Geotechnical characterization of calcareous soils for the foundation design of offshore production platforms

Characterization géotechnique de sols carbonatés pour le dimensionement des fondations d'ouvrages em mer

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ABSTRACT
The world's ever growing demand for oil and gas with the consequent increase in the production costs together with the Brazilian government's policy towards self-sufficiency are challenges that require innovative technological solutions and as a result more thorough geotechnical studies are also needed.
In order to install offshore platforms for the exploration of hydrocarbonates in offshore fields in water depths up to 170 m, the authors have promoted extensive campaigns of soil investigation where piezocone tests and laboratory tests where performed.
Due to the occurrence of calcareous soils, the authors established for the first time in Brazil, a comprehensive geotechnical study where they applied laboratory compressibility performed on crushable calcareous sands as a basis for their study to better define design parameters for foundation design comparing the results obtained with others in literature.

RÉSUMÉ
La demande toujours croissante de pétrole et de gaz avec l' augmentation des prix de la prodution ainsi que la politique du gouvernement brésilien vers l'autonomie, posent des défis qui nécessitent des solutions technologiques innovatives et, par conséquent, un approfondissement des études géotechniques se fait également nécessaire.
Pour installer les structures en mer pour l'exploration des hydrocarbures en mer avec de l'eau jusqu'à des profondeurs de 170 m, les auteurs ont entrepris vaste campagnes de reconnaisance des sols avec l'utilization des essais piezocone et des tests de laboratoire.
Dês qu'il s'agisaint des sols carbonatés avec des concrétions, les auteurs ont mis en place pour la première fois au Brésil, un plan d´études qui avait pour base des essais de compressibilité realisés sur des sables calcaires de façon à mieux définir les paramètres de conception pour l'étude de ces fondations en comparant les résultats obtenus avec d'autres dans la littérature et de commenter leur application à résoudre ces derniers cas étudiés.

Keywords : offshore foundation, pile design parameters, compressibility, calcareous sands

1 INTRODUCTION

The world's ever growing demand for oil and gas, the consequent increase in the production costs together with the Brazilian government's policy towards self-sufficiency are challenges that require innovative technological solutions which in turn reflect in the need for more comprehensive geotechnical studies.

Among the several geotechnical aspects that require a better understanding is the behaviour of calcareous soils which are a very common feature in Brazilian shallow waters, from the Northeastern region to Santos basin.

The choice of soil parameters to be adopted for pile design in carbonate soils has traditionally been made based in the international technical literature due to the lack of a pattern behaviour for this kind of soils and hence of general design procedures to be followed. When it comes to calcareous soils with calcium carbonate contents lower than 50 to 70% the general knowledge points to a trend of mechanical behaviour very similar to that presented by silica sands (Lunne et al. 1997).

However the authors' extensive experience in dimensioning and monitoring the installation of several driven piles for offshore platforms in Brazil in calcareous sands with low $CaCo_3$ contents has shown that these results tend to disagree with the current literature whether considering parameters for silica sands or for carbonate sands.

In an attempt to establish more representative design parameters that apply specifically to these offshore Brazilian soils, the authors have carried out a comprehensive soil investigation campaign for two sites in the Campos and Santos basins including compressibility tests, besides piezocone tests and the standard characterization and strength tests.

Following the development proposed by ARGEMA (1988) that bearing capacity in carbonate sands is a direct function of their compressibility, a methodology is proposed for the first time in Brazil for establishing these design parameters, thus extending their research to Brazilian calcareous soils which seem to be in a transition area and apparently have a different behaviour.

2 DESCRIPTION AND REVIEW OF THE STUDIED CASE

The case studied refers to the project for a fixed platform which was installed at Site A in Campos Basin at 100 meters water depth. It consisted of a structure of 14 open ended unplugged piles with OD 80" which were driven to an average depth of 50.0 m below the seafloor.

The geotechnical investigation plan performed for site A showed a soil profile consisting of calcareous sands similar to others found along the Brazilian coast.

As in the previous cases, strength parameters obtained both from piezocone estimations and laboratory tests produced

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results which the author's experience had proven to be overestimated.

The authors are also involved in the studies and design of a four –legged fixed platform for gas production consisting of 8 open ended piles of OD 102" at site B in the Santos Basin.

