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MARINE SITE INVESTIGATION AND ASSESSMENT OF CALCAREOUS SAND BEHAVIOUR AT THE CAMPOS BASIN, BRAZIL

J. A. R. Ortigão and S. L. F. Capellão
Sondotécnica S.A.

L. De Lamonica
Petrobrás S.A.

INTRODUCTION

Following up the decision of developing the oil fields of the northeastern pole of the Campos Basin, six offshore piled structures were scheduled to be installed at the Carapeba, Pargo and Vermelho sites (figure 1), for a production of 7 200, 2 800 and 6 000 m³/day of oil, respectively. The installation of such structures required specialized marine site investigation and a programme was set up by Petrobrás and has been recently and successfully performed on board the MV Mariner. Up-to-date sampling and testing techniques were employed enabling the assessment of soil profile and engineering parameters.

The purpose of this paper is to describe the site investigation works and techniques used, and the calcareous soils encountered. An assessment of soil strength data yielded by in situ cone testing is made by comparison with laboratory testing results on recovered soil samples. Finally, techniques for improving the sample quality of calcareous sands and sample selection for further testing are recommended.

THE SOIL SURVEY VESSEL

The MV Mariner (figure 2) was chartered by Petrobrás to perform around 1 000 m of soil borings under a recent site investigation contract. She is one of the North sea type converted cargo vessel, having a length of 82 m and a breadth of about 12 m. Mooring is accomplished by up to six 3 000 kg

