USE OF IN SITU TESTS IN GEOTECHNICAL ENGINEERING

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IN SITU TESTING OF CALCAREOUS SAND - CAMPOS BASIN

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Abstract

Sampling and in situ testing were used to investigate soil conditions for the installation of offshore platforms at the Campos Basin, Brazil. At these sites calcareous sand formations varying in the degree of cementation were found. CPT testing proved to be an invaluable site investigation tool which, in conjunction with sampling and standard laboratory testing, enabled an assessment of engineering parameters for the calcareous sands. The method employed for CPT data analysis yielded friction values for the uncemented sands and friction plus cohesion data for the cemented material. A good agreement was observed between friction angles from CPT and laboratory testing for the uncemented sands.

Introduction

Following the decision of developing the oil fields of the northeastern area of the Campos Basin, six offshore piled structures were scheduled to be installed at the Carapeba, Pargo and Vermelho sites (Fig. 1), for a production of 7,200, 2,800 and 6,000 m^3/day of oil, respectively. The installation of such structures required specialized marine site investigation and a programme was set up by Petrobrás which has been recently and successfully performed onboard the MV Mariner. Up-to-date sampling and in situ testing techniques were employed enabling the assessment of soil profile and engineering parameters.

This paper describes the site investigation works which included in situ cone testing of the calcareous soils. An assessment of soil strength data yielded by in situ cone testing is made by comparison with laboratory testing results from recovered soil samples.

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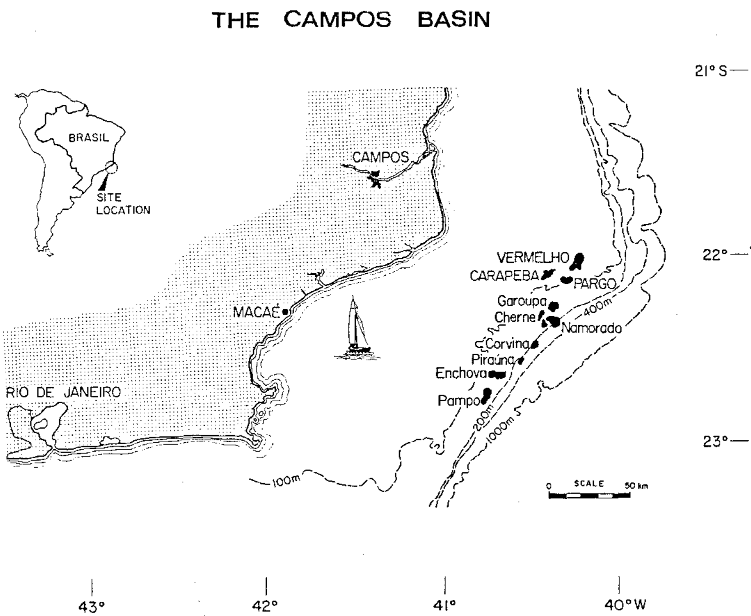

Figure 1. Site location

Site investigation programme

The site investigation programme for the six platforms of the northeastern area of the Campos Basin followed the practice already adopted by Petrobrãs (e.g. Spatz et al., 1979) in the same area. It consisted in drilling, at each location, four boreholes according to the pattern shown in Fig. 2, as well as one additional borehole for cone penetrometer testing (CPT).

The boreholes B1 to B4 were scheduled to reach 120 m below mudline and sampling was performed as shown in the following table:

DEPTH (m)	SAMPLING INTERVAL (m)
0-30	1.5
30-80	3.0
80-120	5.0

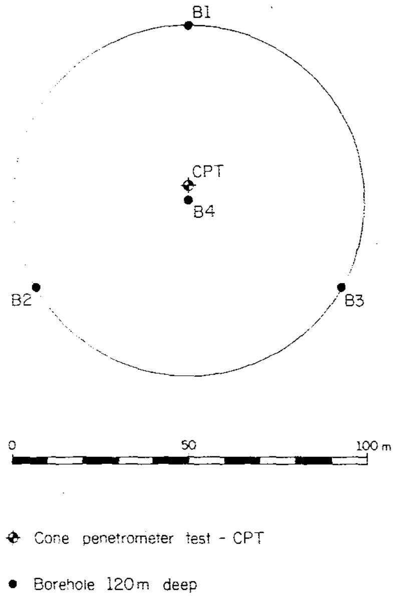

Figure 2. Typical site investigation programme for jacket structures at the Campos Basin

In some cases, in order to reduce costs, only borehole B4, which coincides with the centre of the platform, was taken 120 m deep. The remaining borings were drilled to a depth of only 90 m.

