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Acceptance criterion and driving procedure of open-end piles

Critère d'acceptation et procédure de battage de pieux tubulaires

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ABSTRACT
Open-end pile foundations are largely used in near shore projects, such as jetties for loading and unloading of Oil, LPG, etc. Since the construction of these offshore structures implies very heavy and expensive marine equipment, any delay in construction time has to be avoided. The pile installation is often the main part of the critical path in the execution schedule and no construction interruption can be accepted due to acceptance problems of installed piles. It is therefore mandatory that a clear installation procedure, a simple acceptance criterion as well as a fast remedial program for non accepted piles is available for each part of the foundation. This paper deals with the procedure of fixing these criteria.

RÉSUMÉ
Les pieux tubulaires sont largement utilisés pour des projets marins, tels que des jetées pour chargement ou déchargement de Pétrole, Gaz liquide, etc. Comme ces structures marines nécessitent un matériel très lourd et coûteux, il va de soi que tout retard doit être évité. L'installation des pieux gouverne souvent le chemin critique dans le planning des travaux et il est dès lors inacceptable d'avoir des interruptions des travaux dues à des problèmes d'acceptation des pieux réalisés. Pour cette raison, il est absolument nécessaire de disposer de procédures d'installation très claires, de critères d'acceptations simples, mais également de méthodes très rapides pour y remédier dans le cas où un pieu ne répondrait pas aux critères imposés. Cette contribution expose les procédures qui peuvent être suivies pour fixer ces critères.

1 INTRODUCTION

Near-shore projects must be designed to enable the contractor for a fast track execution, in order to minimise the utilisation time of expensive marine equipment such as Self Elevating Platforms (SEP-see figure 1), tugs, working vessels, dredging equipment, etc.

Figure 1

The construction time is in general governed by the execution time of the pile foundations. The standard foundation type for this type of structures consists in open-end steel piles because these piles can be applied in ALL types of soil: sandy soils, clayey soils, cemented soils, weathered rocks and even sound rocks. Of course, in some cases driving will not longer work and drilling will be needed.
To avoid unnecessary delay due to pile installation, it is needed to provide a method statement for piling, which makes the link between the design to the execution through a clear installation procedure, which includes an acceptance criterion together with a fast remedial program if ever the pile is not acceptable.
This paper deals with the methodology to define the process from the design to the acceptance of open-end piles.

2 METHODOLOGY

The following steps are to be followed in the foundation engineering procedure:

- Geotechnical design of the piles (1)
- Selection of the driving equipment (hammer)
- Driving records on trial piles
- Dynamic tests (PDA) on trial piles
- Maintained load test on trial piles
- Analyses of results
- Acceptance criterion report (including remedial program for not accepted piles)
- PDA on working piles (with feed back to the proposed acceptance criterion)

(1) Geotechnical design is not treated in this paper.

3 SELECTION OF DRIVING EQUIPMENT

An accurate selection of driving hammer(s) is one of the main elements for a successful pile installation.
Selection of the hammer is to find the best compromise between the hammer weight (linked to the crane capacity), the hammer capacity (linked to the ability of driving the pile to the required depth and/or resistance) and the installed driving energy (linked to avoid damaging the pile).
In a first approach, one can assume that the weight of the hammer (kN) is 1.2 times the hammer energy (kJ). The hammer helmet is not included (+/- 60% of the hammer weight).

Appropriated software (for example PDP-Wave, developed by Delft University) can help to predict for a known soil profile and a given pile the blow count, the stresses in the pile during driving and the expected SRD (Static Resistance During Driving) for a given hammer.