THE CAMPOS BASIN

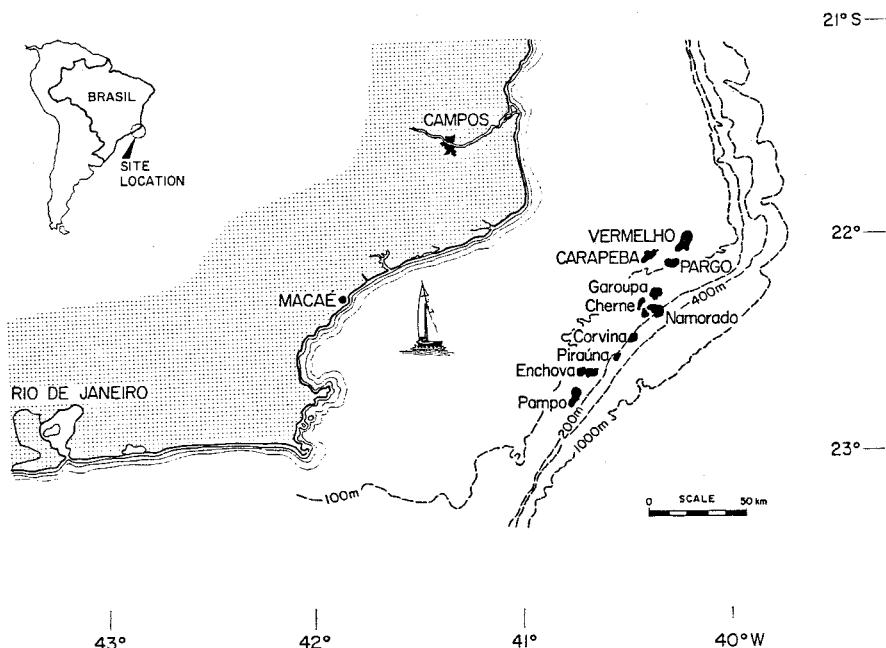


Figure 1. Site location

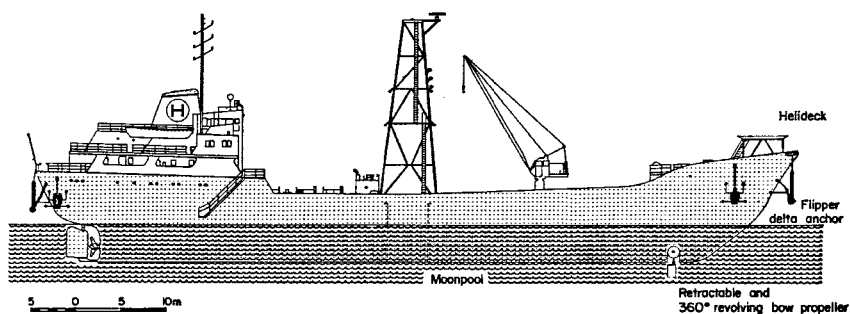


Figure 2. The drill vessel MV Mariner

Delta Flipper anchors which enable her to anchor in soft seabed soils to a maximum water depth of 240 m. Midship mounted winches, each one having up to 2 000 m of 32 mm

diameter anchor cables, operate the anchors and allow repositioning within an oval area of 500 by 300 m at water depths up to 150 m. A retractable bow thruster, capable of rotating 360°, enable anchoring operations without the support of a supply vessel. The necessary time for laying anchors is typically 4 hours. However, despite the increase in costs due to delays for mooring operations, hire rates of an anchored vessel are considerably less than a more up-to-date dynamically positioned vessel, due in part to the significant savings in fuel consumption. This, plus the fact that the ship was scheduled to operate in waters of about 100 m deep, led Petrobrás to choose the MV Mariner, among other competitors, for this site investigation campaign at the Campos Basin.

Drilling at the MV Mariner is performed from a 23 m high derrick mounted over a 4.6 m square centerwell or moonpool. This moonpool is covered by a drill floor grade which can be opened for the access of seabed tools or reaction mass. The drill string is the standard API 127 mm OD pipes with internal flush joints and inside diameter of 100 mm approximately, enabling site investigation tools up to 90 mm in diameter to be wire-line operated. Rotary drilling is performed by a Wirth power swivel which was recently installed (figure 3), replacing the more cumbersome power tongue system. This piece of equipment contributed considerably to a high drilling and sampling rate which has been in the order of 10 m/h in loose sands, and about 2 to 3 m/h in strongly cemented sands and corals. The overall mean drilling rate including time spent in harbour, anchoring, etc, has been in the order of 40 to 50 m per day.

Borehole walls are kept stable by drilling mud, which is pumped through the drill string by two special mudpumps, capable of delivering 200 to 600 l/min, at a maximum pressure of 7.5 MPa. Mud characteristics and quality (Lamonica, 1973) depends on soil type and was checked and adjusted frequently, requiring the presence on board of a specialized mud engineer. Since no recirculation facility is provided, a considerable amount of costly mud is wasted.

In order to keep the drill bit in position during rotary drilling and to increase sample quality, a heave compensator is used as an important piece of the system. Its principle of operation consists in a hydro-pneumatic actuator system, capable of maintaining a constant load on the drill string. Hence, the drill pipes movement is considerably dampened in relation to the ship heave. The heave compensator available at the MV Mariner has a maximum stroke of 5 m, and an accuracy of 1 to 2% of the maximum operating load of 270 kN. This system allows work with a midship maximum heave of 2.5 m. However, high quality work, i.e. in situ testing, is only feasible up to a ship heave of 1.8 m.

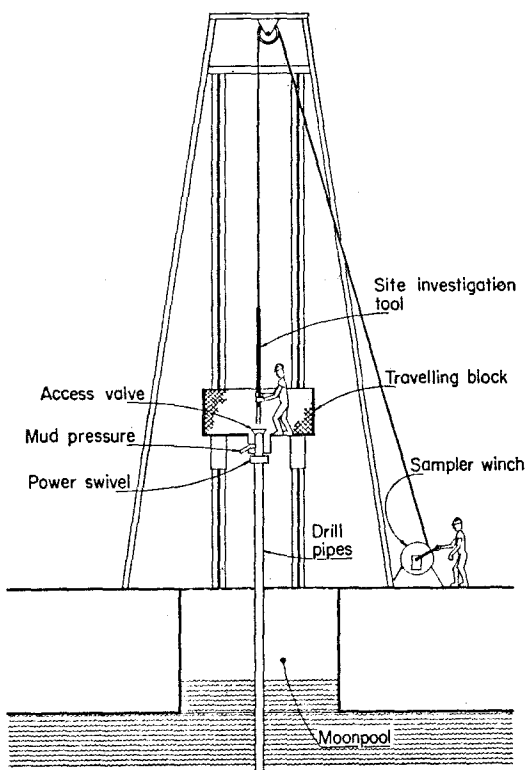


Figure 3. The power swivel drilling system, showing how sampling and in situ testing tools are introduced in the drill pipes

