Cone penetration response in carbonate sediments

Shambhu Sharma[1#], *Cathal* Colreavy[1], and *Noel* Boylan[1]

[1]*Norwegian Geotechnical Institute (NGI), Level 7/40 St Georges Terrace, Perth WA 6000, Australia*
[#]*Shambhu.Sharma@ngi.no*

ABSTRACT

Cone penetration testing (CPT) is one of the most used site characterisation tools in geotechnical engineering. In offshore areas dominated by carbonate sediments, CPT is extensively used to characterise material types and assess their strength and flow characteristics. However, unlike for non-carbonate sediments where large number of empirical relationships are available correlating the CPT response with the corresponding soil behaviour and associated engineering parameters, there is still a lack of data correlating the CPT response with engineering behaviour of carbonate sediments. This paper presents CPT responses for different types of marine carbonate sediments. First, a brief background on carbonate sediments including key terminologies used and their characteristics in comparison to their non-carbonate counterparts are discussed. This is followed by examples of CPT data from major offshore project sites representing different type of materials ranging from uncemented fine grained (Muds and Silts) and coarse grained (Sand) sediments to variably cemented carbonate materials. The CPT results are then used, in combination with laboratory test data, to evaluate the suitability of standard soil behaviour type charts and indices available in the literature. Typical zone of results for carbonates sediments as a function of normalized cone parameters are also presented for reference purposes. Some challenges on the direct use CPT based methods to engineering analyses for carbonate sediments and the key areas of research from a practical engineering perspective are also briefly discussed.

Keywords: Cone penetration testing, carbonate sediments, soil classification, geotechnical engineering

1. Introduction

Carbonate sediments are a common type of geological material which can be found in many parts of the world. These sediments are often found in marine environments. Over 90% of the carbonate sediments found in the modern environment originate from biochemical processes attributed to the sedimentation of skeletal debris produced by marine organisms (Milliman et al., 1974).

Carbonate sediments are composed of highly fragile particles that can be easily broken or deformed under loading conditions. This characteristic of carbonate sediments makes them behave differently to non-carbonate materials and exhibit engineering properties that often lie outside the range typically observed for non-carbonate counterparts.

Cone penetration testing (CPT) is one of the most used site characterization tools in geotechnical engineering. CPT data in combination with the laboratory tests performed on representative in-situ samples are commonly used to develop correlations and relationships to derive the soil parameters required for engineering analyses. Although the behaviour of carbonate sediments has been extensively investigated in recent decades, there is still a lack of data in the public domain on CPT response in these sediments. Also, the interpretation methods and relationships available in the literature are based on non-carbonate materials. Therefore, their use for carbonate sediments needs further investigation.

This paper presents typical CPT responses for different types of marine carbonate sediments and highlights the key features that are specific to these sediments. The CPT results are then used, in combination with laboratory test data, to evaluate the suitability of standard CPT based soil classification charts available in the literature. The CPT data are correlated with standard soil parameters commonly used in geotechnical engineering. Typical ranges of geotechnical data for carbonate sediments as a function of normalized cone parameters are also presented. Some comments on the direct use CPT based methods for engineering designs on carbonate sediments are also discussed.

2. Material behavior under consideration

2.1. Terminologies used

In geotechnical engineering, the terminologies "carbonate" and "calcareous" are sometimes used interchangeably to describe materials with significant carbonate (CO_3) mineral which impact their geotechnical behavior. However, as noted in Fookes (1988), these terminologies are not synonymous, as the engineering properties of these sediments may depend on the amount of CO_3 mineral present in the sample. For engineering purposes, the following terminologies are generally used as per Clark and Walker (1977):

- *Carbonate*: Materials containing more than 90% CO_3 content.
- *Siliceous Carbonate/ Clayey Carbonate*: Materials containing 50% to 90% CO_3 content.
- *Calcareous*: Materials containing 10% to 50% CO_3 content.

- No prefix is used for materials containing less than 10% CO_3 content.

In this paper, the term "carbonate" is sometimes used in a generic sense (e.g. title of the paper) to describe materials with high carbonate content.

2.2. Basic properties of carbonate sediments

The depositional environment and mineralogy of the grain constituents has significant influence on the engineering characteristics of carbonate sediments. In general carbonate sediments consist of highly angular, weaker (relative to siliceous particles of similar size) and often hollow soil particles, which are susceptible to significant particle crushing under loading. In addition, these sediments have a wide range of particle types, shape, and grain size distribution. This combination of highly variable and weaker soil particles often results in a wider range of engineering parameters with a typical range of parameters for carbonate sediments that often lies outside the range defined in the literature for other non-carbonate/siliceous soils.

Carbonate sediments found in regions where a substantial percentage of quartz or other non-carbonate mineral grains are present due to terrestrial weathering process may have different engineering properties. In these instances, the engineering properties can be significantly different due to closer packing and higher strength of the resulting materials compared to marine carbonate sediments.

