Comparison of Two Calcareous Sands in Relation to a Novel Offshore Mixed-in-Place Pile

By G. SPAGNOLI and P. DOHERTY*

Abstract
Carbonate (or calcareous) sands are encountered in several locations where offshore petroleum activities are underway, in particular the Southern Mediterranean Sea, the Persian Gulf, Brazil and Australia. These locations, and in particular developments in the Arabian Gulf, have encountered significant piling difficulties, where driven piles were observed to free fall through carbonate sand. As a result, drilled-and-grouted piles are the preferred foundation solution in these soil types. The MIDOS (Mixed Drilled Offshore Steel) pile is a new type of offshore foundation, which has been successfully installed in an onshore field trial in silica sands. The feasibility of this pile in calcareous (or carbonate) sediments was extensively examined in a laboratory scale investigation, conducted as part of a joint research project between BAUER Maschinen GmbH and University College Dublin (UCD). The results show that the mixed-in-place technology is particularly suitable for these challenging deposits.

Introduction
Offshore fixed production platforms are installed in the seas and oceans throughout the world, usually in water depths of less than 200 m. In the period 2008–2012, the majority of fixed platforms were installed in Asia and the Middle East, particularly in Malaysia and China, with most platforms situated between 25 and 50 m water depth [1]. The most common type of offshore foundation is the open-end driven steel tube pile [2] with diameters ranging from 1 m up to 6 m (for offshore renewable energy) and lengths up to 300 m [3]. However, there are situations where pile installation by means of traditional impact hammers is not possible, for instance in rock conditions, where boulders and/or cobbles are encountered or in calcareous deposits. Therefore, drilled piles are normally used in these conditions. According to [2–4] offshore drilled piles can be installed with top drilling units with facilities for both direct and reverse circulation. Offshore piles resist compression and tension forces, by transferring the load along the shaft and by mobilising end bearing at the base (for compression loads). However, calcareous soil deposits pose several problems with respect to both piles installation and the subsequent capacity mobilised (e.g. [5–7]). Calcareous (or carbonate) sands are found mainly in the warm seas between latitudes 30°N and 30°S in coastal areas of Australia, India, Saudi Arabia. However they are also frequent up to latitudes 50°N and 50°S (Fig. 1 [5]). Several research studies have demonstrated that calcareous soils have comparable friction angles to silica sands at low confining stress, but at higher pressures, the material contracts, due to crushing of the calcareous grains.

The Mixed-in-Place Pile Technology
The MIDOS (Mixed Drilled Offshore Steel) pile is based on the deep-mixing technology, where the soil is mixed in with binder-water slurry. According to [14], deep mixing involves “mixing by rotating mechanical mixing tools where the lateral support provided to the surrounding soil is not removed”. Deep mixing involves “treatment of the soil to a minimum depth of 3 m” [14]. Most of the deep mixing methods use paddle-formed blades or augers mounted on one or more shafts. It is typical of wet deep-mixing technology to further differentiate the driving mechanism of the mixing tools: blades at...
A water/cement ratio (w/c) of 1 was used for the trial test. After 28 days a static tension test was performed reaching an uplift capacity of 9 MN [12]. Ige et al. [12] described the application of this pile for offshore oil & gas platforms and the ultimate tension showed to be in good agreement with the expected shaft friction for conventional D&G piles. Recently Spagnoli et al. showed Plaxis simulations on large MIDOS piles in calcareous and silica sands, demonstrating how the compressive and uplift capacity almost the same is, irrespective of the geology [17].

**Engineering Geological Characteristics of the Calcareous Sands**

[4] and [7] investigated the feasibility of employing the MIDOS mixed-in-place system in two carbonate sands, which were compared with control samples of silica sand from Blessington (East Ireland). The two soils tested are known as Dogs Bay and Ballyconneely sands from the West of Ireland. Dogs Bay sand is a carbonate sand and it was intensively investigated in the past for BP pile behaviour research studies, because of the lower pile capacity encountered at the North Rankin offshore platform [18]. The Ballyconneely sand is a whitish orange dense rounded uncemented calcite carbonate algal sand typically encountered in beaches of Ballyconneelly Bay in the Conna marra region (West Ireland). This sand was chosen because of its chlorozoan grain type and offers a strong contrast to the Dogs Bay sand. It is important to highlight the different morphological characteristics of the two sand types. In fact, various micro-scale soil properties are known to affect the macroscale behavior of sand. For example, particle size and grading curves have a direct influence on sand shear strength as well as properties such as maximum and minimum void ratios. The effect of particle shape (morphology) is another significant but often overlooked property which can have a huge influence on the behavior of a sand mass at various scales of strain. The term particle morphology can refer to a number of measurable shape properties of an individual particle. The three main properties used to describe a particle’s shape are roundness (or angularity), sphericity, and roughness. SEM pictures were taken to confirm the mineralogy of the sand and to categorize the sand’s shape by calculating the sand’s average morphological properties. These properties can then be used to estimate the sand’s maximum and minimum void ratios as well as the constant volume friction angle.