During this site investigation programme at the Campos Basin, 95% of the work was performed with a midship heave of less than 1 m. In a few occasions, however, sea conditions worsened a little, nevertheless the overall stand-by time did not exceed 24 hours.

THE SITE INVESTIGATION PROGRAMME

The site investigation programme for the six platforms of the northeastern pole of the Campos Basin followed the practice already adopted by Petrobrás (eg Spatz et alii, 1979; Machado and Lamonica, 1982; Lamonica, 1985) in the same area. It consisted in performing, at each location, four boreholes according to the pattern shown in figure 4, as well as one additional borehole for cone penetrometer testing (CPT).

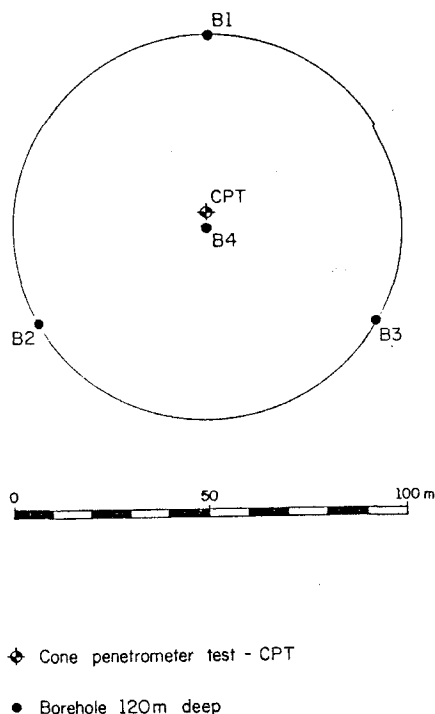


Figure 4. Typical site investigation programme for jacket structures at the Campos Basin

This pattern's dimensions enabled the ship relocation by operating the anchor cable winches and bow propeller, without having to pull out anchors. 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

In some cases, in order to reduce costs, only borehole B4, which coincides with the center of the platform, was taken 120 m deep. The remaining were drilled only down 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 seafloor, which was a requirement from the mudmat stability and lateral pile response analysis. Soil data from 30 m deep downwards is less intensive, according to design requirements of the driveability and pile axial capacity analysis.

SAMPLING AND TESTING TECHNIQUES

Prior to lowering the drill pipes, a gravity sampler suspended from a cable is used to assess the soil type occurring at the seafloor (Lamonica, 1985) level.

This information enables a decision regarding which sampler type and drill bit will be used in the drill pipes, for special precautions have to be undertaken if very hard soils or rock are encountered at seafloor level.

The sampler type employed in the calcareous sands found at the northeastern pole of the Campos Basin was the driven sampler, as shown in figure 5. A sliding mass of 80 kg dropping from a height of 1.5 m was used to drive four alternative types of samplers. In loose and uncemented sands a thin-walled 75 mm diameter sampler was preferred. However, if hard materials, such as corals or gravels, were struck, this sampler tube had to be changed, for 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.

These sampling procedures followed the standard practice previously adopted by Petrobrás, 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.

