Nachweis der Lastabtragung in großer Tiefe
72 m lange Stahlrammpfähle für LPG-Tanks

Verification of Load Transfer to a Large Depth
72 m Long Driven Steel Piles for LPG-Tanks

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Contents

Summary

Dynamic pile testing has been applied to verify the bearing capacity of 1200 pcs of driven steel H-piles with length 60 to 80 m for the foundation of the LPG-tanks in Bonny-Island, Nigeria. The testing procedure consisted of 28 pile tests in three sets – preproduction, at start of production and during production. Among others special objectives had to be achieved by the tests – first the verification of the driving resistance and bearing capacity in the base layer at 55 to 75 m depth considering negative skin friction in the upper layers – second a reliable definition of driving criteria considering soil compaction due to driving neighbouring piles.

Zusammenfassung

Die Tragfähigkeit der Gründung von LPG Tanks auf 1200 Stahlpfählen von 60 bis 80 m Länge auf Bonny Island, Nigeria, wurde durch Dynamische Pfahlprüfungen nachgewiesen. Insgesamt 28 Pfähle wurden in verschiedenen Bauphasen getestet – Testpfähle vor Beginn des Rammenarbeiten, Produktionspfähle beim Beginn und während des Rammens. Die Tests wurden beim Einrammen sowie auch beim Nachrammen durchgeführt. Besondere Aufgabenstellungen der Tests ergaben sich unter anderem daraus, daß der Rammwiderstand und damit die Tragfähigkeit der Pfähle nur in einer Schicht von 55 bis 75 m Tiefe nachzuweisen war bei gleichzeitiger Berücksichtigung möglicher negativer Mantelreibung in höheren Bodenschichten, sowie daß die sinnvolle Formulierung von Rammkriterien die Verdichtung des Bodens durch das Rammen der Nachbarpfähle zu berücksichtigen hatte.

1. Introduction

Bonny Island is situated at the coast of the Atlantic Ocean in the delta of the Niger river. The whole delta area is a region of very weak and soft alluvial soils mainly covered with mangrove woods. It is the center of onshore and offshore oil exploration activities.

In order to improve the environmental impact of these activities a large gas liquifaction installation was built to avoid the burning of gas during production. For the construction of the large industrial facilities the soil had to be strengthened. For the LNG process plant and tanks an overburdon was used and compacted the drained soil. As this process took several years it was decided to use a deep foundation for the LPG plant extension.

2. Soil conditions and safety concept

Soil investigations by deep coring showed that the soil is consisting of a number of layers of uncompacted silty sands above a competent sand strata at a depth starting at 57 m. This strata is of limited thickness of 10 to 20 m and is overlaying another deep layer of more or less compacted clay of thickness 2 to 8 m.

As for the construction of the tank base-plate a 4 m thick sand fill had to be imposed on level ground it had to be assumed that this additional load will induce compaction of the uncompacted upper silty clayey layers. This situation was giving additional load to the piles as negative skin friction and no load transfer was allowed for in these upper layers. It was therefore necessary to design a piling foundation where the tank loads in addition with the negative skin friction had to be safely transferred to the deep layers.

For the definition of the required design capacity of the piles the loads from a hydrostatic load test including self-weight of the tank (1.469 kN) and piles (123 kN) and estimated negative skin friction (172 kN) was decisive. For the hydrostatic load and the selfweight of the tank a global safety factor of 1,5 had to be applied to give the required capacity for a pile as **2.498,5 kN**.

As timewise only a foundation of driven piles could be considered the question had to be discussed how to verify the capacity of the piles. Whereas international specifications (e.g. EC7-drafts, ASTM 4595) mention the possibility of dynamic testing during driving the clients specifications explicitly demanded a static test. To determine the resistance of the deep layer would either demand to install an instrumented pile or to install a pile where all skin friction in the upper layers is totally suppressed. In both cases it seemed not to be possible to drive the test pile.

In the first case the danger of destroying the instruments (strain gages) during driving was high.

In the second case the driving should be done in a casing where the length of the casing above the competent sand should be filled with frictionless bentonite.

To avoid buckling of course guides must be placed along the pile eventually producing uncontrolled friction. Also during the borings for soil investigations a number of the records have the remark „blowing sands“ when reaching the sand layer. So it must be assumed that the competent sand might loose its consistency when the natural overburden is removed.

