

Consolidation characteristics of an offshore clay deposit

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Abstract

This paper summarizes the results from a comprehensive laboratory and in situ investigation of an offshore clay deposit in the northeastern coast of Brazil. Laboratory permeability data from oedometer and triaxial cell are presented and compared with in situ test data from piezocone and piezometers. The coefficient of consolidation obtained from various methods is compared with settlement analysis based on Asaoka's (1978) method.

Introduction

A comprehensive site investigation program was carried out at an offshore clay deposit in northeastern Brazil (Fig. 1), 2.7 km from the shoreline, where the water depth is about 10 m. An offshore breakwater was proposed to be constructed in stages to allow for partial drainage and consolidation.

A preliminary site investigation was carried out from a diving bell (Ortigao, 1988) and included SPT's, field vane tests (FVT) and soil samples. Poor ground conditions were detected. A detailed offshore site investigation program was then carried out on board the drilling vessel *Mariner* (Ortigao et al, 1985) and included piezocone (CPTU), FVT's and undisturbed sampling. Triaxial and oedometer tests were carried out at the onshore laboratory.

The first loading stage was applied at the mudline for a period of 6 months. At the end of this period, a thorough reassessment of the foundation properties was carried out. The purpose of this paper is to summarize the results of this investigation.

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The behavior of the additional construction stages are out of the scope of this paper and will be described in forthcoming publications.

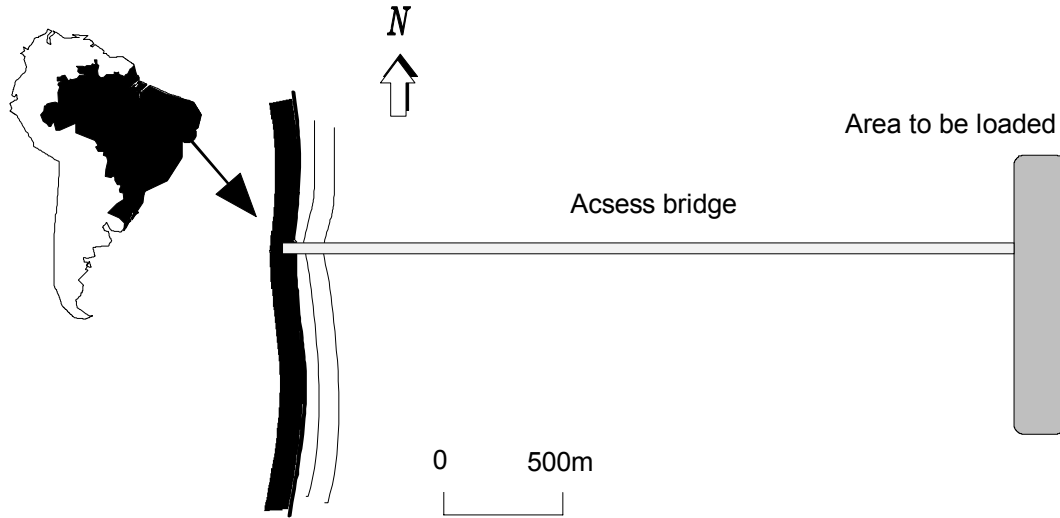


Figure 1 Site location

Soil conditions

Soil profile at the offshore loading area is presented in Fig. 2. A first loading stage of 50 kPa was applied at the elevation -10 m (mudline). It was designed as a berm to stabilize further loading stages. Soil conditions consisted of a 4 m thick upper fine sand layer followed by a 8 m thick fairly homogeneous soft clay overlying dense clayey sand. The upper sand layer can be described by a friction angle of 30-32° and a total unit weight of 19 kN/m³.