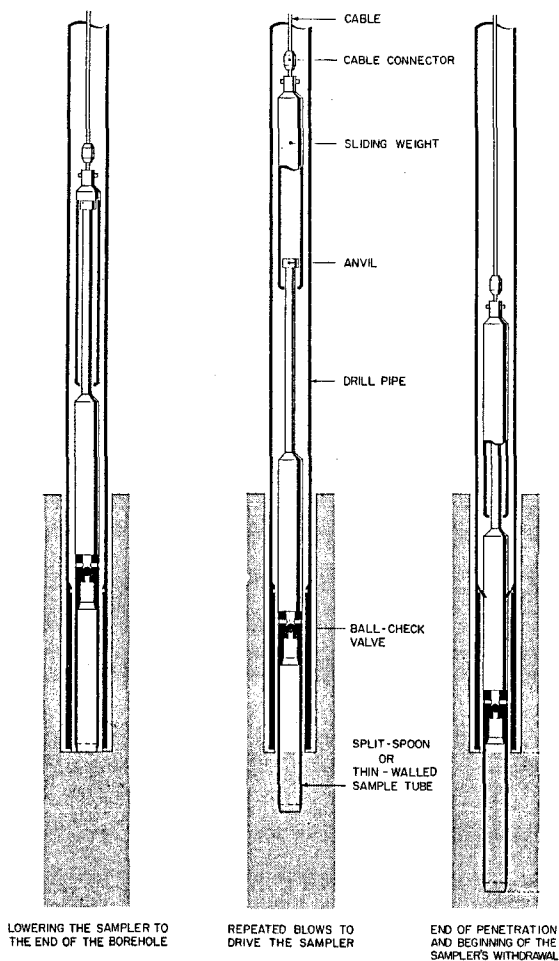


Figure 5. The wireline drive sampler

Following sample recovery and extrusion in the ship's laboratory, soil description and a few simple soil tests were performed. In sands it included: assessment of carbonate content through reaction to HCl, unit weight, moisture content, and sieve analysis on selected samples. Sand samples were, then, kept in plastic bags until further testing onshore, which consisted in direct shear and classification tests, including sieve analysis and chemical tests to determine the

carbonate content. Additional special triaxial tests under high cell pressure for grain crushability studies are being conducted at the Federal University of Rio de Janeiro, but the results are not yet available.

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° apex angle and 10 cm² electrical cone, a 150 cm² sleeve friction. The equipment is allowed to fall free into the drill string until it strikes the bottom of the drill pipes and is latched on it. Mud pressure is used, then, to advance the cone into the soil up to a maximum stroke of 3 m. All cone information — point, friction and rate of penetration, and time data — were stored in microchips in a similar way as described by Muromachi et alii (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 from the aforementioned investigated sites at the Campos Basin.

● Soil description

The soil profile, as shown in figure 6, consists in 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 firstly observed through on board tests of reaction to HCl, and later confirmed through more accurate chemical analysis onshore, yielding values of carbonate content around 30 to 40%. From 24 to around 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%, and the unit weight is considerably lower than the values measured in the upper non-calcareous layer. This interesting feature 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 was 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 a silt or clayey silt interlayered in the sand matrix. Below 114 m, the soil consisted in a non-calcareous sand layer up to the end of the boreholes, which occurred at 120 m below mudline.