After the difficulties of a static test have been demonstrated to the client and his consultants a site specific procedure on the basis of dynamic testing was developed and accepted as a key part of the quality management system.

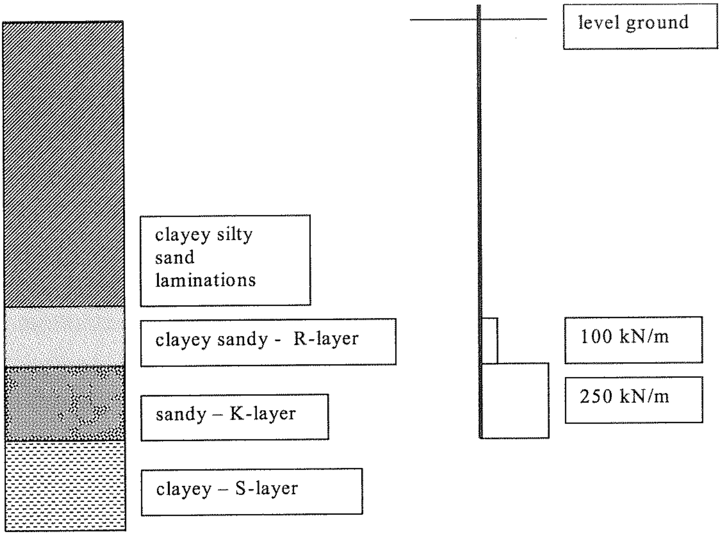


Figure 1 : Schematic soil conditions and anticipated skin friction to be verified

3. Preparation of piling works by driveability analysis

For the preparation of piling works extensive calculations by wave equation analysis have been carried out. By this WEAP®-analysis the driving process is fully simulated. Modelling of hammer, helmet, cushion and pile for a given soil profile results in data on

- pile compression and tensile stresses during driving,
- number of blows to be applied for a certain resistance and depth,
- development of blows per unit length and resistance with depth,
- duration of driving for given blow rate with time.

From this analysis an optimal choice of pile type and hammer is determined.
As a result of this optimization process steel H piles were chosen because they offered best control for the on-site-welded splices.

With the necessity to drive the piles down to 70 m penetration a very heavy equipment was needed. Although the chosen piles were very slender the hammer to be applied was chosen to be the largest available. Wave equation analysis showed that the compression stresses will be near to the limit. Therefore a pile cushion was used. The stresses could be reduced without unfavourable prolongation of the total driving time.

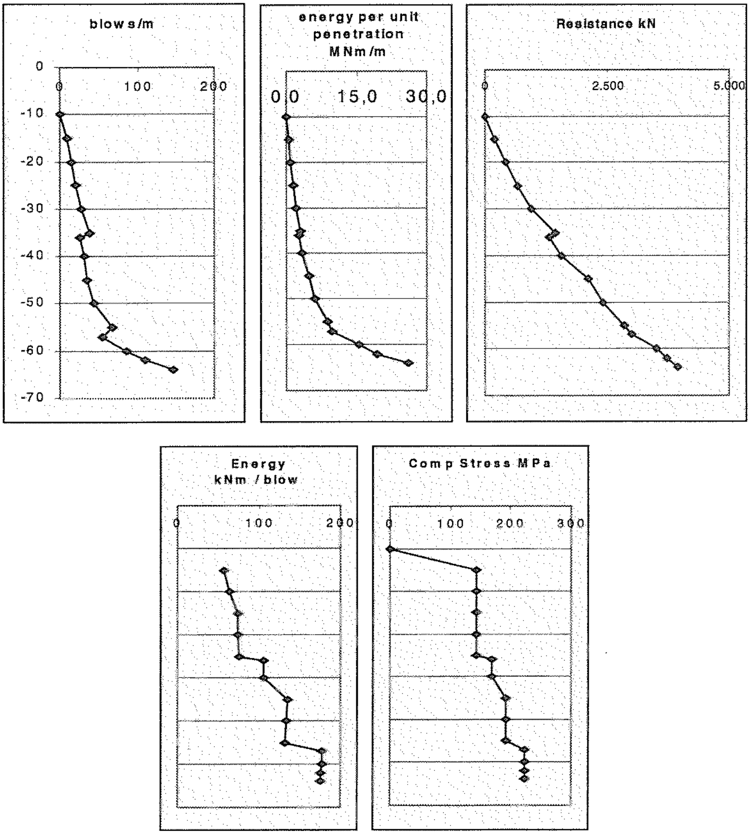


Figure 2 : Resistance and blows with depth – driveability analysis

Selected results of the wva equation analysis are summarized in a graphical representation in figure 2. It can be seen that from the soil profile as found by soil investigations a gradual increase of resistance with depth should be expected.

