Assessment of spudcan capacity is typically undertaken using the approaches in [59], where the applied preload is used to anchor the size of a foundation yield envelope, from which the applicable material factor under storm loads is determined. However, this approach does not account for either consolidation or cyclic loading effects. Accordingly, a 'Modified SNAME' approach was proposed in [57], where the measured preload is replaced with a calculated vertical capacity that accounts for both consolidation and cyclic degradation. Since a calculated (rather than measured) capacity is used to anchor the yield envelope in this case, a higher material factor is appropriate and is specified to be consistent with 'conventional' design practice for most offshore shallow foundations.

This approach has been adopted successfully for multiple jack up rig installations conducted offshore Australia, as reported for example in [60] and [61].

6.4. Anchoring solutions

Anchoring of floating facilities, whether for temporary (such as exploration drilling) or permanent (such as for production facilities) purposes, requires design approaches that address both the characteristics of the seabed and the applied loading conditions. This section outlines considerations for common anchor types.

6.4.1. Drag anchors

The design of drag embedment anchors requires a thorough understanding of anchor behavior in various soil conditions, in order to ensure an adequate margin of safety in the anchor holding capacity and to ensure that no anchor movement ('dragging') occurs during a design storm event. This is particularly important for carbonate sediments, where the complex interacting effects of sensitivity, consolidation and cyclic loading will dictate the minimum level of preload at installation that is required to ensure no in-place anchor movement. Importantly, for carbonate sediments, the combination of these effects often results in drag anchor preload levels exceeding the in-place design loads, as outlined in [62] and [63], a situation that is rarely found in other soil types.

Drag anchors are also susceptible to premature refusal (i.e. insufficient embedment during installation) in layered soil profiles, which is a common feature of carbonate sediments – where such layering often takes the form of shallow cemented horizons. In this scenario, the resistance offered by the cemented materials may be sufficient to prevent the anchor fluke tips from embedding through the horizon, resulting in the fluke tips 'scraping' along the 'weak-strong' interface, and the anchor being unable to attain the required preload.

A similar but more subtle scenario can occur in carbonate soils with transitional drainage conditions, where drained (i.e. 'strong') soil resistance is mobilized on the shank but undrained (i.e. 'weak') soil resistance is mobilized on the fluke. In fact, this appears to be the critical mechanism in many drag anchor installations and seems to explain the often very low anchor efficiencies (i.e. ratio of static capacity to weight) that has been reported during field installations in carbonate soil.

6.4.2. Anchor piles

Despite a well-documented history of problems associated with driving piles into carbonate sediments, large diameter driven piles have recently been used successfully in seabeds comprising highly variable weak carbonate sediments [31]. Design issues for such anchors include pile free-fall during installation, driving through localized hard (cemented) layers, the assessment of the pile in-place lateral and axial response, and assessment of the post-seismic response of the pile.

Special consideration must be given to the influence of the embedded portion of the anchor chain – where locating the anchor padeye below mudline level may lead to excessive uplift loads due to low shaft resistance. While the simplest solution for this is to move the padeye close to mudline, this is inefficient in terms of lateral capacity. Drilled and grouted piles may be considered in this case in order to enhance the axial capacity, although this introduces other installation challenges in uncemented soils. For cemented seabeds, drilled and grouted piles are generally a preferred anchoring option and can now be installed using riserless heave-compensated reverse circulation drilling equipment (as in [44]).

6.4.3. Suction anchors

Suction caisson anchors have also been installed successfully in carbonate sediments, where seabeds have comprised predominately softer materials, per [64], [65] and [66]. Due to the low shaft friction offered by carbonate sediments, suction anchors can have reduced application in deeper waters where semi-taut or taut mooring configurations are generally adopted, as applied vertical loads (at the pad eye) are long term and rely on frictional resistance to provide stability. However, should the vertical loads be of a transient nature (as for catenary moorings) then suction may provide adequate resistance.