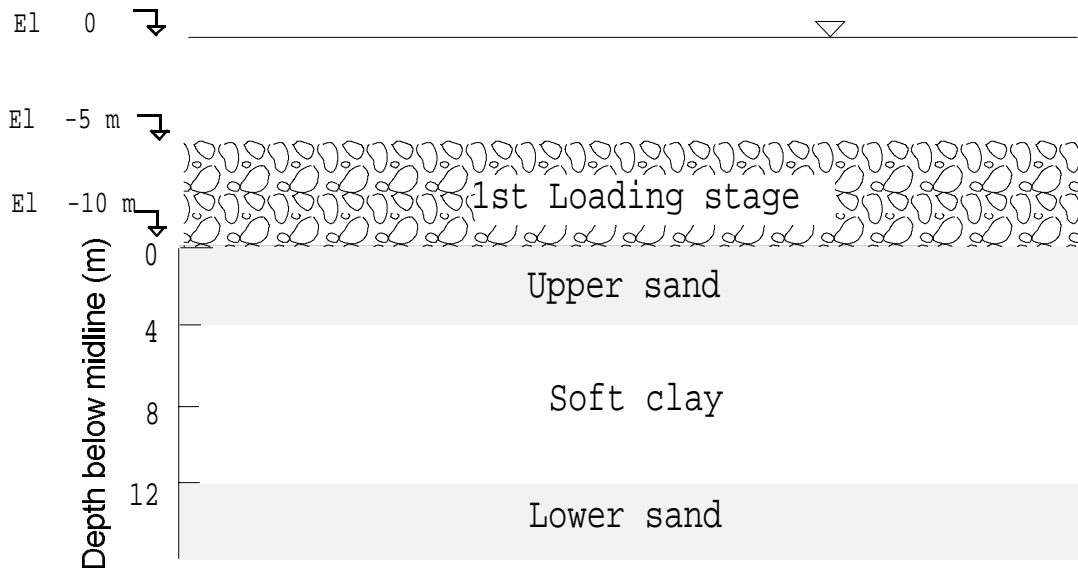


Figure 2 Soil profile

Clay properties are summarized in Fig. 3 and a CPTU profile is presented in Fig. 4. The clay is fairly homogeneous and presents a liquid limit LL of 60%, a plastic limit PL of 22%, resulting in a plastic index PI of 38%. The mean water content is 64%. The stress history of the deposit was evaluated through oedometer tests. It was concluded that the clay may be considered normally consolidated. Only at the top, the overconsolidation stress σ'_{vm} exceeds slightly the in situ overburden stress σ'_{vo} , as shown in figure 3. The unit weight of the soft clay is 17 kN/m^3 and its undrained strength c_u ranges from 15 to 20 kPa.

