Drilled and grouted offshore pile foundation in calcareous sand – Pat-3 experience

Fondations en mer par pieux battus et par pieux forés dans les sables calcaires – L'expérience de Pat-3

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SYNOPSIS: Drilled and grouted piles have a great potential of utilization in carbonatic sand soils. In case as the one reported in this paper, the installation contract presented more attractive economic condition for drilled and grouted piles than for driven openned-end pipe piles. A summary of the design and of the executive problems which occurred during the installation is included. In addition comments are made about the employment of pre-load cells on the main pile insert tips.

1- INTRODUCTION

Several Brazilian offshore platforms are located on deposits of carbonatic soil origin the major part of them having driven pile foundations.

Both pile driving monitoring and load tests bear out the general understanding that this type of foundation crushes the calcareous grains, thus reducing the confining pressure and the unit skin friction. As result, conventional foundations with high fabrication and installation costs had to be designed.

The urge to reduce offshore oil price has fostered investigations of other techniques, among which better soluctions for foundations in calcareous soils. Following this trend, a drilled and grouted foundation was executed in the 43m water depth platform of Atum-3 (figure 1).

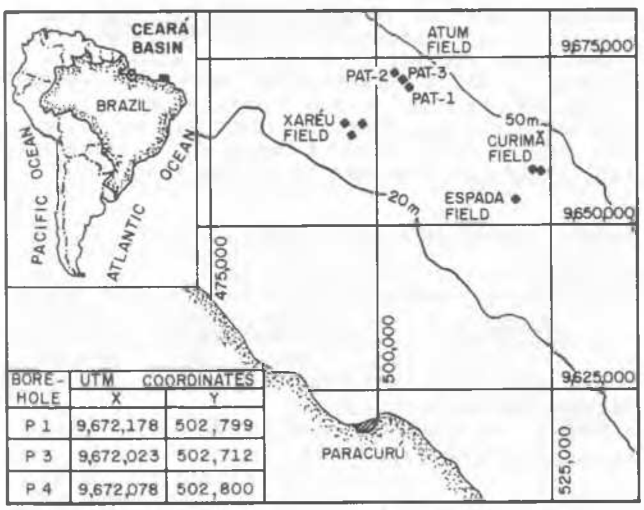


Figure 1. PAT-3 Platform location

This paper presents the geotechnical data that guided the foundation design and also relates the relevant facts which took place during installation, in order to transfer the experience for the use in similar designs.

2- GEOTECHNICAL DATA

Three boreholes with percussive sampling every two meters were done to 100m depth.

The simplified geotechnical profile (figure 2) shows a carbonatic silty sand, weak to well cemented, with coral inclusions. Beneath 94m siliceous fine sand predominates.

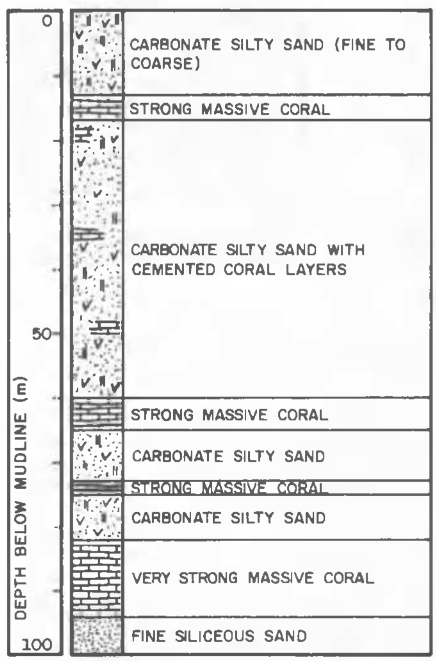


Figure 2. Simplified Soil Profile

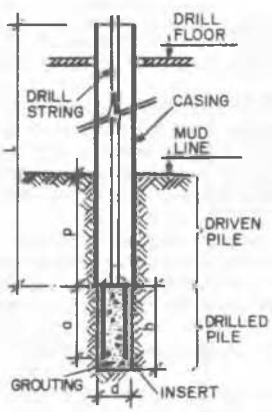
Experience obtained in the previous PAT-1 and 2 installations supplemented the scarce geotechnical survey. CAPWAP-Case Pile Wave Analysis Program-analyses (Goble & Rausche 1980) of the dynamic pile test (DPT) pointed to a degradation of unit skin friction during continuous driving. This degradation is assumed to be the outcome of the grain crushing (leading to a reduced confining pressure on the pile wall) and the granular contact surface abrasion at the soil-steel interface. A residual value of 12.5kN/m² was interpreted for unit skin friction. A two days redriving indicated a partial recovery of the strength.

At the engineering phase the available informations led to a 12 driven pile foundation, settled on 85m penetration. The foundation self-weight amounted to 40MN, whereas the jacket plus deck weight was of about 56MN. In virtue of loads and weights unbalancement, a technical-economical study sizing up drilled and grouted (D&G) pile utilization was undertaken.

As a jack-up was drilling PAT-3 template wells, pull-out tests of driven and D&G piles were scheduled.