The key basic properties that differentiate carbonate sediments from non-carbonate/siliceous counterparts include:

- Carbonate grains are generally extremely angular, platy, and often includes hollow particles. Fig. 1 shows typical micrographs of carbonate sediments compared to silica sand.
- Carbonate sediments generally show very high in-situ void ratios. In-situ void ratio (e_0) values ranging between 1 and 3 are commonly encountered in carbonate sediments, which is significantly high compared to the typical void ratio values of 0.5 to 1.0 commonly reported in the literature for silica sand.
- Carbonate sediments consist of very weak, soft, and fragile sediment particles compared to silica sand; Moh's hardness of carbonate mineral typically ranges between 3 and 4 while the Moh's hardness of silica sand is 7.
- Due to the presence of weaker grains, carbonate sediments generally undergo significant particle crushing under loading.
- The grain size composition of carbonate sediments can be as wide as non-carbonate/ siliceous materials. Carbonate sediments deposited in areas of high depositional energy generally consist of coarse-grained particles with stronger grains, whereas areas of low depositional energy are responsible for formation of fine-grained particles with weaker grains (Sharma and Ismail, 2006).
- Carbonate sediments generally show very high liquidity index (I_L) values. I_L values greater than one are common and are often associated with the high sensitivity values and low remoulded strengths of these sediments.
- Compared to clays, the liquid (w_L) and plastic limits (w_P) of carbonate soil are not strong indices for correlations (e.g., strain rate effects on strength and setup of friction).
- The concept of relative density commonly used to define the behaviour of coarse-grained materials (such as sand) is not suitable for carbonate sediments. This is because carbonate sediments are highly susceptible to particle crushing and hence maximum density values measured on these samples may not be representative of the in-situ/tested specimens.
- Intact carbonate samples generally consist of loose soil structure and very high void ratio which is very difficult to replicate in the laboratory using reconstituted samples. Therefore, laboratory testing on carbonate sediments is generally carried out on intact samples and significant emphasis is given to recover intact samples during site investigation for engineering projects.
- The behaviour of carbonate sediments is very sensitive to the degree of cementation. Cementation observed in these sediments can from lightly cemented sands through to strongly cemented calcarenite rocks.
- Application of cyclic loading to these materials can result in shear strength degradation that that is greater that similarly composed non-carbonate sediments (Sharma et al. 2023).

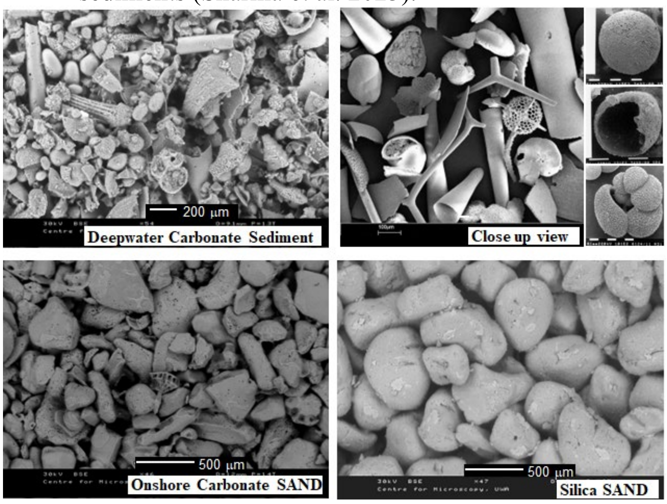

Figure 1. Typical micrographs of carbonate and silica sand (Sharma and Joer, 2015)

3. In-situ Testing on carbonate sediments

In-situ testing techniques used in carbonate sediments are the same as non-carbonate materials. In-sity testing generally includes the cone penetration test (with/without pore pressure measurement, CPTu/CPT), pore pressure dissipation testing (PPDT), full flow penetrometer (FFP) and seismic CPT (SCPT) tests. The testing equipment and procedures adopted are typically the same as non-carboante material. However, there may be some differences in how the results are interpreted. The following sections summarise the tests and and any special considerations required for carbonate sediments.

3.1. Cone penetration testing

Cone penetration tests are routinely used for site investigations on carbonate sediments. This test includes continuous measurement of cone resistance (q_c), sleeve friction (f_s) and excess pore pressure (u) with depth. The excess pore pressure is typically measured at the u_2 (cone shoulder) position. The CPT is generally performed using seabed or downhole modes depending on project requirements. Tests are generally performed using a standard 10 cm^2 cone. However, other cone sizes (e.g., 5 cm^2 and 15 cm^2 cones) can also be used. The 15 cm^2 cone is generally used on deepwater location where shallow soft sediments are encountered, while the 5 cm^2 cone (which is not generally fitted with a pore pressure sensor) is commonly used in variable cemented units where refusal is routinely encountered using the standard 10 cm^2 cone. The maximum q_c value that can be measured using 10 cm^2 cone is generally limited to about 60-80 MPa, while using the 5 cm^2 cone, q_c up to 150 MPa is routinely measured.

In the seabed mode, the test is performed until the target depth is reached or refusal in a hard layer, whichever occurs first. However, as most carbonate sites may include cemented layers, the downhole mode is generally preferred so that the any hard layers can be drilled out and tests can be continued to deeper depths. As carbonate sites are often highly variable, any drill out due to refusal is generally limited to 0.5 m to minimize the data gap. Typical penetration responses for different types of carbonate sediments are presented in Section 4.

3.2. Full flow penetrometer testing

The full flow penetrometer (FFP) testing such as the Ball penetrometer and T-bar test are routinely performed on carbonate sediments. The FFP tests are performed in a similar manner to the CPT except a cone is replaced by either a ball or T-piece. Typically, a ball with a projected area of 2,800 mm^2 and T-bar with nominal diameter of 40 mm and length of 250 mm are used. Alternative size FFPs such a miniature ball and T-bar tests are also carried out on recovered box core samples.

The resistance and pore pressure are measured both during the penetration (push) and extraction (pull-out) phases of the FFP test. In addition, cyclic tests are also performed by cycling the probe between selected depth intervals. Typically, a cyclic amplitude of ~0.5 m and number of cycles ranging between 10 and 20 are used offshore.

The results from FFP are used to ascertain the in-situ strength, the degradability of strength in cyclic tests, and remoulded strength (sensitivity) of the material. A typical example of the cyclic T-bar test is shown in Fig. 2.