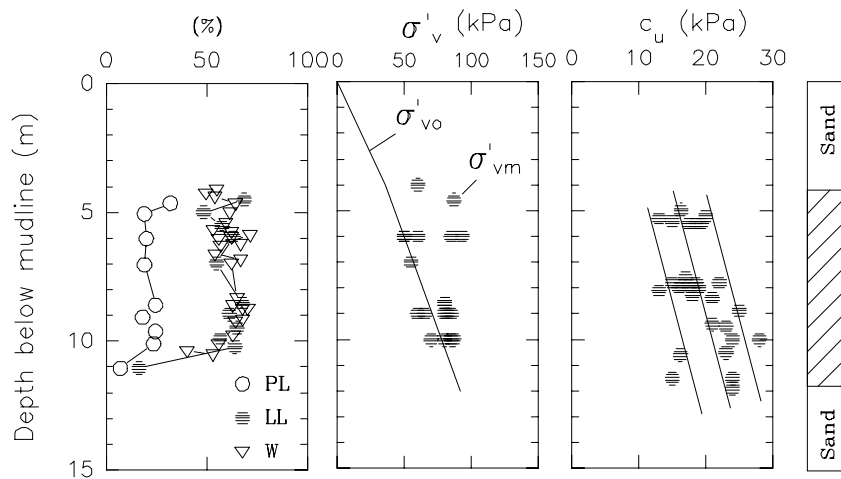


Figure 3 Soft clay properties

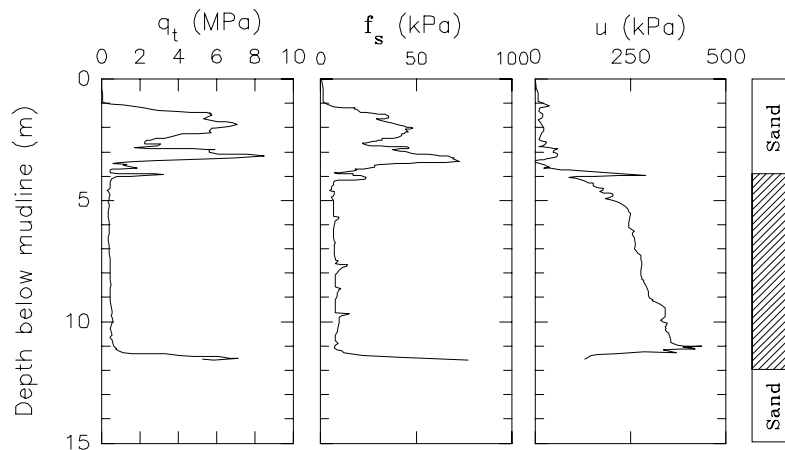


Figure 4 CPTU profile

Instrumentation

An access bridge was constructed prior to the placement of loading. Two open-ended 1.5 m diameter steel casings, named *instrument towers* (figure 5), were tipped into the mudline and enabled the instrumentation to be installed. They also provided protection to the instruments during the placement of loading. The towers were free to move vertically, therefore provided a practical way to monitor settlements.

Each instrumentation tower included an inclinometer casing, 4 Casagrande piezometers, one magnetic extensometer comprising 6 settlement detection devices (*spiders*) similar to the instrument reported by Campanella et al. (1994), and a pneumatic piezometer column. The piezometer column consisted of a 100 mm diameter steel pipe pile with piezometers attached flush to the outside. This instrument configuration has been used with success for porepressure monitoring around piles (eg, Dias & Soares, 1992) but, in this particular case, the results were very poor due to instrument malfunctioning.

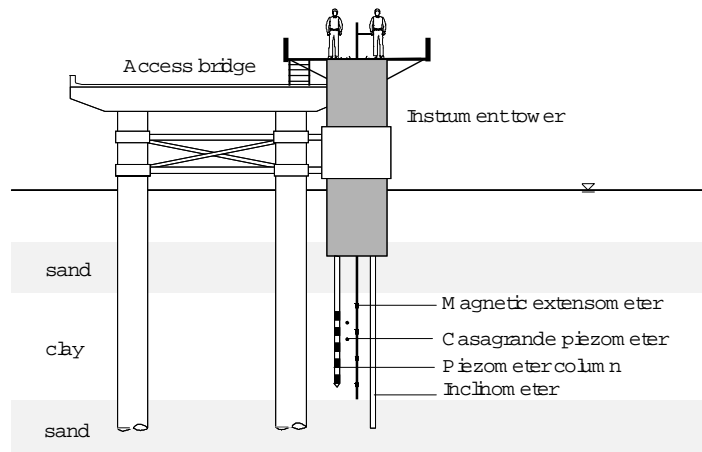


Figure 5 Instrumentation

The Casagrande piezometers comprised a 32 mm diameter 600 mm long tips made of porous bronze. They were connected to EX drilling rods that enabled the unit to be pushed into clay. The access tubing consisted of a 12.5 mm ID plastic tubing protected inside the drilling rods.

Results of the instrumentation during the first loading stage are presented in Fig. 6. Surface settlements were about 180 mm over a period of 180 days.