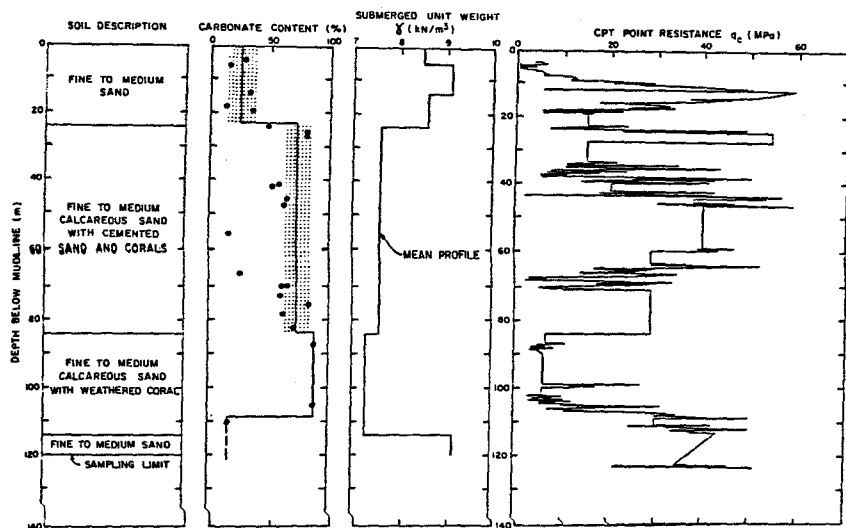


Figure 6. Summary of soil properties at Carapeba-2A site, Campos Basin

● Cone penetration test

A summary of the CPT results for the Carapeba-2A site is shown in figure 6. This is an interpreted version of the point resistance q_c versus depth, which is exempt from data void intervals between CPT strokes which reached 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 alii (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 on 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 alii (1982) and Robertson and Campanella (1982). 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:

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

where:

N_q = bearing capacity factor;

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

$\sigma_{vo}, \bar{\sigma}_{vo}$ = respectively total and effective in situ vertical stress (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, the cohesion intercept 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, equation 1 can be rewritten in the following form:

$$N_q = \frac{q_c - \sigma_{vo}}{\bar{\sigma}_{vo}} + 1 \quad (\text{Eq 2})$$

The evaluation of the shear strength parameter $\bar{\phi}$ can be performed theoretically (eg Senneset et alii, 1982) or through empirical methods. Figure 7 compares the relationship between the bearing capacity factor N_q and $\bar{\phi}$ recommended by Senneset and Janbu (1984) 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 figure 8.

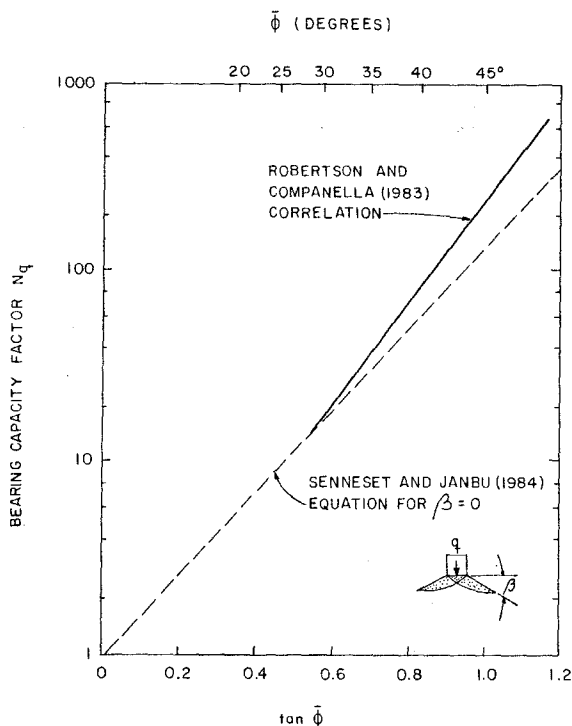


Figure 7. Relationship between N_q and $\bar{\phi}$

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 equation 1, the cohesion intercept due to cementation can be obtained from:

$$\bar{c} = \left[\frac{q_c - \sigma_{v0}}{N_q - 1} - \bar{\sigma}_{v0} \right] \tan \bar{\phi} \quad (\text{Eq 3})$$

all terms being defined previously.