A detailed soil investigation campaign was performed for this site showing the occurrence of a 4.0 m layer of calcareous sand over a soft to hard clay profile.

Although the relatively narrow sand layer was not a defining factor as far as the pile design studies were concerned, the results of the investigation were used to estimate the bearing capacity and punch-through probability of the temporary foundation consisting of four 100 m² mud mats.

The authors have extended the soil investigation for this layer due to its great similarity to those soils encountered at the studied site (site A). The laboratory tests thus included compressibility tests as well as a detailed mineralogical analysis and these results were used in the scope of this study with the purpose of further enriching the authors' understanding of the behaviour of these sands.

3 GEOTECHNICAL CHARACTERIZATION

3.1 *Site A:*

The field investigations for this site were carried out in two stages. In the preliminary stage, three soil borings were performed by use of rotary drilling procedures to depths around 70 m. The profiles being exclusively sandy, samples were obtained with wireline percussion (hammer) samples of I.D. 52.5 mm. Wireline sampling was performed by lowering the sampler assembly, consisting of a 75 kg hammer and slide inside the drill pipe and allowing it to free-fall from a height of 1.5 m several times so as to achieve the penetration of the 0.6 m thin-walled steel tubes.

In the second stage, one soil boring was performed with the alternate execution of wireline percussion sampling and downhole Dolphin piezocone tests at preset intervals until a depth of 73.9 m. Percussion samples were obtained with 54.0 mm I.D. thin-walled tube. The piezocone used was a standard 5 ton probe with base area of 10 cm².

Standard index tests like submerged unit weights, moisture content and HCL reaction were performed at the onboard laboratory on representative samples.

Table 1 shows a summarized description of the soil profile for site A.

Table 1. The soil profile for site A.

Depth (m)	Soil Description
0,0 to 40,0	Silty fine to medium calcareous sand, with shell fragments, calcareous concretions, grey.
40,0 to 67,0	Silty fine calcareous sand, with shell fragments, calcareous concretions, grey.
67,0 to 75,0	Silty fine to medium calcareous sand, with shell fragments, calcareous concretions, grey.

The laboratory investigations comprised grain-size distribution, determination of $CaCO_3$ contents, direct shear tests for maximum and minimum density conditions, tests for the determination of steel/soil friction and compressibility tests.

Submerged unit weights determined showed results in the range between 17.1 and 19.4 kN/m³. $CaCO_3$ contents presented the average value of 27% for 60% of the samples which lead to the classification of calcareous sand (ARGEMA 1988).

Friction angles determined from saturated direct shear tests ranged from a lower bound starting at 35.5º for samples in minimum density to a higher bound of 49.6º for those molded in maximum density.

Relative density Dr results were estimated both from correlations with piezocone results (Baldi et al. 1988) and from field determined natural submerged density and laboratory minimum and maximum densities, according to Equation 1.

$$D_r = \frac{1}{C_2}.\ln\left(\frac{q_c}{C_0\left(\sigma'\right)^{C_1}}\right) \quad (1)$$

where C_0, C_1 and C_2 are soil constants, σ' the effective stress in kPa, either mean stress σ'_{mean}, or vertical stress σ'_{v0}, and q_c the cone penetration resistance, in kPa.

Figure 1 shows cone resistance qc and sleeve friction fs obtained from piezocone tests and relative density Dr results both estimated from piezocone tests and obtained from laboratory tests.

Dr results from laboratory tests ranged between 0.6 and 0.95 and Dr estimated from piezocone tests yielded values concentrated between 0.4 to 0.6 (Lunne et al. 1997).

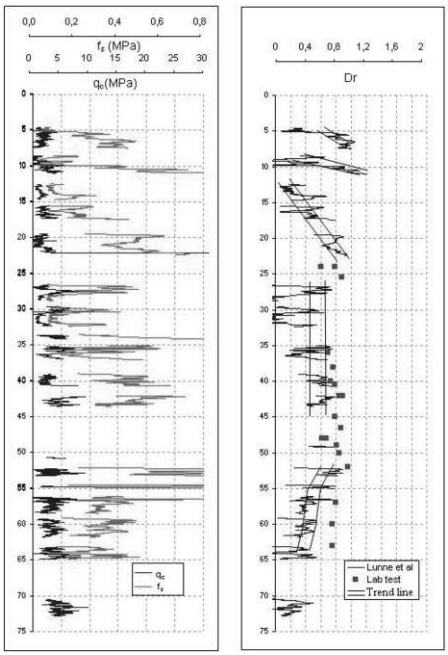

Figure 1- Piezocone data q_c and fs, and Dr values from lab tests and estimated from piezocone tests correlations.

