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Evaluation of the dynamic load test on bored piles in sandy soil

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ABSTRACT: This paper summarizes the detailed planning of an evaluation project for dynamic load tests on bored piles in sandy soil. A test site had to be prepared, which ensures comparable conditions at all pile locations as well as a detailed knowledge on soil parameters and other boundary conditions. A detailed site investigation program was performed at a dedicated area on the BAM test site near Horstwalde south of Berlin, Germany. The site consists mainly of well graded, partly well compacted medium sands. A test program is designed that aims to give full responsibility for the testing performance to the operating consulting engineers. While each consultant is responsible for the testing of one of eight similar virgin piles, the test results will be compared to static load tests performed after the pile capacity analysis. The tests aim at a better understanding of the reliability of dynamic load tests and the necessary precautions for a good quality result.

1 INTRODUCTION

Bored piles are used in many construction projects of the German waterways authorities, e. g. bridges, piers or locks. Their load carrying capacity varies with pile type and geometry as well as soil type and soil parameters and is thus not easy to calculate in advance. Whenever the pile behavior cannot be estimated from observations in a similar structural situation, load tests have to be performed to fulfill the requirements for the valid European and German Design Codes. Dynamic load testing (DLT) as a cost effective alternative for expensive static load tests (SLT) is accepted in many places (Rausche et al. 2008) but it is also still questioned in others. The two governmental research institutes BAM and BAW have designed an experiment in a geological setting typical for glacial and post-glacial areas in northern Germany. It is intended to build 8 bored piles with 900 mm in diameter and a length of 10 m.

For this purpose a proper site had to be selected and characterized in a manner that comparable boundary conditions are guaranteed for all tests. An intensive geotechnical and geophysical investigation program had to be carried out. A test program is scheduled to evaluate the dynamic load tests on bored piles in sandy soil. The tests continue a tradition of previous pile capacity evaluation events, but there are also some major differences.

2 PREVIOUS EVALUATION STUDIES

Several attempts have been made to evaluate the prediction of pile capacity using dynamic load testing. Likins and Rausche (2004) have compiled a summary of different studies related to the stress wave conferences and found a good agreement comparing the results of static and dynamic load tests in their database. The results depend on the type of piles and are generally more convincing for driven piles than for bored piles. Whenever differences are found between DLT and SLT, lower values for the pile capacities are obtained in the dynamic load tests, which at least would be on the safe side. However, due to the lack of full background information it is not clear whether static and dynamic load test results were evaluated completely independent in all cases.

In a Belgian prediction event (Maertens and Huybrechts 2003) pile capacities for screw piles were predicted according to design calculations and/or dynamic load testing. Different types of screw piles were tested in static and dynamic load tests and even using the rapid load test. The test site consisted mainly of sandy silt and sand. For the DLTs the tests themselves were performed using a given scheme of drop heights. Predictors were given the measured test signals, but the individual predictors were obviously not in full responsibility for the load test and the acquisition of the data. Static and dynamic testing was done at different piles. The test results are a bit mixed concerning the accuracy of the predictions using dynamic load tests, as compared to a reference pile capacity resulting from static load tests. The statically and dynamically tested piles are in relative large distance to each other. Its influence on the comparative assessment of pile capacity cannot be judged.

In the international prediction event for piles in residual soil carried out in the framework of ISC'2 (Viana de Fonseca and Santos 2008) different piles were tested dynamically and statically. The tests include also bored piles. The test site was classified as silty sand. As in Belgium, the predictors were given measurement data for several blows. Generally, the result is quite good but also shows some scatter comparing the individual predictors and the blows chosen for prediction. As can be expected, the agreement in results is better for driven than for bored piles. Again the predictors were not given the full responsibility for the pile test. However, in this analysis and prediction event the dynamic load tests showed a slightly larger pile capacity for the evaluated bored pile than was measured in the static load test, unlike in Likins and Rausche (2004). It should be noted that especially the analytical predictions for the bored piles showed some scatter and in one case deviated by a factor of 5.

In our pile testing event the main emphasis is to turn over full responsibility to the pile testing consultants concerning the entire test procedure. Each of them is in charge of one individual pile. The test operator is given a drop weight. He is responsible for the drop heights or more general for the blows chosen for the assessment of the pile capacity. The testing personal is also responsible for the measuring instrumentation, the data acquisition and the interpretation using CAPWAP or similar routines. Each participant will additionally get the soil investigation data but not the results of the static load tests which are performed after the dynamic load testing. More details on the test schedule are given in section 7.