Requirements for CPT consisted of:

(a) down-the-hole testing, with 3 m maximum stroke and 60 MPa maximum point resistance;

(b) continuous testing along the first 30 m depth, each stroke starting at the level where the previous reached refusal or full stroke;

(c) below 30 m depth, each CPT stroke started at 3 m intervals.

Such a site investigation programme provided more intensive information on soils close to the seafloor, which was a requirement for the mudmat stability and lateral pile response analysis. Soil data from below the 30 m depth is less intensive, which is in accordance with the design requirements for the driveability and pile axial capacity analysis.

Sampling and testing techniques

The sampler type employed in the calcareous sands in this work was the driven sampler, as shown in Fig. 3. In loose and uncemented sands, a thin-walled 75 mm diameter sampler was preferred. However, if hard materials, such as coral or gravel, were struck, this sampler tube had to be changed, because sample recovery became difficult or simply impossible. In such cases the following alternatives, listed in order of preference, were tried:

(a) a 50 mm diameter thin-walled sampler;

(b) a 75 mm diameter split-spoon sampler;

(c) a 50 mm diameter split-spoon sampler.

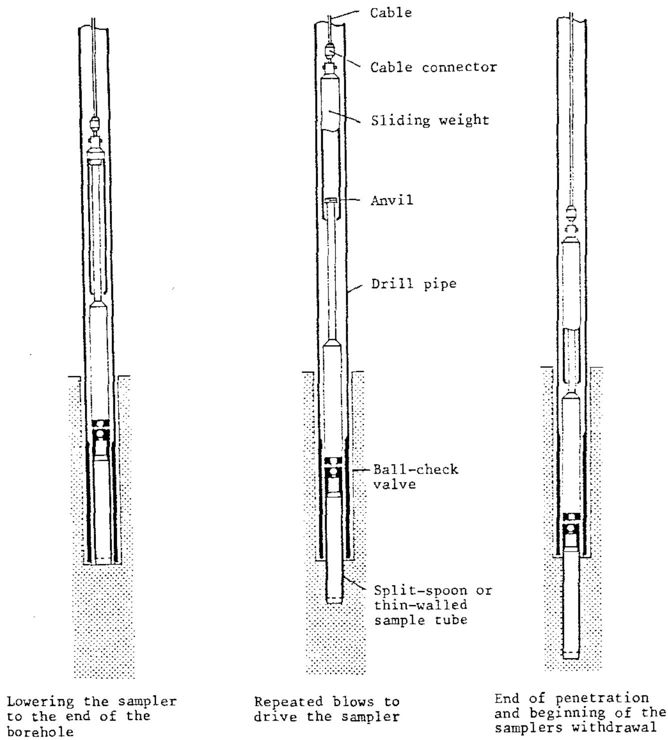

Figure 3. The wireline drive sampler

These sampling procedures followed the standard practice previously adopted by Petrobrās and no attempt was exerted towards obtaining intact samples from the cemented layers. Indeed, since the installation of piles greatly disturbs the soil, these samples are expected to represent a post-installation soil condition.

Following sample recovery and extrusion in the ship's laboratory, soil description and a few simple soil tests were accomplished.

In situ cone testing was performed with a wire-line and umbilical-less apparatus developed and operated by McClelland Engineers. It comprised a standard 60^0 apex angle and 10 cm^2 electrical cone, with a 150 cm^2 sleeve friction. The equipment was allowed to fall freely into the drill string until it stroked the bottom of the drill pipes and was latched on a special drill collar at the bottom of the drill string. Mud pressure was used to advance the cone into the soil up to a maximum stroke of 3 m. All cone information – point, friction, rate of penetration and time data – was stored in microchips in a similar way as described by Muromachi et al. (1982). Upon penetration, an overshot device was used to raise the apparatus to the deck level, where data were retrieved by means of a desk-top microcomputer.