The tests were conducted in the three 30" docking template piles.

After driving the casing the soil plug was removed and an additional drilling was done for the insert installation. The insert was grouted and the casing was retrieved immediately. Afterwards the grouting curing, the drill string was connected to the insert, to pull-out the D&G pile. Figure 3 shows the tested piles as-built.



DIMENSIONS	DOCKING PILE		
	A	B	C
p(m)	28	21	30
l(m)	101	84	103
a(m)	4.14	4.00	-
b(m)	6.00	5.00	-
d(m)	0.66	0.45	-
$A_{LAT}(m^2)$	14	8	-

NOTE:
LATERAL AREA ESTIMATED FUNCTION OF GROUTING VOLUME.

Figure 3. Tested piles as-built

Was shown in the tests that installation procedure is of the utmost importance for D&G foundation quality: at first, it was intended to use seawater as drilling fluid. Pile "C" was abandoned after some cave-ins (the soil had been disturbed during the previous installation of a conductor close to the pile). When cave-in start to happen in pile "A", the hole was grouted, and redrilled with bentonitic mud. Because the bit had a diameter close the casing size, in the D&G test the casing came together with the pile. The knowledge permited the improvement of pile "B" test. The hole was drilled with a small bit, the insert was altered and bentonite was recognized as mandatory.

Tests of casings "A" and "B" shown yields on the range of 6 to 8mm, pointing to average frictions of 12kN/m² ("B" pile for 6 hour set-up) and 14kN/m² ("A" pile for 150 hours).

The D&G test results contradicted Angemeer & al (1973) comments that piles drilled with bentonitic mud in calcareous soils, may attain high skin friction values. A value of 38kN/m² was interpreted for pile "A". The ultimate capacity of pile "B" was not obtained, for it exceeded the rig safety limit. Under maximum load, 210kN/m² was mobilized, still in the linear portion of the load strain curve.

3- PILE DESIGN

A careful analysis of all data indicated an ultimate skin friction of 15kN/m² for the driven pile soluction. Furthermore, if it was possible to assure the plugging at 85m, only eight 66" piles would be designed (figure 4).

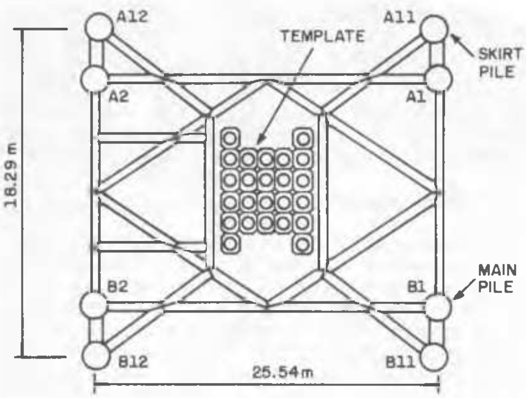


Figure 4. Foundation sketch (elevation at the mudline)

Murff (1987) prepared a comparison between "in situ" test results published in the literature, all relating to driven and D&G piles on carbonatic non cohesive soils. A summary for D&G piles is presented in table 1. It was referred that the effect of bentonite cake on the soil-grout interface is not completely understood. Agarwal & al (1977) studied these effects by means direct shear tests. They reached a significant drop of the friction, only for calcium carbonate contents ($CaCO_3$) in excess to 45%. On the other hand, Fleming and Sliwinski (1977) did not consider there was reduction.

Table 1. Drilled & Grouted pile "in situ" test parameters *

REFERENCES	PILE DIAMETER (m)	PILE LENGTH (m)	SKIN FRICTION (KN/m²)
Wess e Chamberlin (1971)	0.91	27.5	85
Angemeer et al (1973)	-	-	10(2)
	-	-	70(1)
Angemeer et al (1975)	0.48	12	81(1)(3)
	0.48	12	95(1)(4)
Nauroy e Le Tirant (1985)	0.22	7.85	100(1)(5)
Settgast (1980)	-	-	550(6)

* After Murff 1987

Notes:
(1) Seawater as drilling fluid
(2) Bentonitic mud as drilling fluid
(3) Tested section in 90m depth
(4) Tested section in 120m depth
(5) Non cimented soil
(6) Carbonatic rocks

Based on the study and D&G pile tests, a friction limit of 100kN/m² was assumed. For the same foundation configuration, with the piles embedded at 55m (a 66" o.d. casing driving to 20m penetration and an additional drilling with 60" bit) an end-bearing of 2MN/m² would be sufficient to give stability to the foundation.

The choise of D&G piles was based on the analysis of the installation companies proposals which coted on the "lump-sum" bid.

Taking into account the doubts about the effectiveness of the installation quality control procedures and the low end-bearing capacity of this type of foundation, at the main piles insert tips preload cells (Lizzi 1976) were installed. These cells (figure 5) render possible to improve the shear strength of the soil in the pile base vicinity, controling together the base capacity of the pile. The improvement is acquired both by the compression on the soil below the cell, exerced by its piston and the cement injection done through micro holes which are disclosed when the piston displacement reaches 14cm.