The FFP test may be affected by depth offset, offset in measured resistance value, etc. The results from the initial push and final retrieval are compared to check for any depth bias. Similarly, the results from the cyclic phase of the testing are used to check for any offset in the measured resistance. Also, as in the case of the CPT, the measured value of FFP are corrected to account for the effects of pore pressure and overburden stress on the measured resistance.

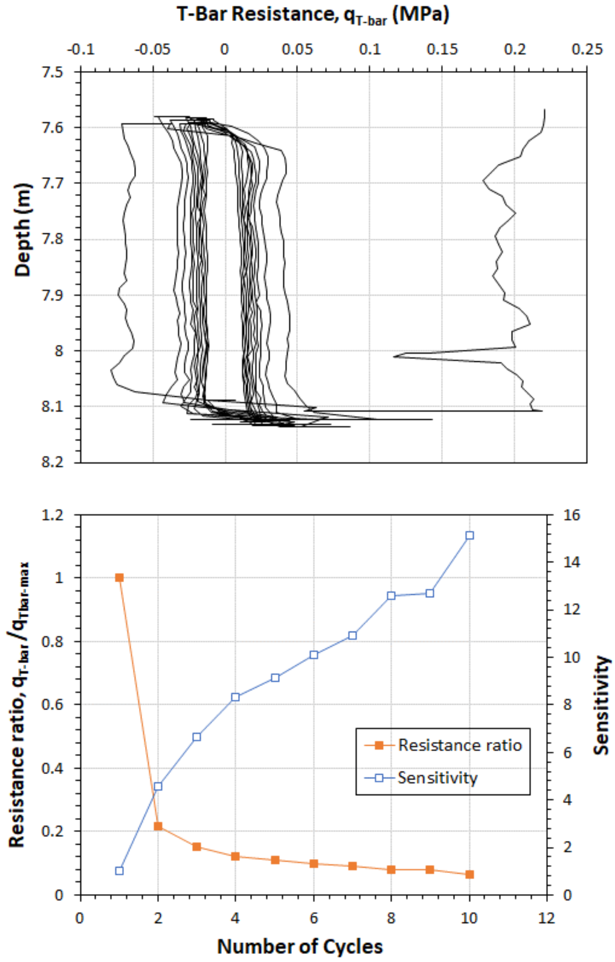

Figure 2. Typical T-bar test results (Sharma and Joer, 2015)

3.3. Seismic cone penetration testing

The seismic CPT (SCPT) is similar to a standard CPT but incorporates one or more geophones within the cone shaft. The standard CPT parameters (q_c, u_2 and f_s) are recorded as the SCPT is being penetrated. At regular intervals, penetration is stopped, and a seismic source is triggered from the mudline. The arrival of the compression and shear waves is recorded by the geophones.

The SCPT has been used with low to moderate success in carbonate sediments. In general, the quality of seismic data is found to depend on ground condition (i.e., in cemented sites the recovery of seismic data is generally poor). In addition, the variability of seismic data that may sometimes be obtained in (uncemented) carbonate sediments are affected due to poor contact between the energy source and the seabed.

4. Cone penetration behavior in carbonate sediments

Fig.3 shows typical CPT data from the literature for different types of carbonate sediments in water depths ranging between approximately 60 m and >500 m. To compare the data the results are presented in terms of net cone resistance (q_{net}), normalized cone resistance

($Q_t = q_{net}/\sigma'_{v0}$, where σ'_{v0} is the in-situ vertical effective stress), friction ratio ($F_r = f_s/q_{net}$), pore pressure ratio ($B_q = \Delta u_2/q_{net}$, where Δu_2 is the differential pore pressure above hydrostatic) and normalized pore pressure ($\Delta u_2/\sigma'_{v0}$). Based on these results and the authors' experiences on different types of carbonate sediment from across the world, the key penetration behavior of carbonate sediments can be summarized as follows:

- The overall CPT response for carbonate sediments is similar to non-carbonate materials. However, the grain composition of carbonate sediments depends on their depositional environment, which is also reflected in the penetration behaviour.
- In general, carbonate sediments deposited in low energy environments (e.g. deepwater locations) consist of fine-grained material (Mud and Silt) and exhibit undrained CPT responses often associated with low q_{net} and high F_r and B_q. On the other hand, the material deposited in high energy environments (e.g. shallow water locations), generally consist of coarse grained and cemented materials, which shows drained CPT response often associated with high q_{net} and low F_r and B_q.
- The cone penetration behaviour of carbonate sediments can be highly variable both laterally and with increasing depth. It is common to find different types of carbonate sediments ranging from uncemented sediments to variably cemented material within a narrow depth range as shown on Fig. 3.
- The occurrence of cemented materials is influenced by the depositional environment and changes in these environments that have occurred over time, which affect the CPT response.
- In shallow water locations, variably cemented layers are commonly encountered due to favourable diagenesis environments. Cone refusal which is often accompanied by low F_r and B_q is often encountered in these variably cemented layers. These layers may also affect the CPT behaviour, in particular the pore pressure due to potential cavitation, for both the overlying and underlying weak layers.