3.2 *Site B*

Field investigations for this site were performed in two stages due to a particularity of the profile. Three borings were performed by rotary drilling with alternate execution of piezocone tests reaching depths of up to 113.0 m. The profile encountered consisted of a top layer of calcareous sand (0.0 m to 3.0 m) with an underlying soft to hard layer of olive grey clay.

The presence of coral in the initial 3.0 m together with limitations of the equipment made it impossible to perform piezocone tests in this layer which was important for the definition of soil parameters for the installation of a mud mat.

As sample recovery was also poor, a second campaign was carried out including available piston corer sampling, in the attempt of recovering larger quantities of the soil for the execution of laboratory tests.

Besides grain-size distribution, determination of $CaCO_3$ contents, direct shear tests for maximum and minimum density conditions, laboratory tests also included a description of the material origin of the sands and compressibility tests.

The soil classification was grey fine to medium silty sand with small shell fragments and small to coarse calcareous concretions.

A mineralogical description was performed establishing that the coarse fraction of these sands (>200 mm) are constituted of shell fragments, which are frequent in all fractions, with a constant (10 to 50%) presence of bryozoans and foraminifera throughout the samples, among others, adding up to 14 different

types of bioclastic material. Calcareous algae are constant in the fractions larger than 1.0 mm (Figure 2 and Figure 3).

$CaCO_3$ results presented an average value of 25 % which lead to a classification of calcareous sand (ARGEMA 1988).

Friction angles obtained from direct shear tests yielded results from 37.1º for minimum density to 46.7º for the maximum density.

Figure 2 . Particle distribution for ranges: 0.15 to 0.25 mm; 0.25 to 0.5 mm and 0.5 to1.0 mm.

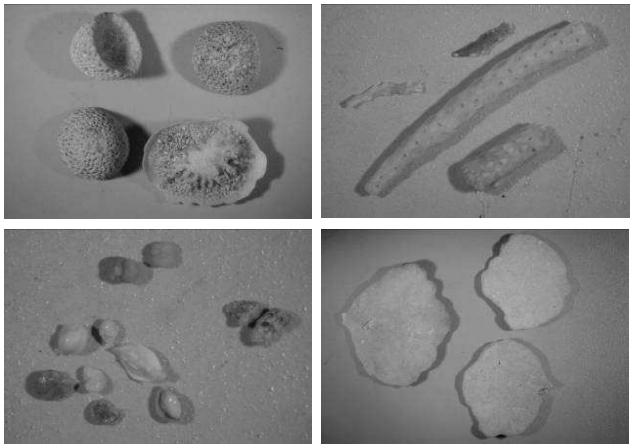

Figure 3. Bioclastic features encountered: bryozoans (top right and left); foraminifera (bottom left) and calcareous algae (right).

4 LABORATORY COMPRESSIBILITY TESTS

The isotropic compressibility tests were performed using a triaxial apparatus. These tests were performed on the calcareous sands and also on dosed quartz sands, with different grain size distributions (well graded, medium, and coarse) and states (loose and dense). Tests were carried out to a confining pressure of 1000 kPa.

The calcareous and dosed silica sands specimens were molded by hand vibration, using an acrylic cylinder. The soil was placed inside the cylinder in equal layers which were scarified prior to the addition of material for the next layer. Specimens were molded based on an average unit weight, around 18 kN/m³, obtained from *in situ* tests.

After molding, specimens were placed in the triaxial compression chamber, and saturated by a back-pressure of 200 kPa.

Specimens were consolidated in consecutive stages of 100 kPa, ranging from 100 to 1000 kPa. In each stage, changes in volume were monitored until stabilization, when another stress level was applied.