3 THE TEST SITE

3.1 *Location, purpose and history*

BAM maintains a test site for technical safety issues north of the village Horstwalde about 60 km south of Berlin, Germany (Figure 1). Explosives certification, drop tests for safety containers up to 200 t, as well as large fire experiments are performed there (BAM 2011). BAM-TTS covers almost 12 km², but large parts are used for forestry only.

The area is used by many research groups of BAM and guest partners for hazardous and large scale testing. Among other facilities, it includes a test and validation center for various purposes and techniques of the nondestructive testing group, Division 8.2 (Niederleithinger et al. 2009), as well as a facility for the testing of cyclically loaded driven steel piles, Division 7.2, Buildings and Structures.

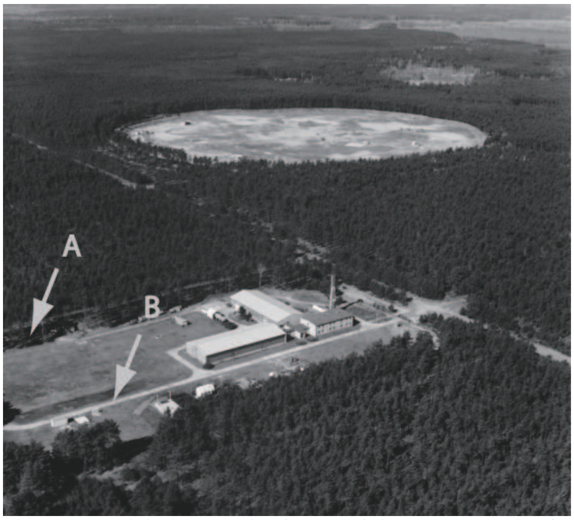

Figure 1. Aerial photograph of parts of the BAM test site for technical safety at Horstwalde (BAM 2006, view direction northwest). A: new pile test site. B: NDT-CE test and validation center.

3.2 *Geological setting*

The site is located in the northern German Basin, which consists of various sediments with a thickness of several thousand meters, affected by salt tectonics. Local geology is mainly affected by glacial epoch (Elster, Saale, Weichsel glaciation). In the late Weichsel glaciation, Aeolian processes formed dunes from fine sands close to the test site. The main part of the site (including the test site discussed here) consists mainly of sandy layers of varying grain size and mixtures of silt and organic material. Peat lenses have also been found locally. The groundwater table is about 3 ± 1 m below the surface, varies seasonally and is influenced by a nearby water works.

3.3 *Pile Test Requirements*

The test site should not be limited to provide space and technical environment to conduct the planned experiment. Firstly, favorable and comparable subsoil conditions had to be ensured for all tests at all pile locations. Furthermore, it also had to be assured that the selected pile type, diameter and length reflected the constructions typically used at German waterways, but at the same time avoiding to provide too much resistance to dynamic load test (i.e. too much skin friction resistance to mobilize completely for the selected drop weight ram mass).

3.4 *Location and layout*

The preliminary location has been chosen in the southwest of the NDT test and validation center. An area of about 30 by 20 m, which can be expanded if required, was prepared for use (Figure 2).

Figure 2. Location of the new test site (view direction northwest).

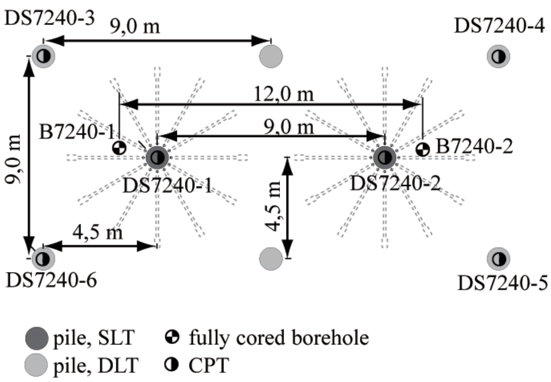

Figure 3. Sketch of the new test site with designated pile positions, boreholes (B7240-X) and CPTs (DS7240-X).

Section 4 summarizes the geotechnical conditions. A more detailed description including the geophysical investigations can be found in (Niederleithinger et al 2012).