Increased energy (stroke) leads to a higher penetration per blow (reduced blow count) but also increases the compressive stresses. For this calculation it was assumed that the skin friction during continuous driving is reduced to 60%.

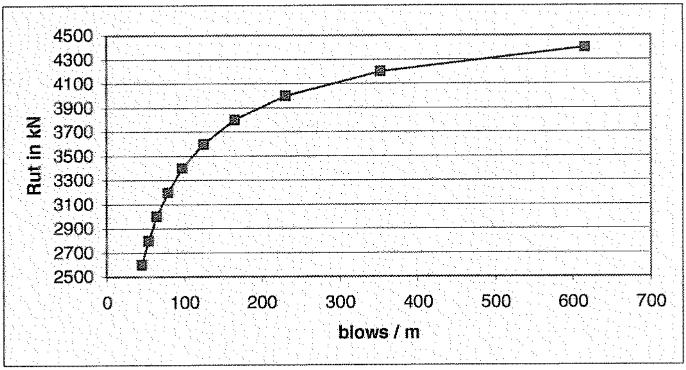


Figure 3 : Resistance and blow count (bearing graph) for 1,2 m stroke

As can be seen by fig. 3 for the given pile – hammer system the number of blows increase very much if resistances of app 4.500 kN are exceeded. Blows per meter will increase without a gain in resistance and so a value of 500 blows per meter can be expected to be refusal.

Compressive stresses are near the limit of 90% of the yield strength of 265 MPa and only depend on the applied forces at impact which are depending on the stroke only. Tension stresses are low in the reange of 10% of yield strength and decrease with increasing resistance.

4. Execution of tests

The original pile capacity verification procedure consisted of

1. the testing of 4 pre-production test piles to be driven in the middle of the two tanks for the determination of trial driving criteria approximately 1 month before the production driving was to start

and

2. a testing sequence at the beginning of production driving of 5 production test piles in each of the sectors of both tanks to reconfirm the driving criteria with respect to the different elevation of the competent sand layer. For a more detailed investigation of soil behaviour another 3 pile were driven and so a total of 13 piles have been tested in this second campaign.

As after driving of app. 50 piles the driving criterium was not met for a limited number of piles

3. additional tests at redriving had to be executed to reveal the nature of the „weak spots“ and assess a possible set-up. In this test campaign 10 piles have been tested in redriving and 1 extra pile during initial driving.

For the pile driving analysis of the preproduction test piles the complete driving of the second segment from 36 m penetration to final penetration was controlled. All piles have been retested after 1 hour set. Piles 1 to 3 have also been tested after 15 hours set.

The production piles have also been PDA-controlled over the whole driving of the second segment and redriving has been analysed after different set up times. In the third test campaign the pile have been redriven 19 to 31 days after installation.

5. Resistance distribution during driving and redriving

For the verification of the soil resistance in the sandy K-layer the modelling process of the CAPWAP-method was used. In this back-calculation from measured force and velocity at the pile top the resistance as activated over the length of the pile is determined.

The aim of the dynamic pile testing was to verify the assumed skin friction in the competent sandy K-layer. For a penetration of 7 m into this layer and a capacity demand of 2.500 kN a skin friction of 2.500/7 = 358 kN/m was the unit skin frcition to be proven. If only the outer circumference of the H-profile is taken into account the skin friction is distributed over an area of 1,48 m^2/m, i.e. a unit friction of 240 kPa was expected. As this is a very high value and unlikely for the alluvial sands a certain portion of the pile forces were assumed to be transferred over the tip.