Figure 2

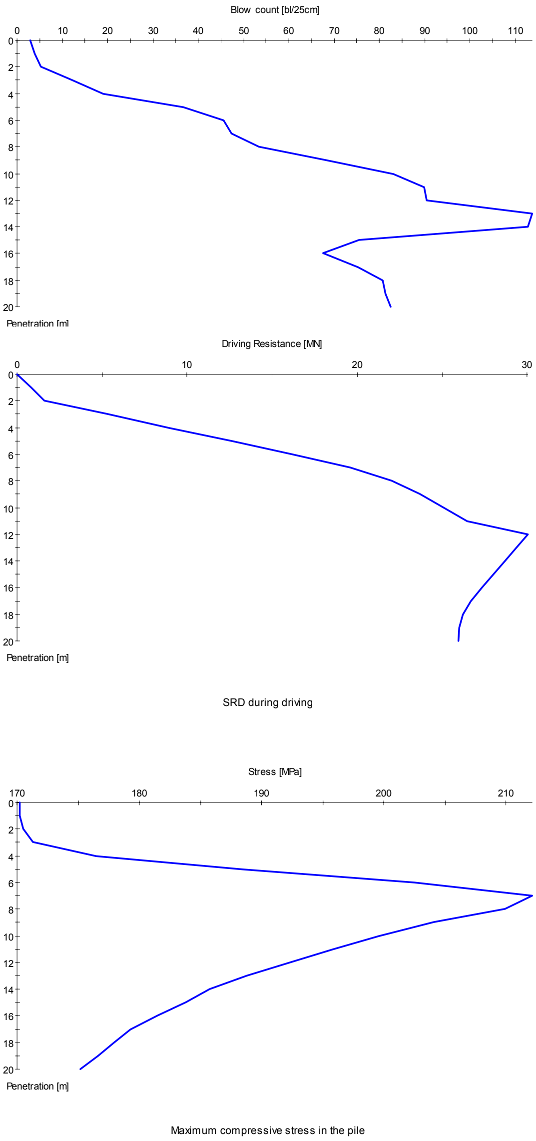

Figure 3

As an example, one can see here above the picture of a IHC S200 hammer (figure2) and the calculated blow count, SRD and pile stresses for a given soil profile (figure3).

4 DRIVING RECORDS ON TRIAL PILES

For all trial piles, the blow count and the energy per blow are recorded. On top, all trial piles are continuously tested using a PDA (Pile Dynamic Analyser) (figure4).

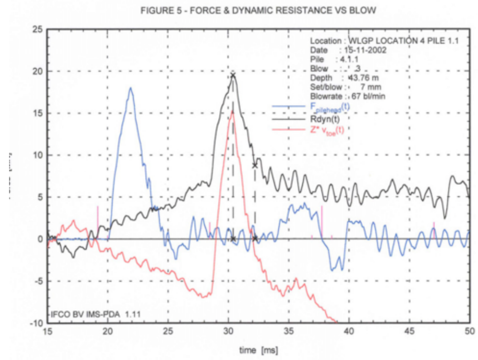

Figure 4

This leads to a graph as given here below:

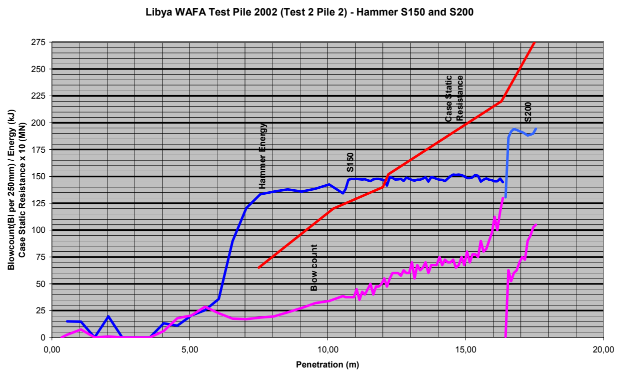

Figure 5

On this chart, various information is given for different depths:(figure 5):

- Hammer Energy
- Blow count
- Static resistance by PDA (CASE)

On top of this, we changed from a S150 hammer to a S200 hammer for the last meter.

By doing this for a series of trial piles, and by working with different hammers, one can prepare a graph, giving the relationship between the blow count and the SRD for 2 hammers for the considered soil profile (for the same example) (figure 6):

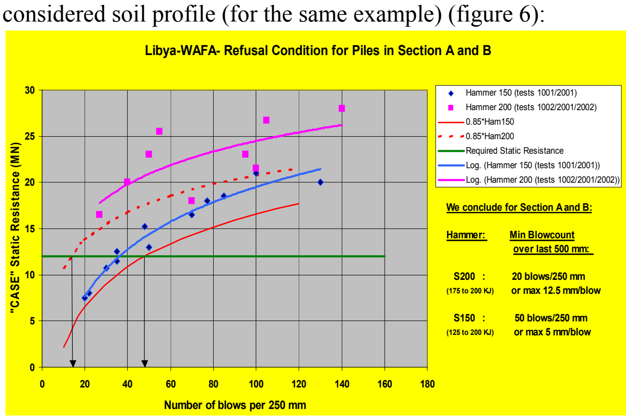

Figure 6

Given that 85% of the SRD is a "trustable" value, one is able to define the blow count which is needed for each considered hammer to guarantee in a safe way the required pile capacity.