4 GEOTECHNICAL INVESTIGATION

4.1 *Boreholes*

Two boreholes (fully cored, 100 mm diameter) have been drilled down to a depth of 25 m at the designated locations of the two piles intended for static load tests (see Fig. 3). The geologic profiles (Fig. 4) are quite similar. Almost the entire column below the top soil consists of medium sands with some fine sand at the top and coarser material at the bottom. In addition, variable contents of silt, coal and gravel have been detected. Borehole B7240-1 features some minor lenses of silt or coal. B7240-2 shows increased gravel content in a depth of about 15 m.

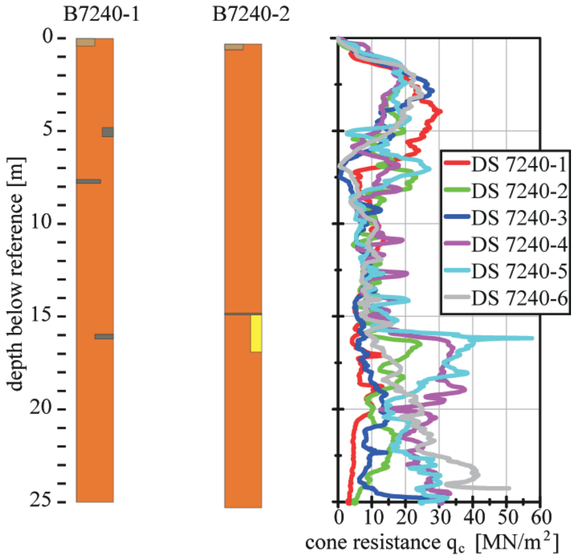

Figure 4. Soil profile of boreholes B7240-1 and B7240-2 and CPT 7240-1 to 7240-6.

4.2 *Cone Penetration Tests*

CPTs have been performed near the borehole locations as well as on the corners of the designated area (see Fig. 3). Figure 4 displays the CPT results. Despite the fact that the soil profiles are similar for all CPT locations, there are some significant differences in the results. The upper 8 to 9 m show quite high cone resistance values (q_c = 20 – 30 MN/m²) which corresponds to medium sands. DS7240-2 and DS7240-5 features a thin intermediate softer layer in this section. Below that, much weaker sediments are encountered with q_c values around 10 MN/m² and some more variability in DS7240-4. But most important are the much higher resistances found in DS7240-2, -4 and -5 below 16 m depth, which might reflect the higher gravel content. In contrast DS7240-1, DS7240-3 and DS7240-6 show no or only slightly increasing q_c values at this depth.

4.3 *Laboratory investigations*

Figure 5 shows the compiled results of grain size analysis of 53 samples from borehole B7240-1 and -2. The data have been grouped in three depth intervals, reflecting the soil profiles as well as the CPT results. Both the consolidated upper sands (depth up to 8-9 m) as well as the weaker middle sands (depth up to 15-16 m) are narrow banded and similar in both boreholes. The lower sands are in general coarser and show larger variation. Especially the samples from B7240-2 have a wider bandwidth and much higher gravel content, which probably causes the higher cone resistance measured here. All other parameters do not differ significantly between both boreholes. Mean values are compiled in Table 1.

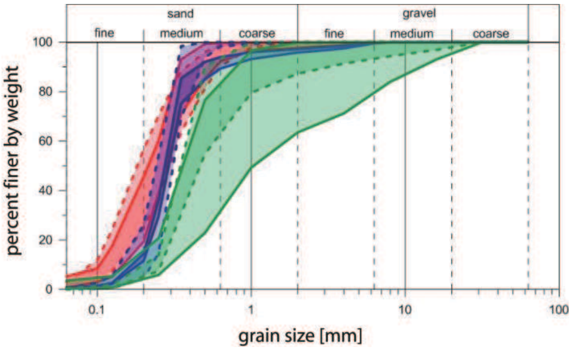

Figure 5. Results of sieve analysis (range of samples in upper, middle and lower part of boreholes). Red: upper sands (1 to 8-9m); blue: middle sands (8-9 to 15-16 m); green: lower sands (15-16 to 25 m); dashed: borehole B7240-1; solid: B7240-2.

Table 1: Compiled soil mechanical parameters.