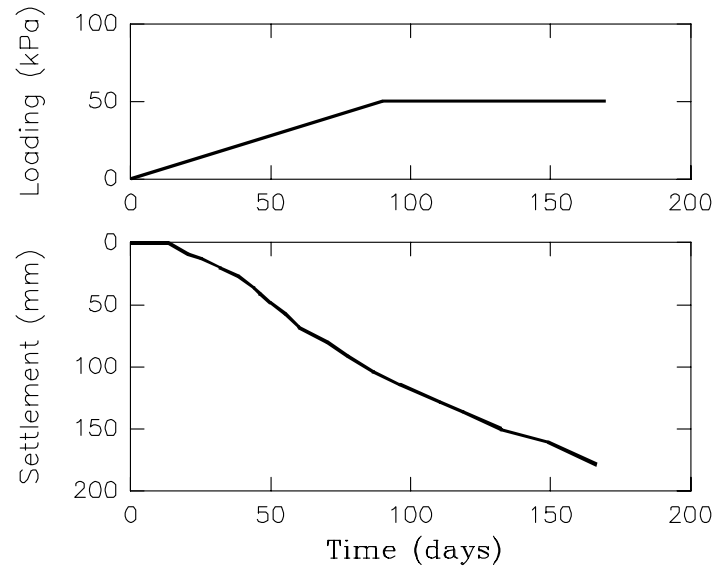


Figure 6 Settlement records

Consolidation properties of the clay

Consolidation properties of the soft clay layer were assessed from several sources, namely: standard oedometer tests, a combination of in situ permeability with laboratory compressibility data, CPTU dissipation tests and analysis of settlement data based on Asaoka's method. Results are as follows:

- **Oedometer tests:** Oedometer tests on 75 mm undisturbed samples yielded the results shown in Fig.7. The coefficient of compressibility C_c presents a mean value of 0.91 and the swelling index C_s is 0.09. The in situ void ratio ranges from 1.5 to 2. A linear regression was fitted through all data points and gave:

$$e_0 = 2.14 - 0.06z \pm 0.28 \quad (z = \text{depth in meters}) \quad (1)$$

The coefficient of consolidation calculated from these tests ranged from 0.6 to 2 m²/year.

- **Combined method:** Values of the coefficient of consolidation were obtained by combining in situ permeability and laboratory compressibility through equation 2:

$$c_v = \frac{kM}{\gamma_w} \quad (2)$$

where: k is the coefficient of permeability, γ_w is the unit weight of water and M is the constrained modulus from oedometer data.

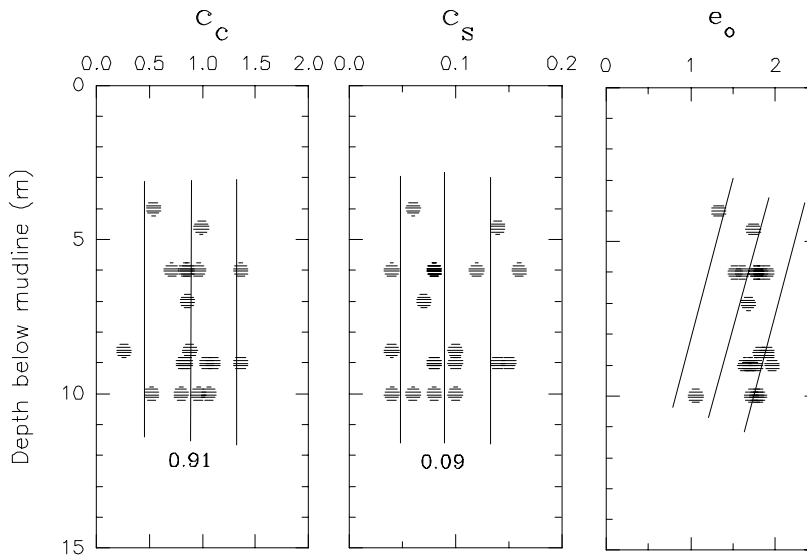


Figure 7 Oedometer test data

Permeability was evaluated from in situ tests and compared to laboratory data. Falling head tests were carried out in all Casagrande piezometers after installation and a resting period of one week.

Direct measurement of permeability in the laboratory by falling head tests at the end of consolidation stages in the oedometer tests gave poor data. Typical results are shown in Fig.8a. A considerable amount of scatter, probably due to leakage, may be seen. Selection of values for design was a difficult task, contrary to Tavenas et al. (1983) conclusions. Alternatively, more consistent results (Fig.8b) were obtained in isotropic consolidation in the triaxial cell of 100 mm diameter by 100 mm high specimens backpressured to 200 kPa. Volume changes were measured both at the entrance and at the exit of the cell, providing a cross-check against leakage.