5 MAINTAINED LOAD TEST

Depending on the needs of the design, different types of maintained load tests can be carried out: Compression Tests, Tensile Tests or Lateral Tests.
The aim of these tests is not only to confirm the ultimate design capacity but also to validate the foundation stiffnesses which are used in the computer models for the design.
These stiffnesses are defined by applying specialised software packages such as ENSOFT (by N. Reese).
Maintained load tests are performed offshore (figure 7):

Figure 7

The maintained load test on the trial pile given under point 4 is performed from the SEP. The two other piles are reference piles.
The SEP can NOT be considered as a reference, since it is moving under the test loads. The result of this test is given below:

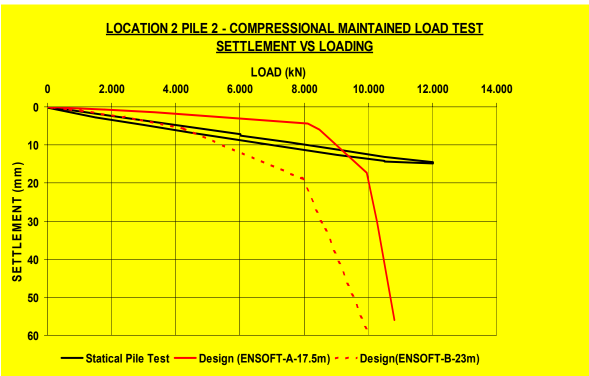

Figure 8

6 ACCEPTANCE CRITERIA

The acceptance criteria have to be formulated as clear as possible to allow for the piling operator to decide very fast what has to be done, especially when two types of hammers are used on the spot.
For the piles described under point 4, following criteria were given:

- Design penetration has to be reached
- Maximal penetration per blow over the last 500 mm:
  - S 150 hammer: 5 mm
  - S 200 hammer: 12.5 mm

In most of the cases, the penetration is reached using the advised hammer and the blow count criterion also (to guarantee the required bearing capacity).
If penetration is not reached, or if the blow count criterion is not met, remedial actions have to be taken as given in the chart given hereafter (figure 9):

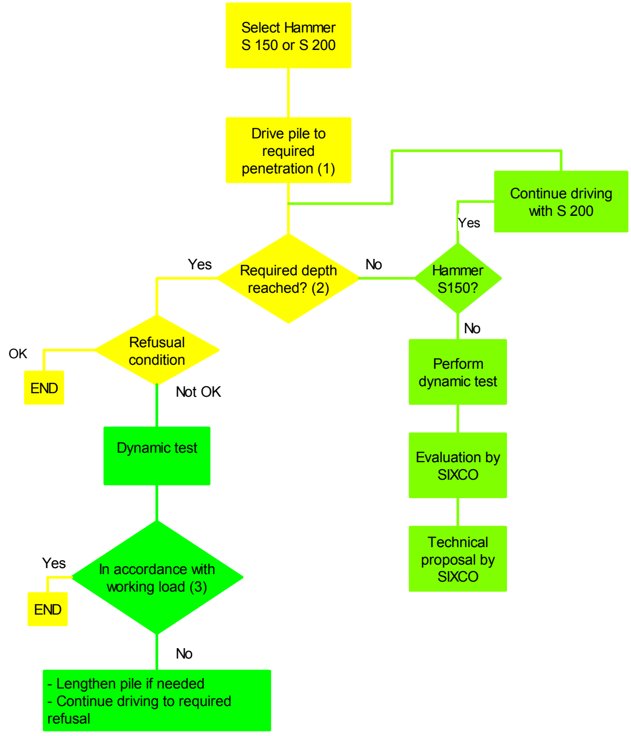

Figure 9

(1) See execution drawings
(2) See criteria above
(3) To be defined by SIXCO (=the Engineering Company)

Furthermore, the results on all the working piles are collected and placed in a chart which gives a statistically more trustable graph due to the large number of results available. The chart below gives the results of such analyses for another section of the same site above (figure 10).

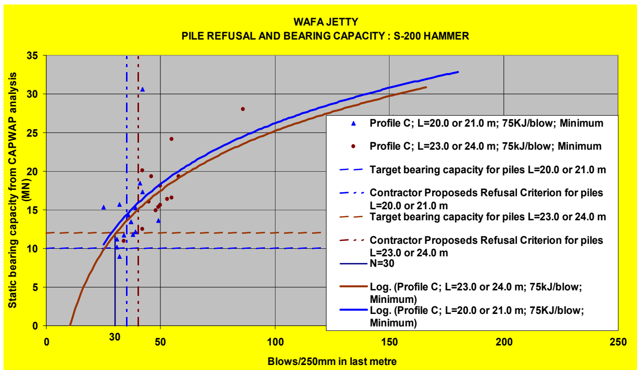

Figure 10

7 INSTALLATION PROCEDURE FOR SOCKETED PILES [1] [2]

When piles are driven to a rock layer, with little overburden, tensile forces can not be supported by friction on the shaft of the open-end piles, and installation of bored sockets or anchors is mandatory. Since sockets are installed by boring equipment which has to operate through the pile, no damage of the pile tip can be accepted.
A compromise has to be found between driving the pile to a sufficient penetration to guarantee the capacity of the pile under compression, and in the mean time to prevent for damaging the pile. Note that damage at the pile tip for compression piles has also to be limited to avoid driving problems.
In Dabhol in India, piles have to be driven in weathered basalt and the following procedure was set up to avoid damaging the pile as shown in the picture below (figure 11):