6.5. Pipelines

The design of an untrenched (or surface laid) pipeline must account for how it interacts with the seabed as it is loaded by waves and currents, experiences cycles of heating and cooling, and is required spans over an uneven seabed (affecting pipeline fatigue). Geotechnical design input is normally provided in terms of 'friction factors', which quantify the limiting soil resistance (relative to its own self-weight) when the pipeline moves laterally or axially on the seabed, and in terms of soil springs describing how the lateral, axial, and vertical soil resistance changes as a function of pipeline displacement and through cycles of loading.

Despite increased documentation of approaches to assess pipe-soil interaction (as in [67], [68]) many of the methodologies are disputed. Importantly, guidelines provided in key codes are rarely appropriate for carbonate sediment conditions [69]. This was stated explicitly in the now superseded [70] where it was stated that "*Special considerations should be made if the sand contains a high fraction of calcium carbonate*". While this text was not included in the more recent code [71], the same carbonate sediment section from the earlier document *is* included.

With specific regard to the properties of carbonate sediments vs non-carbonate soil, the following is noted in regard to surface-laid pipelines:

- Higher sensitivity results in deeper as-laid embedment for surface-laid pipelines in carbonate sediment [72], in particular carbonate silts that can be subject to greater water entrainment effects than non-carbonate fine-grained soils. Calculations must include consideration of 'apparent' S_t values, which may be greater than measured values in a laboratory fall cone or miniature vane device. Calibration of as-laid embedment methods may be informed by back-analysis of lay records for nearby pipelines, but needs to account for differences in seastate conditions and/or lay vessel characteristics.

- Higher angles of internal friction (due to grain angularity) and higher pipe-soil interface shear resistances often leads to higher axial and lateral seabed resistances – although specialized laboratory interface testing [73] is required to measure this directly.
- Drainage conditions may vary for different pipeline loading events in carbonate sediment, depending on the load duration, the drainage path length and the soil c_v. For instance, carbonate silty sands are likely to behave in an undrained to partly drained manner during a wave loading event, though may be fully drained during a slow (multi-hour) axial pipeline expansion – and design methods must encompass this transitional behavior rather than assuming (for example) that any 'sand' is drained. Drainage conditions in shallow sediments are best assessed using specialist in situ tools [74].
- As highlighted earlier, high spatial variability may be expected along the pipeline length, while variability may also occur within individual zones. Soil parameter ranges are often wide compared to uniform soil deposits, and the ranges of associated pipeline design parameters must take account of this. Since both low and high seabed resistance may govern design as outlined in [75], statistical approaches to assess the pipe-soil resistance parameters are often used to narrow ranges for input to structural reliability analysis.
- Outcropping (and shallow subcropping) cemented layers are common in shallow and intermediate water depths. Rock-pipeline interface friction coefficients will depend on the level of rock cementation, the pipeline surface coating roughness and the anticipated normal contact force between the pipeline and rock surface and may vary from other rock types. Site-specific rock-pipeline interface testing is required. Consideration should also be given to the influence of macroscale features - extremely outcropping (extending above seabed) can act to constrain the pipeline from lateral movement.
- Seabed mobility may lead to changes in pipeline burial state after lay, which can vary both spatially and temporally through the life of operation ([26]). These changes may have to be accounted for to provide inputs to ensure effective thermal management (lateral buckling, end-expansion, pipeline walking), as outlined in [76], or can potentially be 'banked' to improve long-term hydrodynamic stability per [77].

Reliable, fit-for-purpose, inputs to pipeline design can be generated for carbonate sediment conditions, by considering the above differences and performing the following activities:

- Zoning the site by integration of geophysical and geotechnical information along the pipeline length (as illustrated in Figure 18 after [78]) and ensuring appropriate geophysical and geotechnical investigation is conducted.
- Conducting appropriate advanced element testing (such as interface testing, strength testing, c_v measurement) combined with in situ testing to provide site-specific (and pipeline-relevant) ranges of seabed parameters.
- Using calculation methods that explicitly account for the relevant mechanical properties of the seabed. Ideally such approaches will have a sound theoretical basis (such as the failure approach for lateral breakout resistance calculation

proposed by [79]), although where semi-empirical methods are used they should be based on evidence on similar carbonate sediments. This can include project-specific centrifuge testing, as outlined in [80].