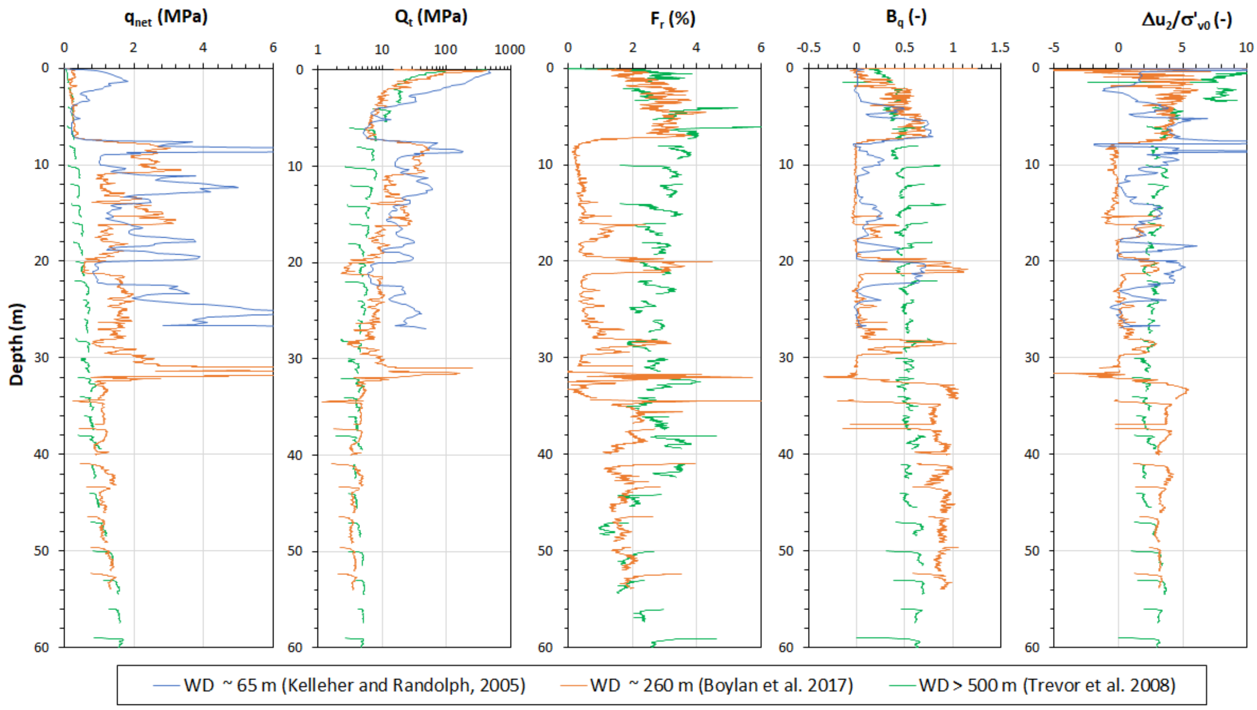

Figure 3. Typical PCPT response for carbonate sediments

5. Material characterization using CPT

CPT based empirical soil behavior type (SBT) charts (e.g. Robertson, 1990 and Schneider et al., 2008) are commonly used for soil classification purposes. However, these charts were developed based on observed behavior of non-carbonate materials and their application in carbonate materials may result in misleading results.

Fig. 4 shows the comparison of CPT based soil classification with the soil description based on visual inspection (boreholes logs) and the laboratory test results provided in the corresponding papers for the three selected CPT profiles discussed above. The figure presents the CPT based soil classification based on Robertson, (1990) in terms normalized cone resistance (Q_t) versus friction ratio (F_r) and pore pressure parameter (B_q) and Schneider et al., (2008) in terms of Q_t versus normalized pore pressure ($\Delta u_2/\sigma'_{v0}$). Based on these results the following key observation can be made:

- The charts broadly capture the difference between the coarse-grained materials with fines content < 50% (predominantly defined as sand and gravel based on unified soil classification system, USCS) and fine-grained materials with fines content < 50% (predominantly defined as clay and silt based on USCS) materials. However, carbonate sediments generally comprised mixtures of coarse and fined grained materials and the soil type for such mixtures was not always apparent based on these SBT charts.

- Different types of fine-grained materials were found to overlap in the chart and there was no apparent distinction between silts and mud[1]. This is particularly important as the behaviour and the associated engineering parameters for carbonate silt can be significantly different compared to carbonate mud.
- The high sensitivity values associated with carbonate sediments can be due to the fragile nature of their particles, which is not captured by the SBT charts.
- The soil type based on different chart is sometimes found to differ. For example, most of the low to high plasticity silt, ML/MH (Trevor et al. 2007) plots in Zone 4 (silt mixtures), in the Q_t-F_r plot in zone 3 (clays) in the Q_t-B_q plot and in zone 1b (clays) in the Q_t-$\Delta u_2/\sigma'_{v0}$ plot. This indicates differences between the SBT zone based on friction ratio and pore pressure.
- The behaviour of carbonate sediments depends on the amount and type of carbonate minerals present in the sample. As expected, the SBT charts do not distinguish material type based on carbonate content.
- In addition, one of the most important characteristics of carbonate sediments is variable degree cementation between particles, which affect their engineering behaviour. The SBT charts do not differentiate the material type based on level of cementation.

In general, the SBT charts available in the literature based on non-carbonate materials are not commonly used in carbonate sediments for classification purposes. Although the CPTu data, in particular Q_t-B_q and Q_t-$\Delta u_2/\sigma'_{v0}$ response is commonly used to differentiate between different material types (e.g., fine grained versus coarse grained), it is a common practice in carbonate sites to use CPTu data in combination with site-specific laboratory test data for soil classification purposes.

6. Link between CPT response and geotechnical parameters

CPT data can provide a continuous measurement of soil response with depth. Therefore, it is advantageous to link CPT data with different geotechnical parameters for engineering use. In the following sections a range of geotechnical properties of carbonate sediments are shown as a function of normalized cone parameters. Note that the objective of this exercise is to show the typical zones of parameters for carbonate sediment in a consistent manner as a function of CPT response and is not intended to provide a detail methodology on how to derive engineering parameters for carbonates. As such most of the data are presented in terms of normalized cone resistance defined in terms of $(q_{net}/p_a)/(\sigma'_{v0}/p_a)^{0.5}$, where p_a is atmospheric pressure (= 101.3 kPa).