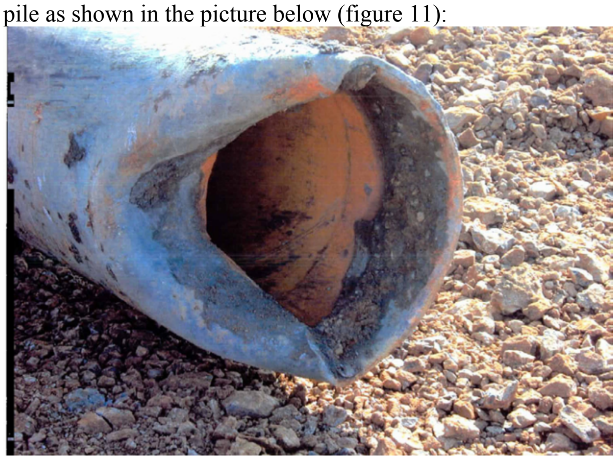

Figure 11

Driving analysis by TNO-WAVE (PDP Wave) can predict for the considered soil profile the SRD (Static Resistance during Driving) as well as the stress in the pile during driving, for different Hammer Energy levels and different penetrations per blow.

In the figure 12 the results of this analysis are shown for a compression pile (760*16 mm).
It shows that the stress during driving decreases significantly when the hammer energy is reduced. For a S90 hammer (hydraulic hammer from IHC), one can see that for an SRD value of 5250 kN, the driving stress is 350 MPa for a full energy setting of 90 kJ and is reduced to 260 MPa when the setting of the energy is reduced to 45 kJ.
On the other hand, the number of blows is increased from 28 to 108 blows per 100-mm penetration. This means that the driving time is almost 4 times longer as the blow rate remains 50 blows per minute.
Field test on full hammer capacity are showing damages between 0.1 and 0.5 m for a driving stress of 380 MPa, close to the yield stress (415 MPa). In fact these maximum driving stresses are computed with the assumption that the stresses are uniformly distributed over the entire cross section. This is of course never true in reality, and an appropriate safety factor has to be used in the definition of the refusal criteria.
Final installation criteria to guarantee the required SRD are governed by in-depth stress and damage analyses. It was concluded to allow 80% of the yield stress (= 332 MPa) for compression piles and 55% (= 225 MPa) for tension piles, since tension piles need a socket.

This criterion was checked by installing two additional raking piles on the test location onshore. After inspection, no damage at pile tip was observed as shown in the picture below (figure 13).

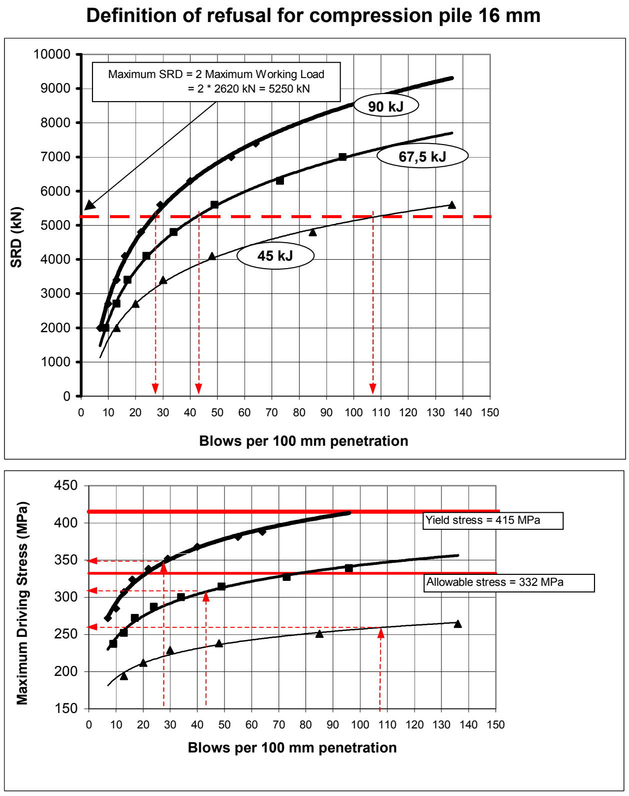

Figure 12

Figure 13

8 CONCLUSIONS

Acceptance criteria can be defined based on driving records, dynamic (PDA) tests during driving and maintained load tests on trial piles. Feed back by PDA testing on working piles allows increasing the accuracy of the criterion.
A clear acceptance criterion together with an easy remedial procedure for non accepted piles can prevent for unnecessary delay during construction of offshore structures.

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