- Accounting for the drainage conditions experienced by the pipeline in different design conditions.
- Considering of sediment mobility effects.
- Employing statistical methods (such as Monte Carlo analysis) to quantify the output design ranges for the specific probability levels required by the project. This will typically narrow the adopted design ranges, by reducing the influence of unrealistic (extreme) parameter combinations.

As a final comment, when approaches have been used that do not take account of the key difference in dealing with carbonate sediments, regular inspection of operational pipelines is recommended to ensure that the embedment conditions are as anticipated and that the pipeline is responding as expected.

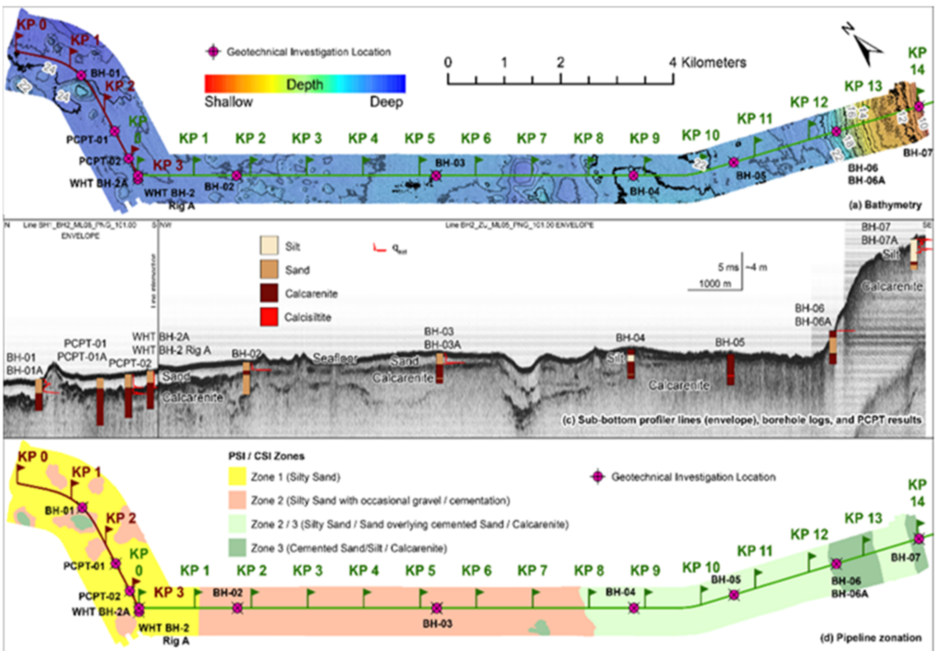

Figure 18. An example of seabed zonation along a pipeline in carbonate sediment conditions after [78] showing (a) bathymetry; (b) sub-bottom profile; and (c) zonation.

7. Concluding remarks

Soils with moderate to high carbonate content are prevalent in many regions of the world offshore, especially in mid latitudes. In this paper we have focused on sediments with high carbonate content and have summarized selective important characteristics – such as the high spatial variability, varying levels of cementation, high compressibility, high shear resistance, high sensitivity, often transitional drainage conditions and propensity for cyclic degradation. We have then explained how these characteristics have important influences on the selection and behavior of appropriate foundation and pipeline systems for a variety of conditions.

The presence of such materials has had an important influence on many oil and gas projects and is likely to become important for the renewable industry as it moves into new territory – although the challenges are not unique to these sectors.

The last 30 (or so) years has seen substantially increased exposure and experience in dealing with carbonate sediments, from characterization to foundation performance, and many lessons have been learned. However, there continue to be challenges – and it is important to remain vigilant when dealing with carbonate sediments.

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