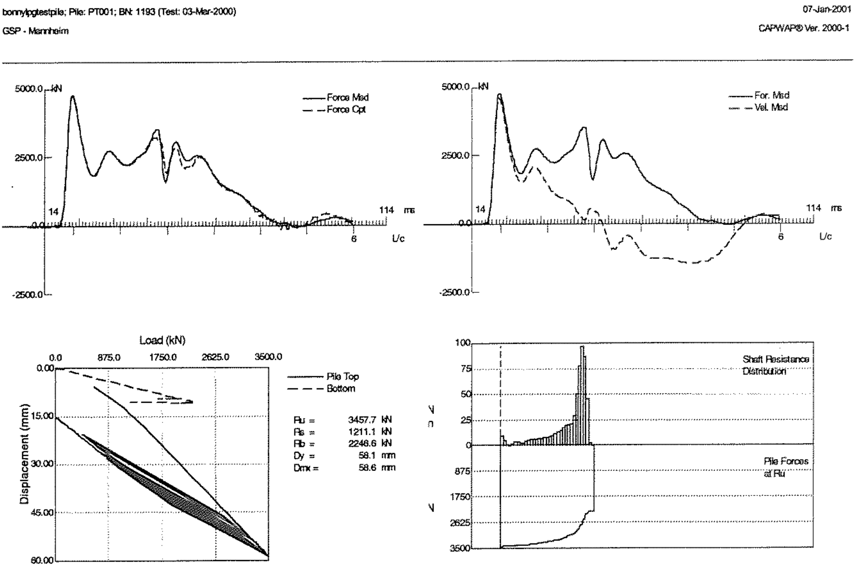


Figure 8 : CAPWAP results for preproduction test pile No.1 at end of initial driving EOI

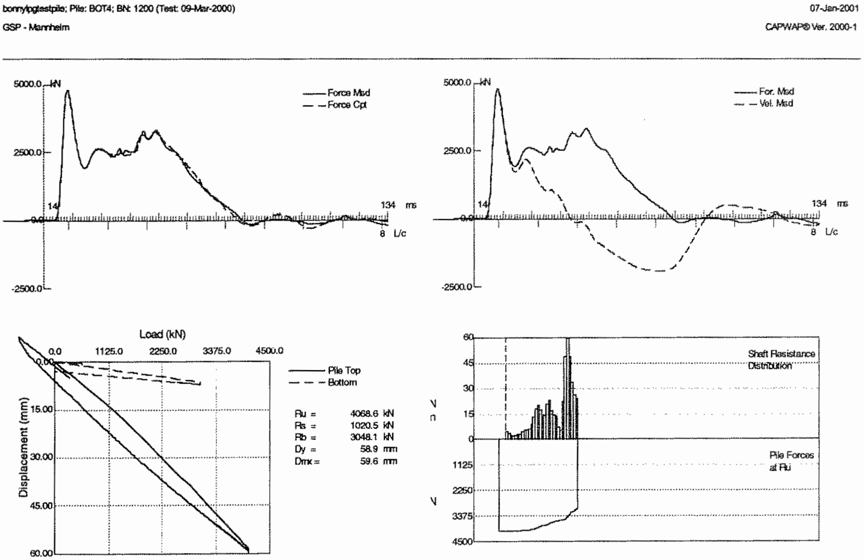
Fig. 8 gives a summary of the CAPWAP results. On top right the measured force and velocity at pile top are given. Both quantities are a function of time. As it is indicated the total duration of the impact is about 60 ms (milli seconds) 0,06 seconds. The horizontal scale also gives the time in multiples of the unit travel time of a stress impulse to propagate through the length of the pile. This travel time is dependent of the wave velocity that is a material constant and c = 5.172 m/s. So the time 2L/c is referring to the time when the wave has travelled to the pile tip and after reflection is arriving back at the pile top. This first portion of the force/velocity is most significant for the evaluation because the difference force-velocity is an indication of the activated skin friction.

This skin friction as determined by the back-calculation is shown on the lower right hand side of the graph as unit skin friction in kN/m above the line and total resistance in kN or internal pile forces (tip resistance and integrated skin friction) under the line. With reference to the time history reflection graph the skin friction distribution is shown from top to bottom as from left to right.