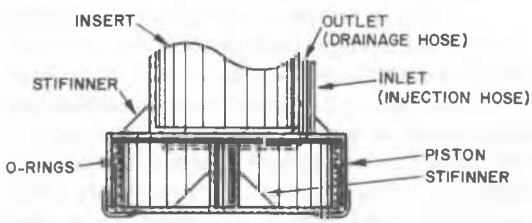


Figure 5. Preload cell internal view

4- PILING

The installation was performed by "Odin" derrick barge.

Two drilling machines Wirth PBA 3.0/56, with reverse circulation were used.

During main pile installation that were executed in the beginning, it was verified the soil had a higher degree of cementation than suggested by the investigations. In addition, the successful use of the preload cells proved possible to reduce the skirt pile penetration to 35m.

The installation time schedule was delayed by a number of problems, nevertheless the seven first piles took, per machine, from 5 to 8 working days each to be executed.

The operational problems were:

- the drilling machines frequently broke due to lack of maintenance;
- remnants of the jacket flotation rubber diaphragm, blocked the air-lift as they were being "chewed" by the bit, and
- the mud plant had underrated capacity for simultaneous equipments use.

A execution problem occurred after drilling the last skirt pile, while disassembling the drill string happened a cave-in, imprisoning it. The usual practice of loosing it by pull-out and push-down at the same time reversing mud circulation, only suceeded to break the drill string.

The accident was caused by the conjuction of three main factors:

- although previous experience had already shown the use of mud was indispensable, during the execution of the main pile of the same corner, some meters below the casing were drilled with water. There was a small cave-in, obliging grouting of the section and then a new drilling. This possibly increased the disturbance in the soil mass;
- the grouting hoses connected to this main pile preload cell, before used, were let to fall down into the casing. As this cell was considered inoperative, it was decided to maintain the original 55m penetration to the skirt pile. If the skirt pile had stopped at 35m, the unstable zone would not have lay "openned" for such a long period and probably no cave-in would have happened, and
- in the drill string disassembling it was verified that some flange rod bolts were loose. It was also remarked some stabilizers were loose too. This may have reamed the hole wall and imprisoned the drill string when it was being removed.

The contingency plan put forth obliging first of all the recovery of the preload cell. After, drive the casing until the bottom hole assembler-BHA. The string above BHA was cut and removed,and the obstructing soil cleaned by air-lift. The insert was put over the BHA and sucessive injections were done below the bit, in order to guarantee the base integrity. The most difficult step of the whole operation came next, at the same time the insert was being grouted, the casing was being pulled to its original position.

In general was compensatory the use of preload cells. All cells brought improvements to the base capacity of the piles, pre-stressing the soil over a range from 6.5 to 12MN/m², consolidating through injections in three of four cases.

In the installation of "A1" preload cell the injection hose and "B1" the return hose, were damaged. The use of only one hose instead of two, prevented the perfect "stress-strain" soil behavior understanding. This is shown in the first portion of the related curves, which may have been affected by the presence of air in the systems (figure 6). By the way "A2" and "B2" pressure-displacement curves have a didatic shape.

5- COMMENTS, RECOMMENDATIONS & CONCLUSIONS

The adopted soluction proved itself feasible, both technically and economically,to be repeated in other structures founded in carbonatic soils.

From the design standpoint the preload cell overcame the low contribuition of end-bearing capacity (both due to stress-relief brought about by drilling and to deposition of disaggregated material coming from the hole wall). Concerns skin friction,tests shown even with bentonitic mud being used, one can expect high adhesion values, much in excess of those in driven piles.

Related execution, it was once more emphasized the soluction effectiveness is closely dependented to the choise of an adequate installation procedure, appropriate equipments and expert team.

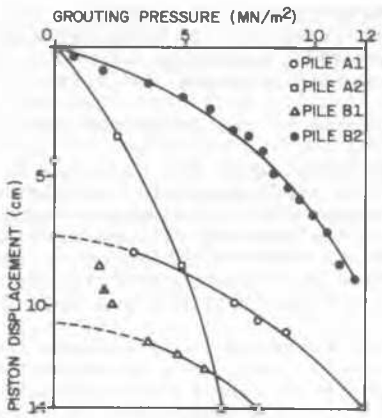


Figure 6. Preload cells pressure-displacement curves

It was also ascertained that maximum attention must "always" be given to all work steps, or else, accidents as the ones reported may bring doubts the rightness of the soluction.

The following recommendations may be suggested:

- Whenever possible realize full-scale load tests, to check up the peculiar conditions of the location;
- In the procedures all steps shall be detalied, with emphasis in what concerns to drilling, defining proper parametric variations, such as: torque, pressure over the bit, string advance speed, mud gradient, drilling fluid properties, mud plant characteristics, as well as contingency plans;
- To reduce over-breaks avoid holding the bit in the same depth for too long time;
- In non-cemented calcareous sand use bentonite as drilling fluid to minimize hole wall instability, and
- Reverse circulation equipments are preferable. Flanged drill strings shall be avoided, for vibrations frequently loosen the bolts.

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