Using the obtained data, a compressibility curve (confining pressure x void ratio) was plotted for each tested sample to establish the compressibility index Cp defined for a given pressure as the slope of the tangent to the curve at this pressure, according to Equation 2.

$$C_{pi} = \left[\frac{\Delta e}{\Delta \log p} \right]_{p_i} \quad (2)$$

where e is the void ratio and p the confining pressure.

The Limit Compressibility Index (Cpl), for driven piles is conventionally considered to be the value of Cp for the stress of 800 kPa (ARGEMA 1988).

Some typical results obtained for the compressibility tests performed, are plotted in Figure 4 showing the consistency with results for silica sands and for soils with the presence of carbonate materials studied by Nauroy e Le Tirant (1983).

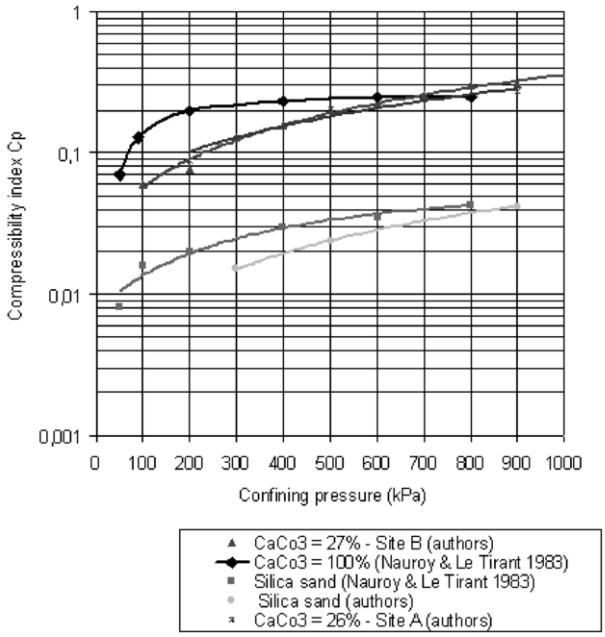

Figure 4. Some Compressibility Index (Cp) versus Confining Pressure results for some Calcareous sands and Silica sands.

When comparing the authors' results in terms of $CaCO_3$ contents, it is clear that the calcareous sands tested presented much lower average $CaCO_3$ contents if compared to those obtained by the French authors, as can be seen in Figure 4, pointing to a new possible trend or "transition zone" for the Brazilian soils due to the presence of silica.

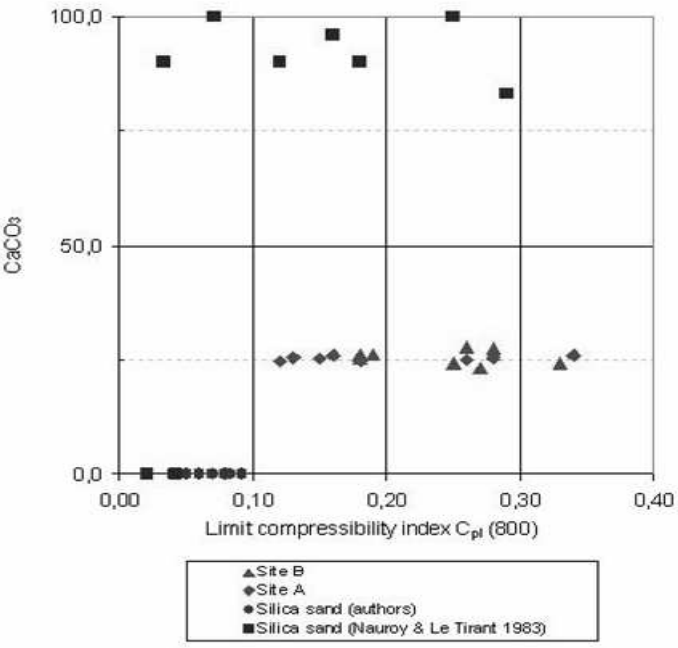

Figure 5. Calcium Carbonate $CaCO_3$ contents versus Limit Compressibility Index C_{PI} .