Results from the site investigation programme

Data interpretation and results will be given herein for the Carapeba-2A site, which is typical of the investigated sites at the Campos Basin.

• Soil description

The soil profile, as shown in Fig. 4, consists of a sequence of sand layers varying in the degree of cementation and carbonate content. The upper stratum is a non-calcareous fine to medium sand extending from seabed to 24 m depth. The low calcareous nature of this soil layer was first observed through onboard tests of reaction to hydrochloric acid ($HC\ell$), and later confirmed through more accurate chemical analysis onshore, yielding values of carbonate content ranging from 30 to 40 per cent. From 24 to approximately 84 m below mudline, a fine to medium calcareous sand layer with cemented sand seams and corals was observed. Accordingly, carbonate content is high, ranging from 60 to 90 per cent, and the unit weight is considerably lower than the values measured in the upper non-calcareous layer.

This decrease of unit weight is a result of the large amount of open space left between particles, which is preserved in calcareous soils, even at high effective stresses, due to cementation bonds between soil grains. This layer also included seams of highly cemented sand and corals, in which drilling and sampling were difficult and time consuming. The following stratum, 30 m thick and extending from 84 to 114 m below seafloor, presented similar characteristics of the overlying deposit, but with an outstanding feature: a high degree of weathering was observed in the recovered coral samples. This resulted in a much softer material with the appearance of silt or clayey silt interlayered in the sand matrix. Below 114 m, the soil consisted of a non-calcareous sand layer to the end of the boreholes, which occurred at 120 m below mudline.

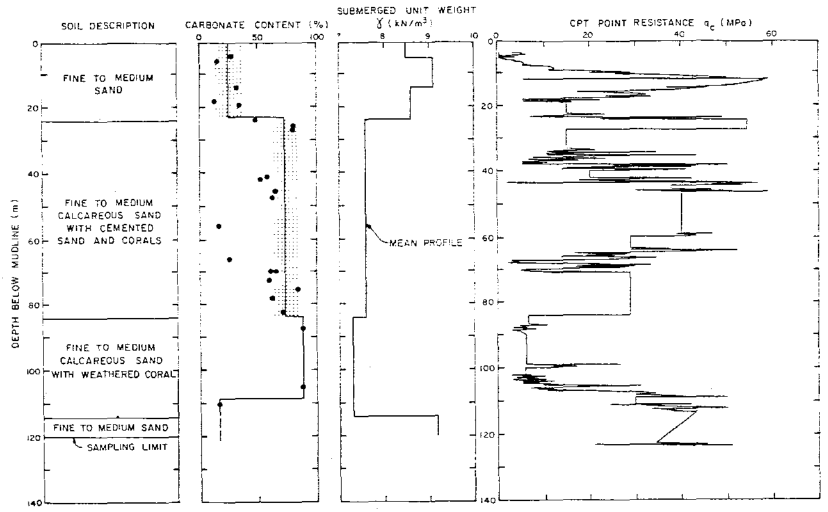

Figure 4. Summary of soil properties at Carapeba-2A site, Campos Basin

- Cone penetration test

A summary of the CPT results for the Carapeba-2A site is shown in Fig. 4. This is an interpreted version of the point resistance q_c versus depth, which is exempt from data void intervals between CPT strokes reaching early refusal in strongly cemented sand and corals. Knowledge of soil type plus engineering judgement have led to this continuous profile recommended for the design of axial and lateral capacity of piles. Soil stratification was also assessed through CPT results by employing the soil classification chart recommended by Robertson and Campanella (1983). This supported and also clarified previous strata identification from borehole logs. It is interesting to note the erratic CPT profile obtained at certain depths within the calcareous sand. As pointed out by Beringen et al. (1982), this stick-slip behaviour seems characteristic of a brittle material whose cementation was broken by the cone.