Note that the typical zone of parameters is shown by the shaded areas on the figures below and these areas cover most of the data based on authors experience of different types of carbonate sediments from around the world. Note that shaded areas are defined manually without any statistical approach/algorithms. However, it is possible that data points may plot outside these zones. The relationship between a geotechnical parameter and the normalized cone parameters may follow a different trend to that suggested by the overall shaded area. Thus, these shaded regions should not be considered as the basis of correlations. They just provide a means to identify the potential range that may be encountered in practice.

6.1. Basic parameters

6.1.1. Fines content and median particle size

Fig.5 shows the typical zone of fines content, FC (defined as particle size < 75 μm) for different types of carbonate sediments. In general, the results show reducing fines content with increasing normalized cone resistance.

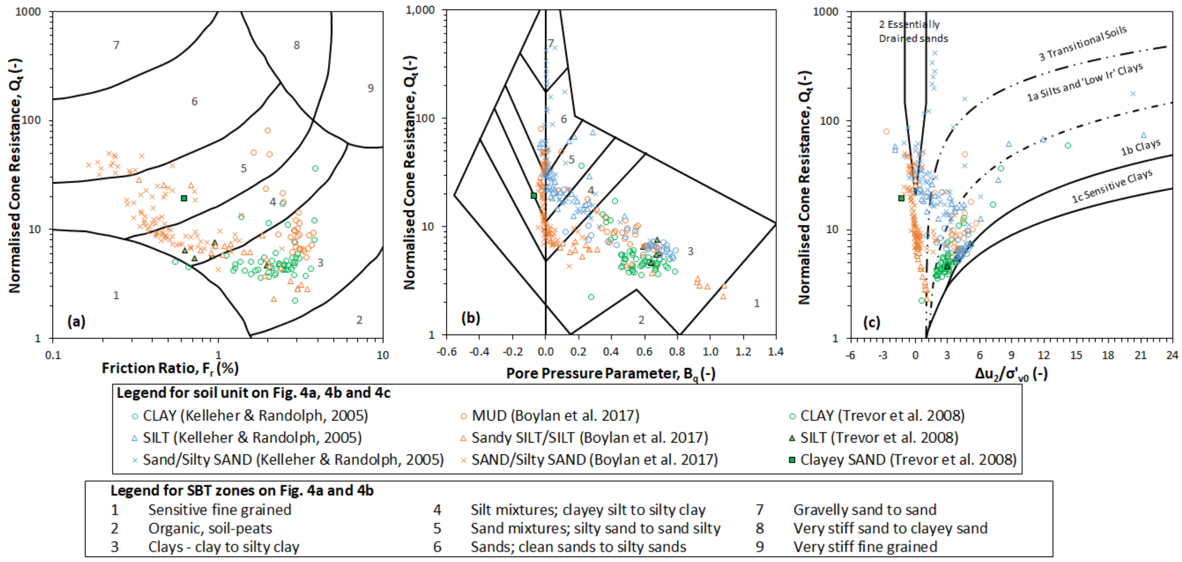

Figure 4. Comparison of CPT based soil classification for carbonate sediments

[1] For carbonate sediments, the terminology 'mud' is used to instead of 'clay' to describe clayey materials as per Clark and Walker (1977)

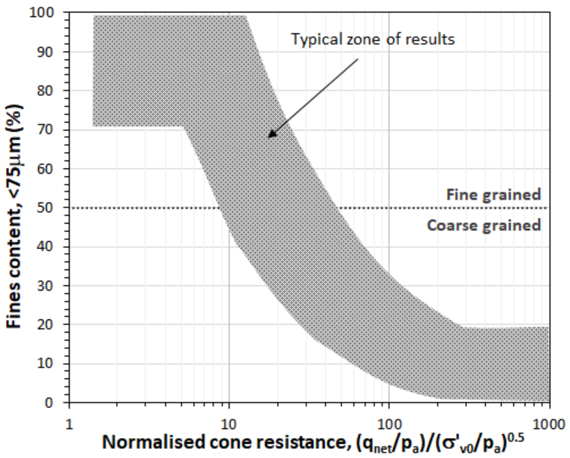

Figure 5. Typical zone of FC data for carbonate sediments.

6.1.2. Void Ratio

Fig.6 shows the typical zone of void ratio (e) data for different types of carbonate sediments as a function of normalized cone resistance. In general carbonate sediments show significantly high void ratios with higher values generally obtained for fine grained sediments. The results also show that the variability in the void ratio is more pronounced for fine grained materials with reducing normalized cone resistance.

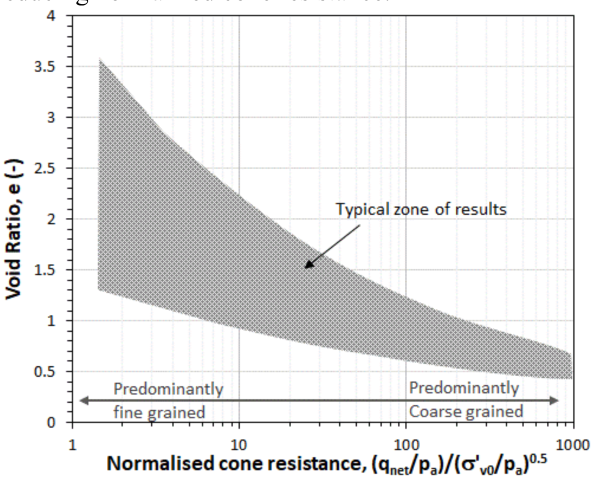

Figure 6. Typical zone of e data for carbonate sediments.