On top of the left hand side the measured and computed force is given on the same time scale as the measured force and velocity on the right hand side. The matching of the two curves is a measure for the accuracy of the description of the real pile by the pile model.

Bottom left the force displacement relationship is given. In the middle between the force-displacement graph and the skin friction the ultimate resitance Ru, the tip or bottom resistance Rb and the skin friction Rs is given together with the maximum displacement Dmx and the elastic displacement Dy is given.

In initial driving a continuous changing of skin friction is to be observed were it is possible that the skin friction distribution in the upper portion of the sand layer is reduced by the dynamic driving process and the target skin friction is only activated at a limited portion of the pile in the sandy layer.



bonnylpgtestpile; Pile: BOT4; BN: 1200 (Test: 09-Mar-2000)
07-Jan-2001
GSP - Mannheim
CAPWAP® Ver. 2000-1

Ru = 4068.6 kN
Rs = 1020.5 kN
Rb = 3048.1 kN
Dy = 58.9 mm
Dmx = 59.6 mm

Fig 9 : End of initial driving for preproduction testpile No.4

For the very first pile at the end of initial driving (EOI) however most of the resistance was concentrated at the tip of the pile (see fig.8). Because of this resistance concentration skin friction in the layer directly above the pile tip could not be verified. The computer modelling of the pile must be understood as to provide a picture of the effect of the load transfer, i.e. there is a high resistance acting by its spring stiffness characteristics like soil in compression. In reality however this compression is not concentrated under the very tip steel area but is transferred by a combination of compression and plugging with increased friction at the pile tip. The model shows only for the higher sandy layer, that was not taken into account in design calculations, considerable skin friction. By taking account of this upper skin friction and the tip resistance the total required capacity was well verified. As can be seen by the matching this overall activated capacity is accurate because the pile movements are fully described even if all the details of the load transfer are not modelled.

This plugging effect was different from pile to pile and occured during initial driving and redriving. For test pile TP4 the tip resistance is even exceeding the target resistance of 2.500 kN (see fig 9).

Whenever plugging was found the skin friction above the tip was low and the required values could not be verified. If however the resistance over the lower portion of the pile in the K-layer and above was taken as total resistance the overall target capacity was verified.

In comparison to the driving record nearly in all skin friction distributions a high resistance was found in the sandy R-layers above the K-layer. By the result of the CAPWAP analysis the strength of this layer could be proven and load transfer was accepted.

After setup the skin friction of the pile increased to values of 300 kN/m in the K-layer and nearly 200 kN/m above the K-layer (see fig. 10). By the end of the redriving the skin friction was released and a plug tip resistance built up (see fig.11).

After 3 to 4 weeks the piles have been „frozen“ to the ground and a high skin friction in the upper layers has been activated. Hence the resistance in the bottom part of the pile could not be activated. In redriving the total resistance was in the range of over 6.000 kN but in the bottom competent sandy K-layer no significant resistance could be activated.

After the pile has been driven about 10 cm at app. 300 blows the skin friction has shifted towards the bottom of the pile but still did not reach the values that have been determined for other piles after 15 hours set. The skin friction in the upper layer was so high that not enough energy could be transferred down to the bottom of the pile.