- Analysis of CPT results

An important application of CPT data is in the evaluation of strength and deformation parameters of soils. For the particular purpose of assessing the bearing capacity of offshore piles, the shear strength parameters should be evaluated. This has been done by the writers' companies following the works of Senneset et al. (1982) and Robertson and Campanella (1983). Accordingly, it can be shown that for a coarse grained soil in which no pore pressures are generated around the cone during its insertion, the point resistance q_c is given by:

$$q_c = [(N_q - 1)\ (\bar{\sigma}_{vo} + \frac{\bar{c}}{\tan \bar{\phi}})\ ] + \sigma_{vo} \tag{1}$$

where:

N_q = bearing capacity factor;

$\bar{c}$, $\bar{\phi}$ = Mohr-Coulomb's effective strength parameters;

σ_{vo}, $\bar{\sigma}_{vo}$ = respectively total and effective in situ vertical stresses (water level assumed coincident with seabed level).

In the above equation, the shear strength of a coarse grained and pervious material such as sand is described by the effective stress parameters $\bar{c}$ and $\bar{\phi}$. In fact, the Mohr-Coulomb envelope of sands may present a cohesion intercept due to cementation or non-linearity of the strength envelope. However, a great amount of grain crushing and destruction of cementation bonds between soil particles is expected to occur in the vicinity of the pile upon installation. Consequently, cohesion may decrease and become close to zero. Therefore, it is advisable to assume an a posteriori uncemented behaviour for the calcareous soils. In such case, Eq. 1 can be rewritten in the following form:

$$N_q = \frac{q_c - \sigma_{vo}}{\bar{\sigma}_{vo}} + 1 \tag{2}$$

The evaluation of the shear strength parameter $\bar{\phi}$ can be performed theoretically (e.g. Senneset et al., 1982) or through empirical methods. Fig. 5 compares the relationship between the bearing capacity factor Nq and $\bar{\phi}$ recommended by Senneset and Janbu (1984) based on bearing capacity theory, and the empirical correlation proposed by Robertson and Campanella (1983). The latter has been chosen for obtaining $\bar{\phi}$ values for the Carapeba-2A site, and the results were automatically processed and plotted by a computer, as shown in Fig. 6.

The assessment of the effective strength parameters $\bar{c}$ and $\bar{\phi}$ through CPT requires further interpretation of one of those parameters. In the case of a calcareous material in which cemented and uncemented strata are interlayered, the latter may yield a value for $\bar{\phi}$. Therefore, rearranging the terms of Eq. 1, the cohesion intercept due to cementation can be obtained from:

$$\bar{c} = [\frac{q_c - \sigma_{vo}}{N_q - 1} - \bar{\sigma}_{vo}]\ \tan \bar{\phi} \tag{3}$$

all terms being defined previously.

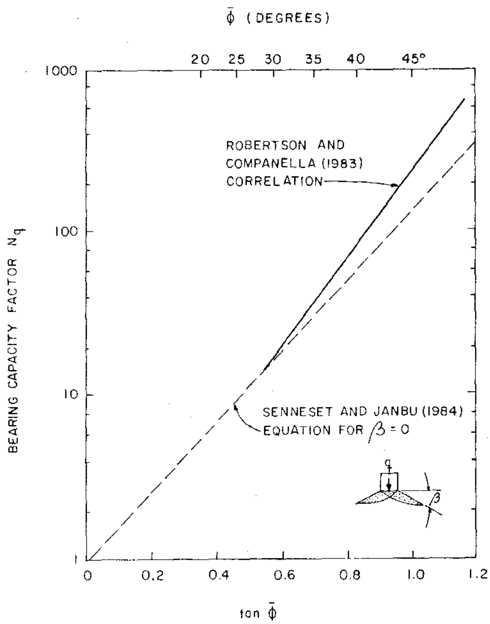

Figure 5. Relationship between N_q and $\bar{\Phi}$

As an example, consider a strongly cemented layer, at depths from 75 to 85 m, in which the field logs indicate hard rotary drilling and CPT early refusal. For this layer, a $\bar{\phi}$ value corresponding to an uncemented behaviour was assessed from Fig. 6 as $\bar{\phi} \cong 36^o$. This value in Robertson and Campanella's (1983) correlation (Fig. 5) renders $N_q \cong 35$. The point resistance was obtained from CPT field logs (not shown) which indicated refusal along this layer being reached at $q_c = 60$ MPa, a value that was subsequently taken as conservative for this layer. Furthermore, through the unit weights shown in Fig. 4 one can obtain: $\bar{\sigma}_{vo} \cong 600$ kPa and $\sigma_{vo} = 800$ kPa.