6.2. Strength parameters

6.2.1. Undrained shear strength (cone factor)

The monotonic undrained shear strength (s_u) is one of the most critical parameters for engineering design in carbonate sediments. The in-situ undrained shear strength profile for carbonate sediments is typically derived by comparing simple shear or triaxial test data with the CPT data using a cone factor, $N_k = q_{net}/s_u$

Fig.7 shows the typical zone of cone factor results for simple shear test condition (i.e., $N_{k\text{-}SS}$) for different types of carbonate sediments. As expected, due to the high variability of fines content and particle shapes/sizes/types associated with carbonate sediments, the cone factor for carbonate sediments is also highly variable.

Note that the cone factor shown on Fig. 7 is based on uncemented sediments. Based on the authors' experiences, any slight cementation between particles may affect the cone factor significantly with cone factor values exceeding 100 are not uncommon for lightly cemented materials.

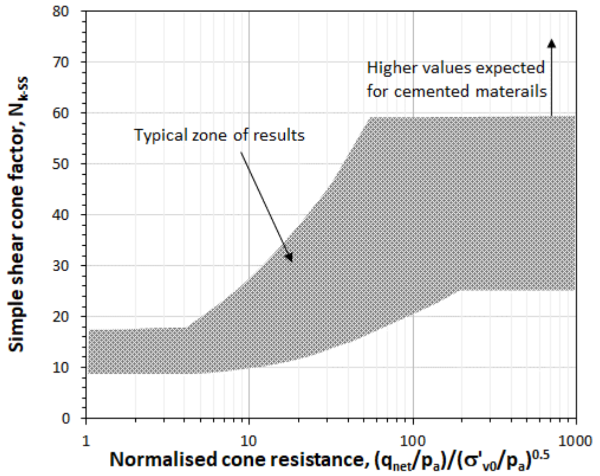

Figure 7. Typical zone of $N_{k\text{-}SS}$ for carbonate sediments.

6.2.2. Effective Friction Angle

Carbonate sediments generally exhibit higher friction angles compared to their non-carbonate counterparts. In general, critical state friction angle values ranging between 33° and 38° are often reported for carbonate sediments (e.g., Sharma and Ismail, 2006), while the corresponding values for silica sand are between 30° to 33° (e.g., Andersen and Schjetne, 2013). The peak friction angle (ϕ'_{peak}) values depend on the soil state/stress condition. Fig.8 presents a typical zone of ϕ'_{peak} values for uncemented carbonate sediments. This shows that ϕ'_{peak} values generally increase with an increasing normalized cone resistance. Note that ϕ'_{peak} values higher than the zone shown on Fig. 8 may exist, but such high values are likely to be for cemented materials due to the cohesive component of strength.

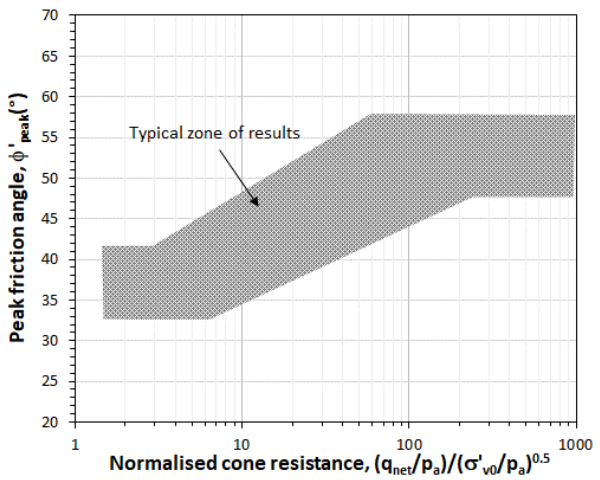

Figure 8. Typical zone of ϕ'_{peak} for carbonate sediments.

For carbonate sediments the peak strength/ ϕ'_{peak} is generally mobilized at large strain, exceeding 20% axial strain which is much higher than silica sand for which peak strength/ ϕ'_{peak} is mobilized at strain levels less than ~ 15% (Sharma and Ismail, 2006).

6.2.3. Soil Sensitivity

Soil sensitivity (S_t) is defined as the ratio between the intact to remoulded strength and is assessed in-situ using cyclic T-bar tests (Fig. 2) and in the laboratory using either fall cone or miniature vane tests. Fig.9 shows the typical zone of S_t data for carbonate sediments.

As noted in Sharma and Joer (2015), the mechanism associated with the high S_t values for carbonate sediments is due to the fragile natures of the particles, which tend to break during the remoulding processes. This mechanism is different to other non-carbonate soils.

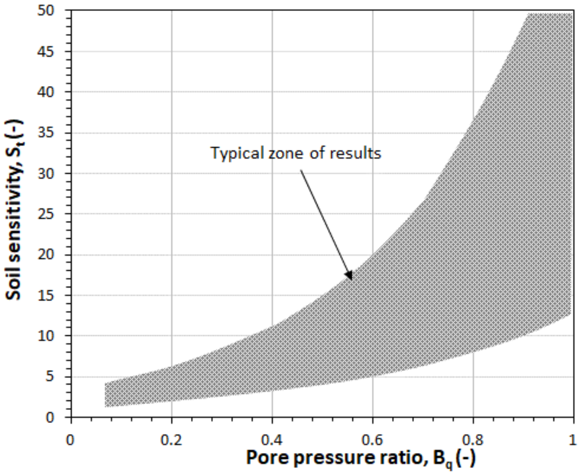

Figure 9. Typical zone of S_t for carbonate sediments.