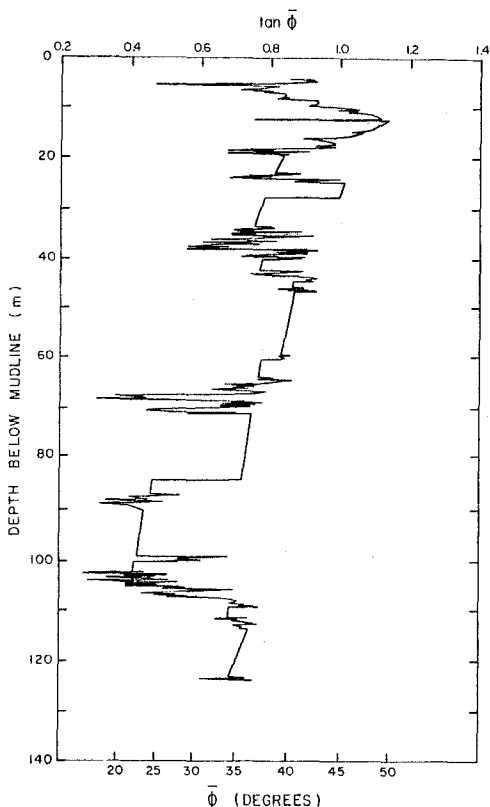


Figure 8. Computer plot of $\tan \bar{\phi}$ versus depth for the calcareous sands, assuming uncemented soil behaviour

As an example, consider a strongly cemented layer, at depths from 75 to 85 m, in which the field logs indicate that hard rotary drilling and CPT early refusal were observed. For this layer, a $\bar{\phi}$ value corresponding to an uncemented behaviour was assessed as $\bar{\phi} \approx 36^\circ$ (figure 8). Furthermore, it was obtained for this layer: $q_c = 60$ MPa (refusal), $\bar{\sigma}_{v0} \approx 600$ kPa, $\sigma_{v0} \approx 800$ kPa, $N_q \approx 35$.

Hence:

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

which corresponds to the contribution of cementation.

Comparison between shear strength from laboratory and in situ tests

Direct shear routine test results from borehole B2 are summarized in figure 9. The ϕ value varies between 25 to 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.

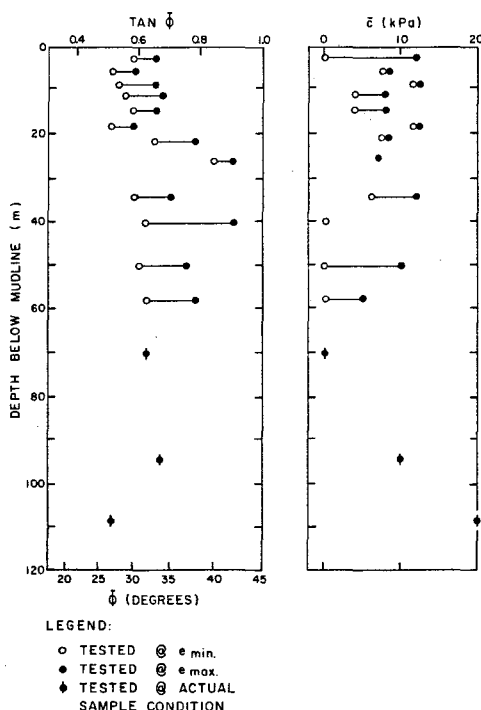


Figure 9. Results from laboratory direct shear tests on samples from borehole B2, Carapeba-2A site

In order to allow comparison with CPT results, data from direct shear tests from all boreholes were assembled in figure 10, from which a lower and upper bound were defined, corresponding respectively to samples tested in minimum and maximum densities. These boundaries are reproduced in

figure 11, 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 boundaries of laboratory tests.

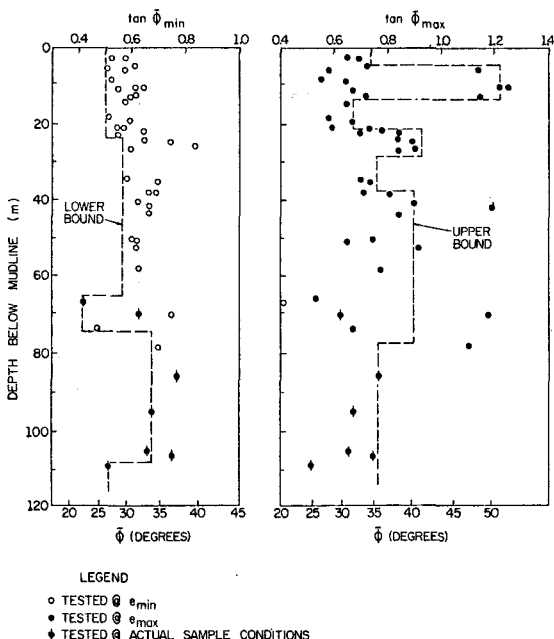


Figure 10. Lower and upper bounds for $\bar{\phi}$ from laboratory direct shear test results