Hence:

$$\bar{c} = (\frac{60 \times 10^3 - 800}{35 - 1} - 600) \tan 36^o \cong 830 \text{ kPa}$$

which corresponds to the contribution of cementation.

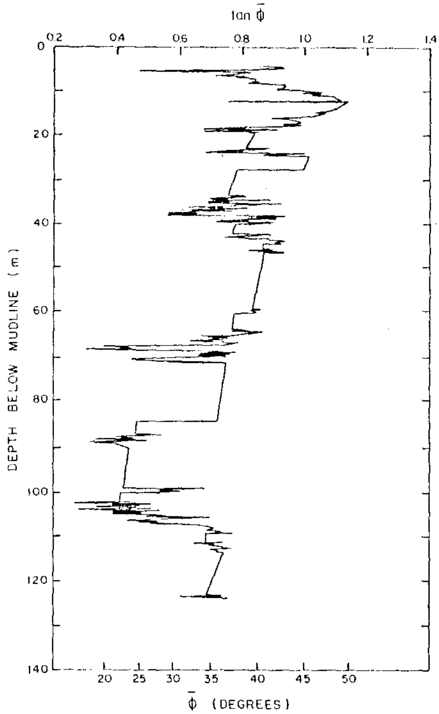

Figure 6. Computer plot of tan $\bar{\Phi}$ versus depth for the calcareous sands, assuming uncemented soil behaviour

- Comparison between shear strength from laboratory and in situ tests

Routine direct shear test results from borehole B2 are summarized in Fig. 7. The $\bar{\Phi}$ value varies between 25 and 42 degrees, whereas the cohesion intercept presents low values of about 10 kPa. The very small $\bar{c}$ values, yielded by the disturbed sand samples, are rather from scattering of laboratory data than from cementation or non-linearity, and are negligible as compared to in situ stresses and strength except at depths very close to seabed. Therefore, they have been disregarded.

In order to allow comparison with CPT results, data from direct shear tests from all boreholes were assembled in Fig. 8, from which lower and upper bounds were defined, corresponding, respectively, to samples tested in minimum and maximum densities. These boundaries are reproduced in Fig. 9, together with the results of $\bar{\Phi}$ from CPT interpretation. A reasonable to good agreement is obtained in this figure for most of the profile, for the $\bar{\Phi}$ resultant from CPT mainly lies within the bounds of laboratory tests.

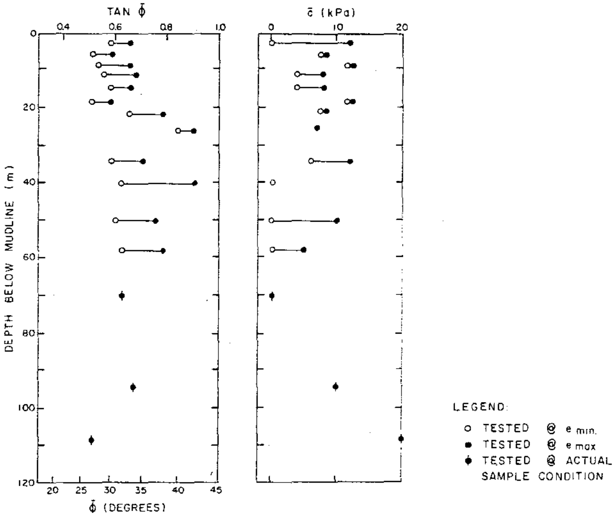

Figure 7. Results from laboratory direct shear tests on samples from borehole B2, Carapeba-2A site