5 DESIGN DEVELOPMENTS

The authors have participated directly in most of the pile dimensioning, installation of more than one hundred piles in calcareous soils offshore Brazil, namely in the Northeastern and Campos areas in Brazil where the definition of bearing capacity factors have been traditionally made, following recommendations, according to existing international literature as suggested in American Petroleum Institute (2000).

These results have often proven to be very conservative leading to pile lengths in excess to what would actually be needed, as shown in pile driving monitoring and back analysis.

For the studied case, these recommendations led to a limit shaft friction 2.0 to 2.5 times lower than the actual value obtained from recommended back-analysis.

Calculations using strength values for silica sands of the same Dr and grain size distribution on the other hand, have yelded overestimated values for limit shaft friction.

Among all the recommendations currently available, the authors have sought to follow those of Nauroy et al. (1986) which resulted from a comprehensive study involving carbonate soils throughout the world. These studies privileged soil compressibility as the major factor influencing the lateral friction and point bearing capacity of these soils.

Nevertheless, an attempt to use these results to estimate bearing capacity values would lead to a limit skin friction f_{lim}=0 which is inconsistent with the monitored results for these kind of sands as can be seen in Figure 6.

Based on the authors own experience and recorded database, a limit skin friction of f_{lim}= 50 kPa was adopted. Back-analysis of the pile driving for this site confirmed the adequacy of this parameter, as shown in the Figure 6.

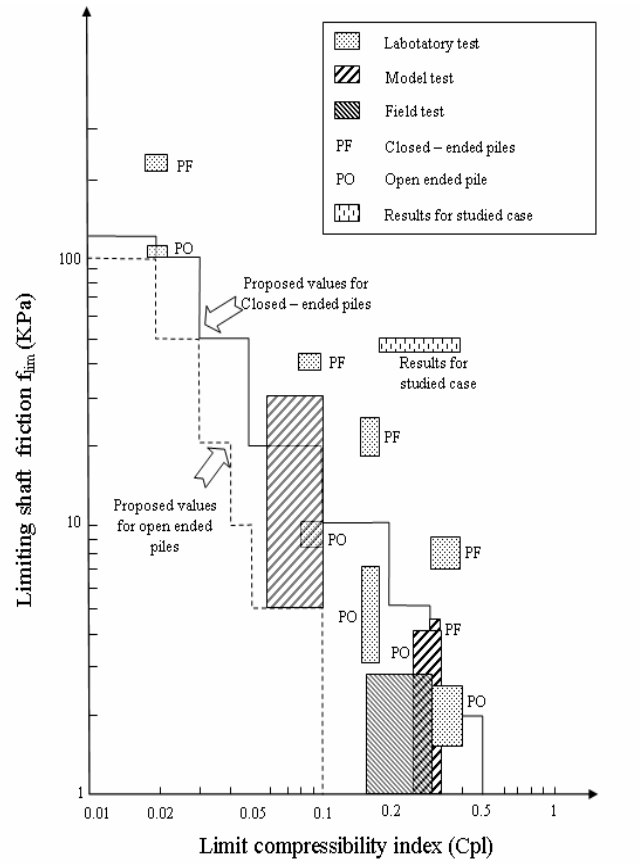

Figure 6- Limit Compressibility Index Cpl versus Limiting Shaft Friction f_{lim} (Nauroy et al. 1986) including results for studied case.

6 CONCLUSIONS

The authors have sought to establish new guidelines for the definition of bearing capacity factors for the pile design in calcareous soils which are a common feature in Brazil.

They have carried out a comprehensive offshore and laboratory investigation campaign including compressibility tests performed with this purpose.

The results obtained, although consistent to the ones presented by ARGEMA (1988) when it comes to mineralogical aspects, as seen in Figure 4, have proven to lead to inconsistent bearing capacity values as shown in Figure 6, probably due to the much lower level of $CaCO_3$ contents in the Brazilian soils studied.

Bearing capacity factors based on the authors' previous experience and later confirmed in the back analysis of the actual pile driving are plotted against the average coefficient of compressibility Cp obtained for this site in Figure 6 presented by Nauroy et al. (1986).

The authors see the use of the coefficient of compressibility as a very promising tool for the difficult determination of reliable parameters for calcareous soils and have adopted this methodology in order to extend the existing research to this kind of transition soils.

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