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

- the presence of an upper dense sand layer between 10 to 20 m of depth in which $\bar{\phi}$ increases up to $45 \sim 50^\circ$, overlying strata with lower friction parameters;
- a layer presenting very low $\bar{\phi}$ at a depth of 65 to 75 m approximately, in which $\bar{\phi}$ is as low as $21-22^\circ$;
- 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 these localized features and certainly is closer to the correct strength than laboratory tests.

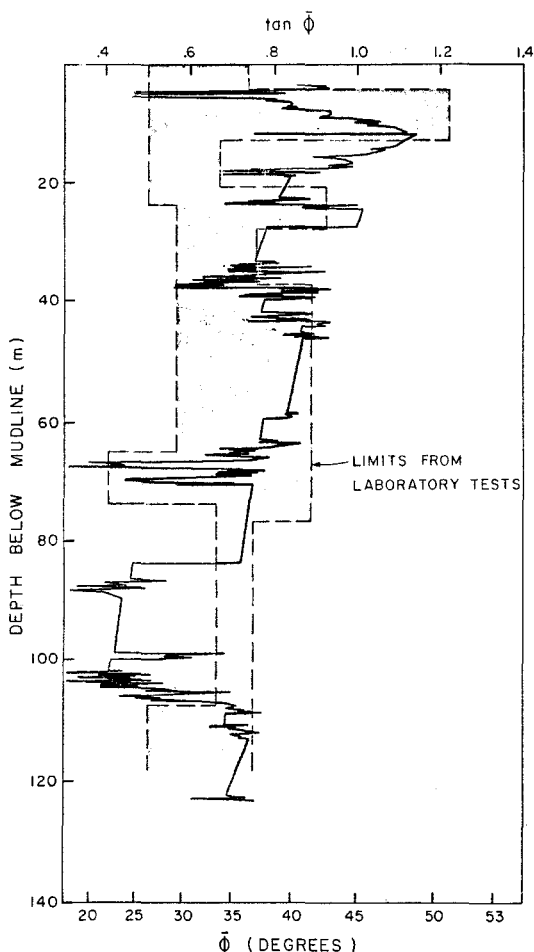


Figure 11. Comparison between $\bar{\phi}$ from CPT and laboratory tests

CONCLUDING REMARKS AND RECOMMENDATIONS

The successful completion of a site investigation programme such as the 1985 campaign in the Campos Basin is a result of

the efforts made by a multidisciplinary team, covering many different aspects, such as: the careful planning of sea operations, the use of high production drill vessel, the use of appropriate drilling fluid and the use of specialized soil sampling, by in situ and laboratory testing. All these efforts end-up with careful interpretation and analysis of soil engineering properties, as shown in the last part of this article.

The overall costs of marine site investigation are such that justify the use of sophisticated and state-of-the-art tools (Toolan, 1983). Therefore, it is the writers' opinion that further work at the Campos Basin should include recent developments such as the piezocone, which has proved to be an useful aid in soil characterization and in the evaluation of engineering parameters (eg Senneiset and Janbu, 1984).

On the other hand, sampling techniques such as core sampling, leading to a better quality of the recovered material, specially in high cemented sands, are recommended. Also, the assessment of sample quality through radiography has been reported (Jamiolkowski et alii, 1985) as a valuable on board technique for selecting samples for further testing onshore. The relatively low cost of radiography, as compared with the cost of seabed samples and the risk of losing the results of a special laboratory test on a bad quality sample (with an intrusion which will mislead results), would justify the adoption of an X-ray facility on board. In conjunction with sample selection, a technique for sand samples preservation until further testing onshore is desirable. Sample freezing in the tubes has been used by Angemeer et alii (1975) with reported success, and is recommended. Furthermore, on board colour photographs of extruded samples would provide a better documentation on the soil texture and description.

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