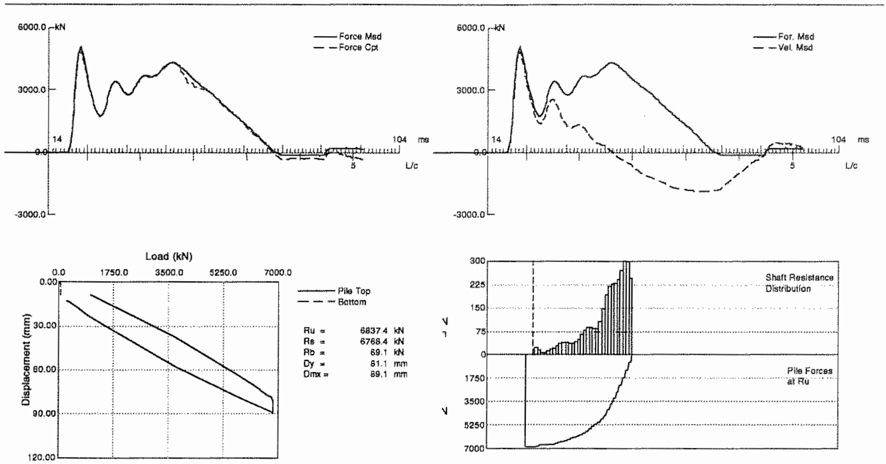


Figure 10 : Begin of 15 h redrive of test pile TP1

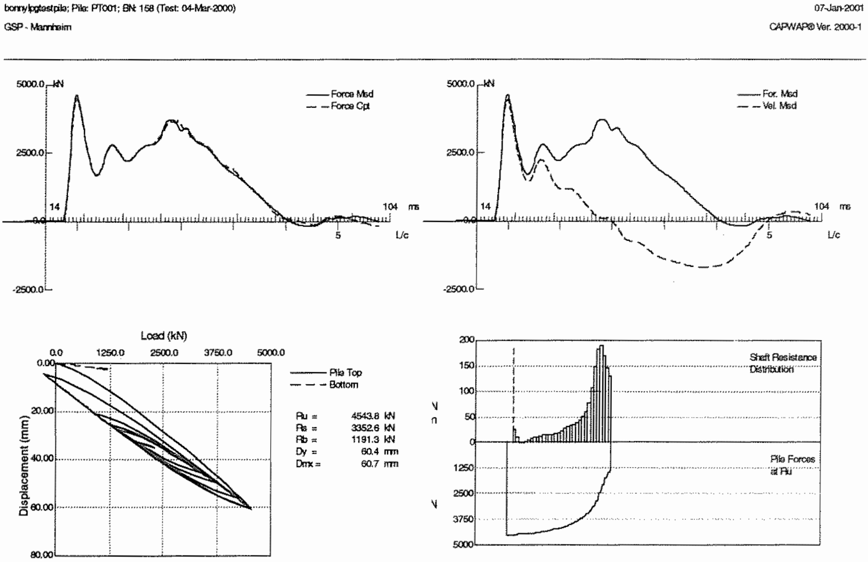


Figure 11 : End of redrive after 15 hours

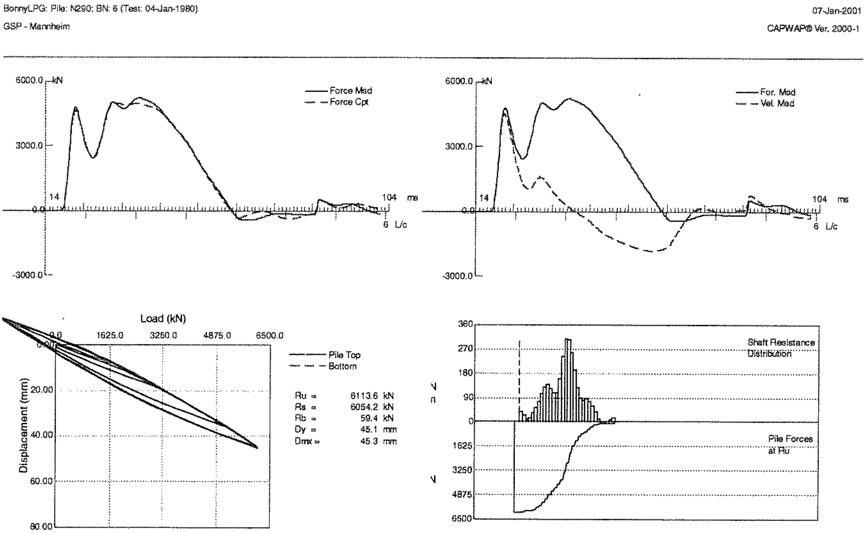


Figure 12 : Begin of Redriving after 21 days set up

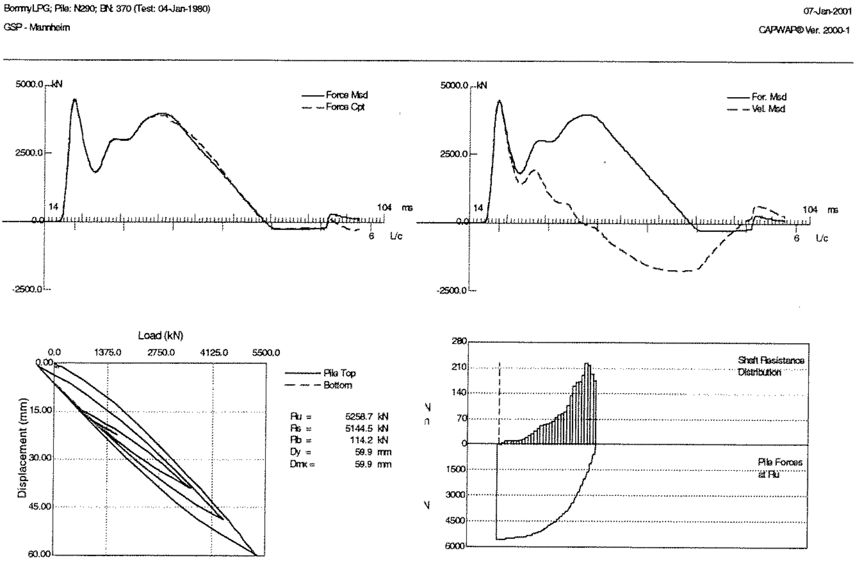


Figure 13 : End of Redriving after 21 days

Even when during redriving a considerable accumulated permanent set was achieved (more than 10 cm) no resistance increase was found for the bottom layers. Residual stress analysis by CAPWAP showed that the pile nearly totally relaxed after each blow and the stress strain relationship always started from the bottom line. So in order to activate the resistance of the competent sand layer more blows had to be applied. In some test piles these additional blows lead to an additional penetration about 50 cm like was possible in short time redriving.

Although in redriving an increased overall resistance was found it was not possible to define a reliable conclusion with respect to the setup characteristic, increase of resistance with time, for the competent sand layer. This was mainly due to the plugging effect. In some cases during redriving no new plug was formed and the resistance was skin friction, in other cases the number of applied blows was different from others so the effect of increased skin friction was not directly comparable. On the other hand, the redriving had to follow site specific demands (and sometimes the tropical rain and thunderstorm prevented a continuation in scheduled time), so that a consistant redriving procedure could not be established.

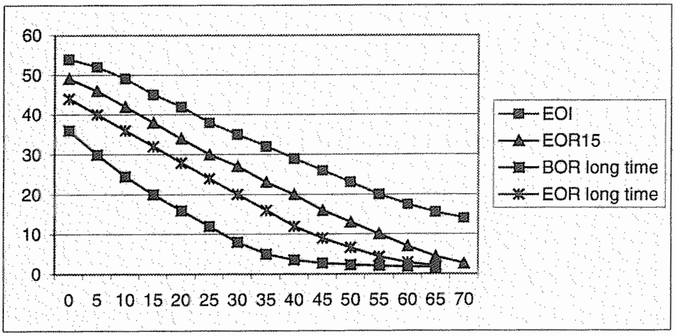


Figure 14 : Maximum displacements for end of initial driving (EOI),