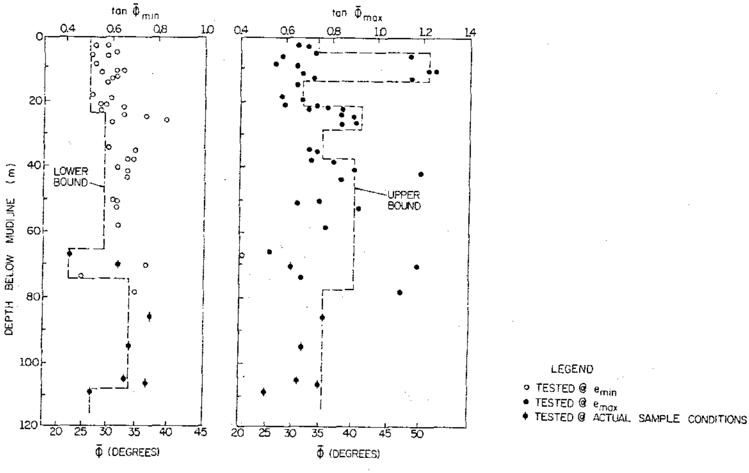

Figure 8. Lower and upper bounds for ϕ from laboratory direct shear tests results

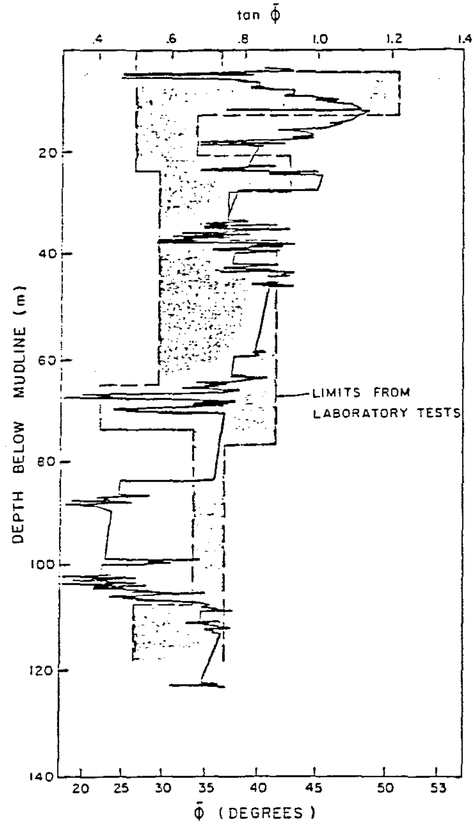

Figure 9. Comparison between $\bar{\phi}$ from CPT and laboratory tests

Indeed, both in situ and laboratory results show a good agreement in respect to:

(a) the presence of an upper dense sand layer between 10 and 20 m depths in which $\bar{\phi}$ increases up to 45 ~ 50°, overlying strata with lower friction parameters;

(b) a layer presenting very low $\bar{\phi}$ at a depth of 65 to 75 m approximately, in which $\bar{\phi}$ is as low as 21-22°;

(c) the increase in friction occurring at 110 m depth, corresponding to the passage from a calcareous to a non-calcareous sand stratum.

On the other hand, CPT interpretation yielded lower results than laboratory tests in the calcareous sand at depths from 85 to 105 m. As a matter of fact, since this material presents a high degree of weathered coral seams, it is argued if laboratory tests on completely remoulded samples are capable of detecting the influence of these weathered formations. In situ continuous profiling is certainly more affected by those localized features and closer to the correct strength than laboratory tests.

Concluding remarks

In the calcareous sand formations found at the Campos basin, CPT testing proved to be an invaluable tool which, together with sampling and laboratory testing, enabled the assessment of the strength parameters $\bar{\phi}$ and $\bar{c}$, the latter being evaluated for the cemented material. An outline of the method of analysis used by the writers is:

(a) for the calcareous sand layers, estimate a profile of uncemented q_c versus depth, as shown in Fig. 4;

(b) obtain N_q through Eq.2 and, for the uncemented material, obtain $\bar{\phi}$ through Robertson and Campanella's (1980) correlation (Fig. 5);

(c) for the cemented formations, evaluate $\bar{\phi}$ from results for the uncemented layers and obtain $\bar{c}$ through Eq. 3.

In offshore pile design the parameter $\bar{\phi}$ can be used for the assessment of skin friction, while for piles tipped in cemented materials, a $\bar{c}$ value as obtained by the writers may be useful for the assessment of point resistance.

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