Equation (3) was fitted to the data in Fig.8b leading to:

$$\log k = \log k_0 + C_k (e - e_0) \quad (3)$$

where: $k_0 = 9 \times 10^{-10}$ m/s is the permeability calculated from the in situ void ratio e_0 and $C_k = 0.52$ is the slope of the fitted straight line, as described by equation 3.

Combining equations (1) and (3), a relationship between initial permeability and depth can be obtained as a straight line (Fig.9). This figure also includes data from in situ permeability tests for comparison. The agreement is remarkable, despite the fact that in situ measurements correspond predominantly to radial flow, opposite

to the vertical flow in laboratory tests. This is an indication that the permeability ratio in vertical and horizontal directions is close to one.

The results of coefficient of consolidation from equation 2 led to values from 0.7 to 1.2 m²/year.

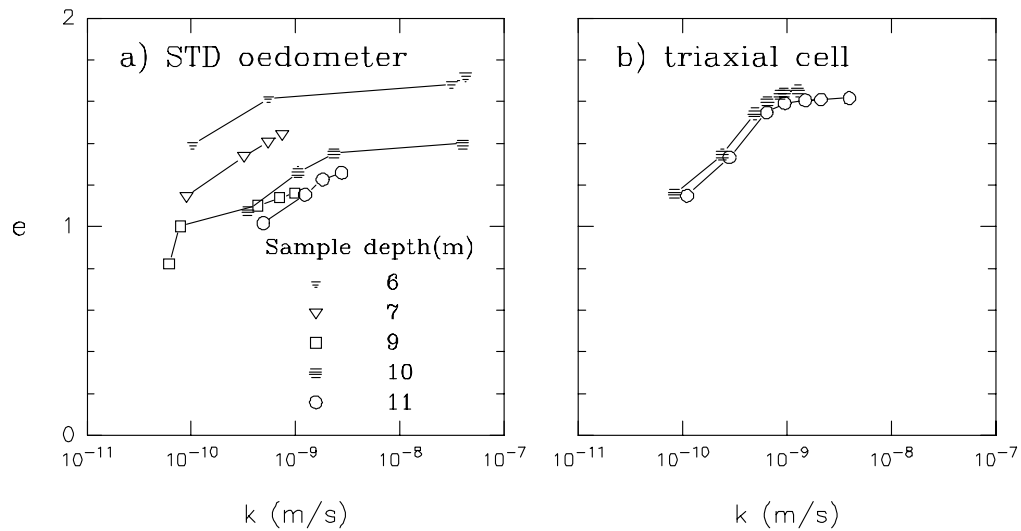


Figure 8 Permeability data

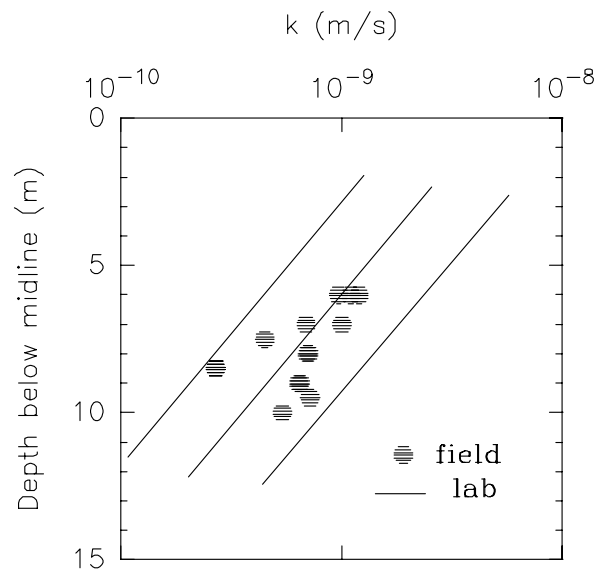


Figure 9 Comparison between in situ and laboratory permeability

- **CPTU:** dissipation test data are shown in Fig.10. The coefficient of consolidation was estimated by Houlsby and Teh's (1988) theory, resulting in values that ranged from 3 to 10 m²/year.

- **Field settlement data:** Asaoka's (1978) method was applied to field settlement data for the evaluation of final settlement and the coefficient of consolidation. This resulted in 0.6 m and 0.8 m²/year, respectively.