begin of redriving after 15 hours (EOR15),
begin of redriving after 21 days (BOR long time),
end of redriving after 21 days (EOR long time)

The displacement graph (Fig. 14) shows that only in initial driving it was possible to move the pile tip and activate resistance. Elastic compression of the pile during initial driving is about 50 mm.

For some of the tested piles the target resistance could be verified at a single blow. But as has been demonstrated for some piles this was not possible. In reviewing all results however it could be seen that individual tip resistances, skin friction values of up to 300 kN/m could be verified and therefore the target of an overall capacity of 2.500 kN has been met.

6. Conclusions

Dynamic pile testing during driving and redriving was used to verify the capacity of the deep foundation of LPG tanks in soft alluvial grounds. With respect to the complexity of the dynamics of driving however the results especially the skin friction distribution did not directly match the anticipated distribution as derived by soil investigation and geotechnical reasoning. It was shown that by a combination of results from different blows of driving and redriving the required values for the skin friction in the deep competent sandy K-layer could be verified and the ultimate capacity proven. By dynamic pile testing i.e. measurement of force and displacement at pile top, the distribution of resistances along the axes of the pile could be determined that would otherwise have been impossible.

References :

The paper does not refer to any special literature. For a general introduction into dynamic pile testing the reader is advised to take advantage of the webpages pile.com and gsp-mannheim.de.

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