6.3. Deformation and consolidation parameters

6.3.1. Small strain shear modulus

The maximum (or 'small strain') shear modulus (G_{max}) is determined in the laboratory from bender element and resonant column tests and in-situ using the seismic CPT. Typical zone of data for uncemented carbonate sediments using the form of relationship available in the literature (e.g. Lunne et al., 1997) is shown Fig. 10.

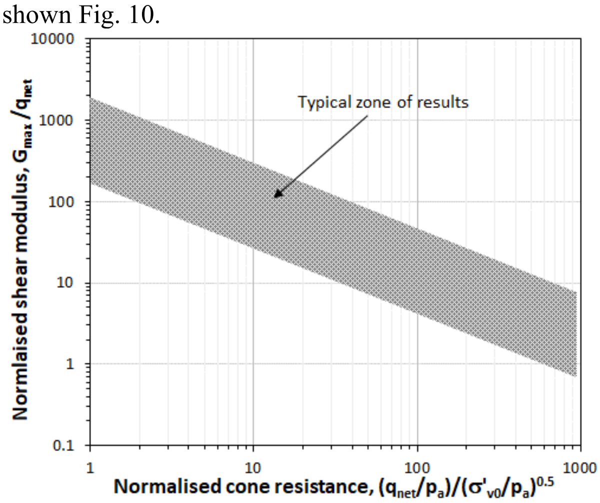

Figure 10. Typical zone of G_{max} for carbonate sediments.

6.3.2. Constrained modulus

The constrained modulus (M) describes the relationship between changes in stress and strain for soil under one-dimensional consolidation (i.e., no lateral strain). This parameter can be estimated from incremental loading and constant rate of strain (CRS) oedometer tests. The typical zone of results for M at in-situ stress levels for different types of carbonate sediments are shown on Fig.11.

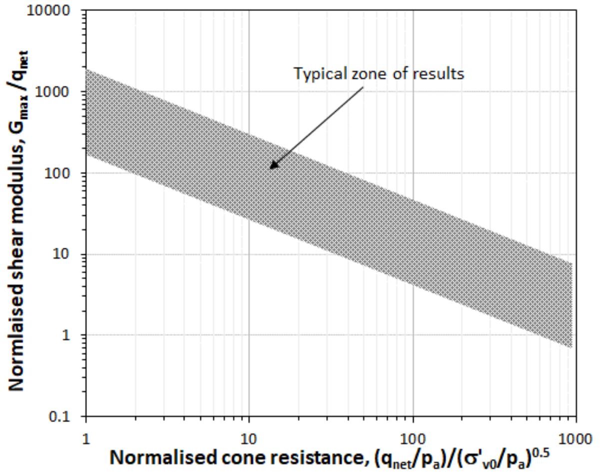

Figure 11. Typical zone of M for carbonate sediments.

6.3.3. Compression and Swelling Indices

The compression and swelling indices (C_c, and C_s, respectively) are defined as the slope of the compression line and unloading-reloading line in a semi-logarithmic plane (i.e., $\log_{10}(\sigma_v) - e$). A typical zone of C_c and C_s values obtained from the oedometer, and CRS tests are shown on Fig. 12. In general carbonate sediments show higher C_c and low C_s values compared to non-carbonate materials. Also, the C_s value for carbonate sediments may depend on the stress level with unusually low C_s values often obtained at high stress levels due to particle breakage. Note that the range shown on Fig. 12 is based on the data obtained at the in-situ stress level.

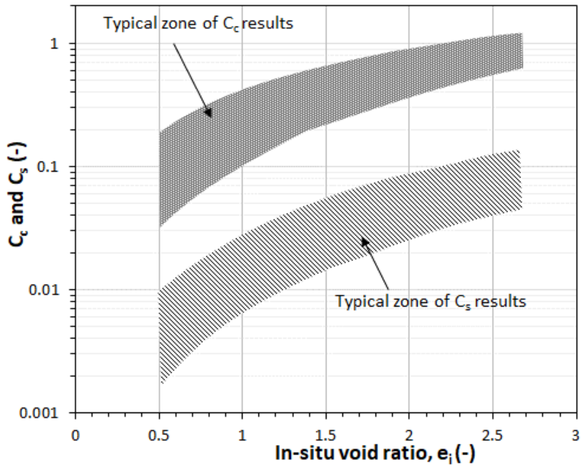

Figure 12. Typical zone of C_c and C_s for carbonate sediments.

6.3.4. Yield stress ratio

The yield stress ratio (YSR) – more commonly termed as the over consolidation ratio (OCR) for non-carbonate materials – is commonly determined from the results of incremental loading and CRS oedometer tests.

For carbonate sediments YSR is estimated using two alternative methods, i.e., a SHANSEP type approach as discussed in Zhou et al, 2020 and CPT based method (Lunne et al., 1997). Using the CPT based method the YSR is defined as YSR = k q_{net}/σ'_v, where k is a material constant. Typical zone of k value for carbonate sediments is shown on Fig. 13.

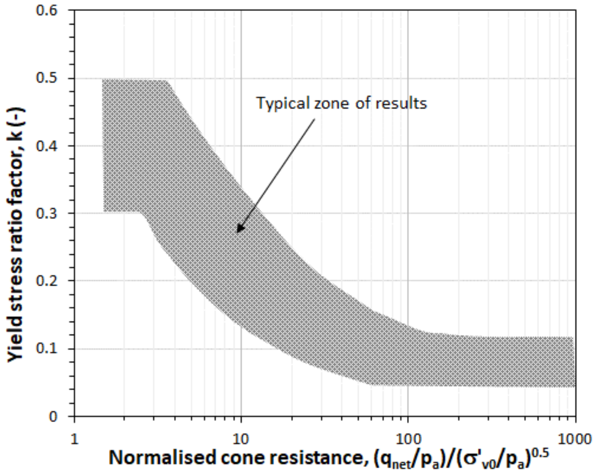

Figure 13. Typical zone of k for carbonate sediments.