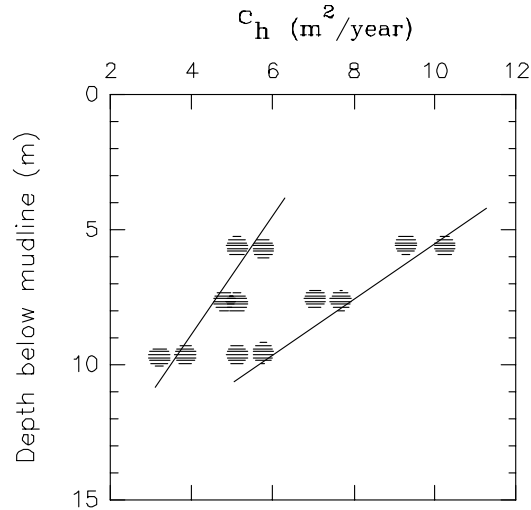


Figure 10 Results from CPTU dissipation tests

Comparison of the results

A comparison of coefficient of consolidation results is presented in Fig.11. There is a fair agreement among three of the methods used, but the CPTU data seems to overpredict the coefficient of consolidation by a factor of 4 to 12. Correction of CPTU data for the analysis of vertical settlement is frequently necessary to account for (a) *direction of flow*: radial consolidation taking place in CPTU dissipation; and (b) *stress level*: dissipation occurs in the recompression range, rather than in the normally consolidated range. Correction for direction of flow seems to be less necessary for this clay, as suggested by isotropy in the coefficient of permeability. For the stress level correction, Baligh and Levadoux (1986) proposed the following equation to transform c_h to normally consolidated conditions:

$$c_h(NC) = c_h(CPTU) \frac{C_s}{C_c} \quad (4)$$

where C_c is 0.91 and C_s is 0.09. A factor of 10 is obtained for the ratio of $c_h(CPTU)$ to $c_h(NC)$. This brings the CPTU data to an agreement with the results from the other three methods (Fig.11). It should be noted that equation 4 gave a reasonable indication of the correction for this particular clay deposit. In many other

cases, it may be rather difficult to evaluate the necessary magnitude of correction (Almeida and Ferreira, 1992, and Ortigao, 1994).

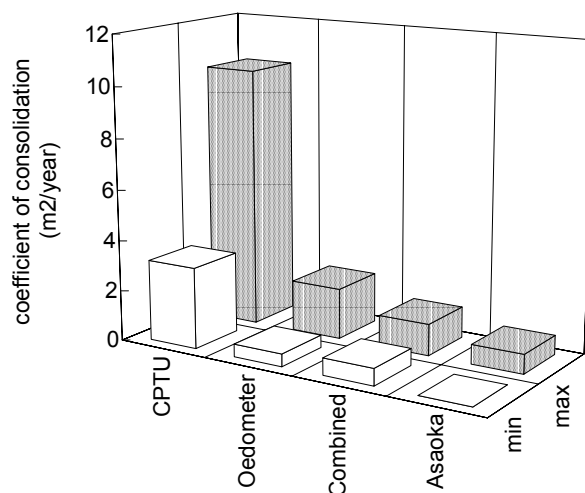


Figure 11 Comparison between values of coefficient of consolidation

Conclusions

Field observations during loading on an offshore soft clay deposit were carried out. The instrumentation comprised inclinometers, magnetic settlement gauges and Casagrande and pneumatic piezometers. This paper focused on the analyses of settlements and consolidation properties of the soft clay.

Settlement properties of the clay deposit were evaluated by a comprehensive site investigation program comprising in situ and laboratory tests. Direct measurement of permeability in the standard oedometer yielded poor data, as opposed to high quality data obtained from isotropic consolidation tests in the triaxial cell.

Analyses of the coefficient of consolidation obtained from various methods were presented and the results compared. A reasonable agreement was observed among the results from field data, laboratory tests and the combined method.

On the other hand, CPTU dissipation tests yielded very high values of the coefficient of consolidation and their application in settlement analyses requires correction. In this particular case, Baligh and Levadoux's (1986) equation seems to give a correct indication of the magnitude of the correction.

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