Visual inspection of the SEM images of the Dogs Bay and Ballyconneely sand samples (Fig. 3) shows some strong differences between the two sands. Firstly, it was noted that the Dogs Bay sand had no visible fines, but the Ballyconneely sand showed fine particles in between and coating the larger particles. Secondly, the Dogs Bay sand showed a large amount of fossil-like particles and symmetrical pitting of particle surfaces. The Ballyconneely sand in comparison had fewer fossil-shaped particles and the pitting on the sand particles was irregular. The surface texture of the Ballyconneely sand appears to be rougher than the Dogs Bay sand. The vast majority of SEM XRD spectra of the Dogs Bay sand showed at least 80% calcium, with trace amounts of silicon, sulphur, aluminium, sodium, chlorine, bromine, magnesium and iodine. Some of the spectra showed 100% calcium. For the Ballyconneely sand the SEM XRD spectra showed at least 89% calcium, with trace amounts of silicon, magnesiu and iodine. Some of the spectra showed 100% calcium. These results confirm that both sands are calcareous sands. The overall average roundness and sphericity for the three samples is shown in Table 1. Based on the roundness classification chart by [19], both sand types are classed as “rounded” and described as “irregularly shaped particles with no distinct corners or edges”. Roundness, R, refers to how “angular” a particle is. It is defined as the ratio between the average radius of curvature of the particle’s corners and the radius of the largest inscribed circle. Sphericity, S, refers to how “ellipsoidal” or “platy” a particle is and is defined as the ra-
tio between the radius of the largest inscribed circle and smallest circumscribing circle of a particle. Particle regularity, $\rho$, is defined as shown in equation 1:

$$\rho = \frac{(R + S)}{2}$$  \hspace{1cm} (1)

Roundness and sphericity can be visually estimated using charts such as the one presented by [20]. Differences in the estimated roundness and sphericity are in the region of 0.1–0.2 [21]. Correlations between particle shape parameters and engineering properties, in particular, the constant volume friction angle and maximum and minimum void ratios, are present in the literature. Using these correlations and the calculated particle shape parameters for this sand, an estimate of these properties was made. The average roundness of sand’s particles has been related to various engineering properties such as constant volume friction angle and maximum and minimum void ratios ($e_{\text{max}}$ and $e_{\text{min}}$). [19] presented an expression linking roundness to the maximum void ratio, $e_{\text{max}}$ and the minimum void ratio, $e_{\text{min}}$ for uniformity coefficient, $Cu = 1$:

$$e_{\text{max}} = \frac{(0.554 + 0.0154)}{R}$$  \hspace{1cm} (2)

$$e_{\text{min}} = \frac{(0.359 + 0.082)}{R}$$  \hspace{1cm} (2)

[21] give an equation relating roundness to constant friction angle, $\phi'_{cv}$:

$$\phi'_{cv} = 42 - 17 \cdot R$$  \hspace{1cm} (3)

In order to correlate the constant friction angle of equation (3), several direct shear tests have been performed on both carbonate sands and silica sand with relative density, $Dr \approx 80–90\%$ [4]. Some of the results are shown in Figure 4. In general, friction angles of calcareous soils decrease with increasing confining pressure.