7. DIRECT USE OF CPT DATA IN GEOTECHNICAL ENGINEERING

For carbonate sediments, the soil parameters required for geotechnical engineering are generally derived by calibrating the CPT data with site-specific laboratory test data. The direct use of the CPT based methods available in literature and design codes developed based on the data from non-carbonate materials are not recommended for carbonate sediments, for the following key reasons:

- Partial drainage effects during cone penetration can affect the measure cone parameters.
- The range of parameters for carbonate sediments may lie well outside the range observed on non-carbonate materials.
- Cementation if present will affect the measured CPT response and this may result in misleading interpretations from correlations.

8. CONCLUSION / RECOMMENDATIONS FOR FUTURE RESEARCH

Some of the unique behavior and characteristics of carbonate sediment, particularly in the marine environment, have been presented in this paper. Typical CPT responses in carbonate sediment have been shown and in combination with laboratory results, typical zone of results as a function of normalized cone resistance are shown. These data highlight the differences between carbonate sediment and other soil types. These can be useful to understand the zone where results may lie, particularly for uncemented carbonate sediment but should not be considered as bounds and correlations. These zones illustrate where most of the results may lie. At a specific site, the relationship between a geotechnical parameter and the cone measurements may exhibit a different trend to that typical zone shown in this paper.

Several challenges remain for CPT in carbonate materials. Some areas for further research include:

- *Seismic CPT in carbonate material*. The seismic CPT has been used with low to moderate success in carbonate materials. The ongoing industry transition to offshore wind has put a greater emphasis on in-situ stiffness measurements. Further research is required to improve seismic measurements in carbonate materials.
- *Evaluation of CPT based soil classification charts for carbonate material.* As shown in this paper, existing CPT based classification systems may not be suitable for carbonate material. Further study on the suitability of these charts and possible development of new charts is required.
- *Soil Resistance to Driving (SRD) from CPT.* CPT is a powerful tool and can be used to directly assess the SRD that is used in pile installation assessments. Presently, there are no methods developed for direct use in carbonate sediments.

References

Andersen, K.H., and K. Schjetne. "Database of friction angles of sand and consolidation characteristics of sand, silt, and clay." *Journal of Geotechnical and Geoenvironmental Engineering* 139, no. 7 (2013): 1140-1155.

Boylan, N. P., A. Roux, J. L. Colliat-Dangus, and A. Sato. "Installation Response of 5.5 m Diameter Driven Piles in Carbonate Soil–The Ichthys Development." In *Offshore Site Investigation Geotechnics 8th International Conference Proceeding*, vol. 674, no. 681, pp. 674-681. Society for Underwater Technology, 2017.

Clark, A. R., and B. F. Walker. "A proposed scheme for the classification and nomemclature for use in the engineering description on Middle Eastern sedimentary rocks." *Geotechnique* 27, no. 1 (1977): 93-99.

Fookes, P. G. "The geology of carbonate soils, rocks & their engineering characterisation and description." In *International conference on calcareous sediments*, (1988): 787-806.

Kelleher, P. J., and M. F. Randolph. "Seabed geotechnical characterisation with a ball penetrometer deployed from the portable remotely operated drill." *In Proceedings of the 1st international symposium on frontiers in offshore geotechnics*, (2005): 365-371. Lisse, Switzerland: Swets & Zeitlinger.

Lunne, T., P. K. Robertson, and J. J. M. Powell. "*Cone Penetration Testing in Geotechnical Practice*." Spon Press, London, (1997).

Milliman, J. D., G. Müller, and F. Förstner. *Recent sedimentary carbonates: Part 1 marine carbonates*. (1974).

Robertson, P. K. "Soil classification using the cone penetration test." *Canadian geotechnical journal* 27 no. 1, (1990): 151-158.

Schneider, J.A., M.F Randolph, P.W Mayne, and N.R Ramsey. "Analysis of factors influencing soil classification using normalized piezocone tip resistance and pore pressure parameters." *Journal of geotechnical and geoenvironmental engineering* 134, no. 11 (2008): 1569-1586.

Sharma, S.S., and M.A. Ismail. "Monotonic and cyclic behavior of two calcareous soils of different origins." *Journal of geotechnical and geoenvironmental engineering* 132, no. 12 (2006): 1581-1591.

Sharma, Shambhu S., and H. A. Joer. "Some characteristics of carbonate sediments from Northwest Shelf, Western Australia." *In Proceedings of the 3rd International Symposium on Frontiers in Offshore Geotechnics* (ISFOG 2015), vol. 1, pp. 1109-1114. Taylor & Francis Books Ltd, 2015.

Sharma S.S., C. Colreavy, and N. Boylan, (2023). "Cyclic Behaviour of an Offshore Carbonate Silty Sand." *Proceedings of the 14th ANZ Conference on Geomechanics*, Cairns 2023.

Trevor, F.A., J.M. Paisley, Y. Konda, and T. Abbs. "Soil Properties of Deepwater Sediments in the Timor Sea, Indonesia." *Proceedings of Geotechnical and Geophysical Site Characterization, Taylor & Francis Group, London* (2008).

Zhou, H., S.S. Sharma, A., Amodio, N. Boylan, and P. Gaunt, P. "Balanced Characterisation of Fine-Grained Soils: Application to Carbonate Sediments." *In Offshore Technology Conference, Houston, Texas, USA*, May (2020).