<table>
<thead>
<tr>
<th>Sand type</th>
<th>Average Roundness</th>
<th>Average Sphericity</th>
<th>Average Regularity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dogs Bay</td>
<td>0.56</td>
<td>0.48</td>
<td>0.52</td>
</tr>
<tr>
<td>Ballyconneely</td>
<td>0.63</td>
<td>0.55</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Table 1: Overall averages of morphological properties

Table 2: Comparison of constant friction angle, $\phi_{\text{max}}$ and $\phi_{\text{min}}$ for both calcareous sands

<table>
<thead>
<tr>
<th>Sand type</th>
<th>$\phi_{\text{max}}$ Laboratory/Youd [19]</th>
<th>$\phi_{\text{min}}$ Laboratory/Youd [19]</th>
<th>$\phi'_{cv}$ Laboratory/Santamarina and Cho [21]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dogs Bay</td>
<td>1.10/0.83</td>
<td>0.85/0.51</td>
<td>34/30</td>
</tr>
<tr>
<td>Ballyconneely</td>
<td>0.84/0.80</td>
<td>0.60/0.49</td>
<td>39/29</td>
</tr>
</tbody>
</table>

Friction Angle of the Mixed-in-Place Calcareous Sands

[4] and [7] extensively investigated the MIP properties of both calcareous sands comparing the results with the silica control sand (Blessington). The outcome of the laboratory testing programme demonstrated that the MIDOS pile would have similar geotechnical and structural properties in both calcareous and siliceous deposits, sug-
gesting that this novel offshore foundation type is suitable for a range of sand conditions. Additional direct shear tests for the interface sand-grout with w/c of 0.4 for 25% cement-to-sand ratio (Fig. 5) and sand Dr ~ 80–90% are presented in this article. Comparision of the calcareous interface friction angles for the soil-soil, soil-steeel (see [4]) and soil-grout tests were nearly identical, suggesting that $\delta_s$ for the soil-steel and soil-grout is directly comparable to the $\varphi_s$ for the soil-soil failure. This suggests that the friction angle controlling the failure mechanism at the pile-soil interface of the MIDOS pile will be comparable to the soil friction angle and no reduction is needed to account for the interface properties. Besides, the calcareous sands typically displayed peak friction angles (soil-soil) that were higher than the comparative tests on the silica sand samples, indicating that the MIDOS pile is able to generate the same friction in calcareous deposits. When image analysis was run on the Ballyconneely sand particles it was found that the average roundness and sphericity were 0.63 and 0.55 respectively. These values are higher than the average values calculated for the Dogs Bay sand, which gave roundness and sphericity values of 0.56 and 0.48 respectively. This indicates that the Ballyconneely sand particles are on average rounder and more spherical than the Dogs Bay sand particles. This increased roundness and sphericity of the Ballyconneely sand particles is evident in the resulting estimated constant volume friction angle which was calculated to be 29°. This value is lower than that estimated for the Dogs Bay sand (30°) since increased roundness and sphericity are known to result in lower friction angles. However, direct shear results on sand-sand and sand-grout show higher peak friction angles for the Ballyconneely sand than for the Dogs Bay. The higher strengths in the Ballyconneely samples are more pronounced for the compressive failure mode and this is possibly attributable to the coarser nature of the Ballyconneely particles as mentioned previously. Estimated values of $c_{uu}$ and $c_{ua}$ are lower for the Ballyconneely sand than for the Dogs Bay sand. However, the estimated void ratios from the SEM analysis are lower when compared to the laboratory results. The lower values for the Ballyconneely compared with the Dogs Bay sand is again a result of the increased roundness and sphericity of the Ballyconneely sand particles.

Conclusions

This article described the use of a novel mixed-in-place (MIP) pile for offshore oil & gas foundation applications in calcareous soils. The MIP technology can be regarded as an innovative type of mechanical wet deep mixing method (DMM). This article presented SEM imagery analysis for two calcareous sands which were compared to the results of laboratory tests. The correlations with the grain imagery parameters were shown to underestimate the soil friction angle. Overall, the test results on calcareous sands have shown that the MIDOS technology may be well suited to these deposits.

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References


Dr. Paul Doherty has been Managing Director of geotechnical engineering consultancy GDG since the company incep- tion in 2011. GDG offers innovative geotechnical and foun- dation design solutions to the international market. Dr. Doherty originally graduated from University College Dublin with a BE (Honors) degree, where he specialised in geotechnical engineering and soil mechanics. He has worked on a range of consultancy projects, in- cluding offshore foundation design, pile design, sub- structure optimisation, and geotechnical instrumen- tation/monitoring. Paul is also an active member of the Deep Foundation Institute (DFI) technical com- mittees for “Marine Foundations” and “Driven Piling”. Dr. Doherty completed a PhD on the topic of off- shore pile design in 2010. He has published over 50 technical articles on piling and foundations and works on projects across Europe.