Unit		upper sand	middle sand	lower sand
Description		ms, fs	ms, fs´	ms, gs
Soil mechanics				
bulk density wet	γ [kN/m³]	18.0	16.5	17.5
bulk density under water	γ' [kN/m³]	10.5	9.0	10.0
permeability	k [10^{-4} m/s]	0.9 to 3	2 to 6	3 to 20
Classification				
DIN 18196		SE (SU/ST)	SE	SW (SE)
DIN 18300		3 (4)	3	3
DIN 18301		BN1 (BN2)	BN1	BN1 (BS1)
Depth				
top	[m]	0.5 to 1	8 to 9	15 to 16
bottom	[m]	8 to 9	15 to 16	---

5 PILE DESIGN AND TEST SET UP

In a first step it has been decided to set the pile length to about 10 m to avoid the lower, harder gravels, which are present in some parts of the site. A pile embedded with the above mentioned length will principally work as friction pile. End bearing and base resistance respectively will not be as dominant as it would be if the pile was embedded into the more compact layers.

The pile diameter was chosen to be 0.9 m, which is a standard diameter used in many waterway projects supervised by BAW. Eight identical piles are planned for testing: Two piles for SLTs, Five piles for DLTs and one as a reserve. Calculations using German standard DIN 1054 indicated the possibility of a maximum load capacity up to about 5 MN for 10 m piles. The German regulations for pile testing (EA Pfähle 2007) recommend using a drop weight of 1 – 2 % of the designed load capacity for dynamic testing. Taking into account that the maximum drop weight currently available in Germany is in the range of 10 t, a maximum design load capacity of 5.0 MN is feasible.

The piles will be designed as bored piles with a temporary casing. Quality control throughout the construction phase is seen to be essential. The concrete work will be controlled by an independent certifier and integrity tests (low strain sonic echo test at all piles, thermal integrity, parallel seismic tests as well as embedded sensors at selected piles) will be part of the test preparation. It is acknowledged, that these piles might have some differences in shape and total mass e. g. due to soil inhomogeneities. But as all piles are tested more than once and by more than one tester, any offsets will be seen in the data. Additional measures to determine pile geometry will be considered, if significant deviations in pile capacity will occur.

The static load tests will be performed by hydraulic jacks. A platform with symmetrically arranged anchors with low-lying force induction section (starting at least 3 times pile diameter below pile tip) serves as a reaction body for the press loads (see Fig. 6). For each instrumented section three strain gages on basis of vibrating wires will be arranged in a uniform circumferential distance (120°). At the pile tip a load cell for measurement of base resistance will be installed, while also the pile head load and settlement will be recorded. Pile head loads are measured by an independent load cell. From the measurements at the pile head, over the pile length and at the base, a resistance-settlement line with separate curves for base resistance and skin friction will be deduced.

The load will be applied in two cycles in which the load for the cycles depends on working load and calculated ultimate capacity. According to EA-Pfähle (2007) the ultimate load will be applied in eight load steps (see Figure 7). If necessary a further loading is envisaged until failure is reached. The progression of load steps is prescribed in dependency of the settlement rate.

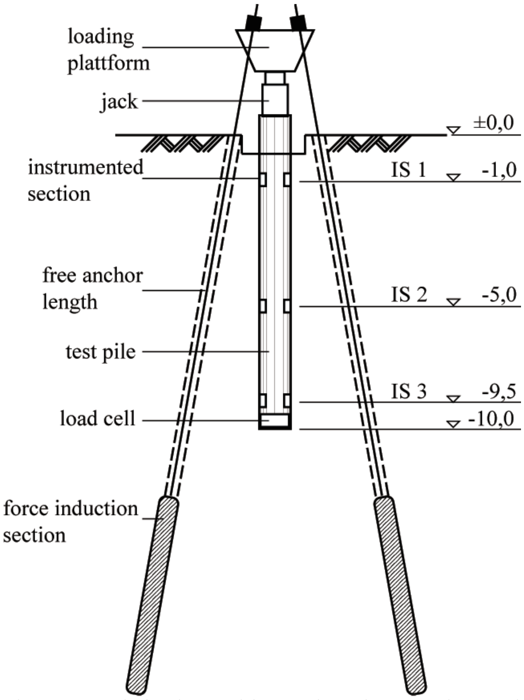

Figure 6. Static load test with star-shaped arranged, spread grout anchors and instrumented sections.

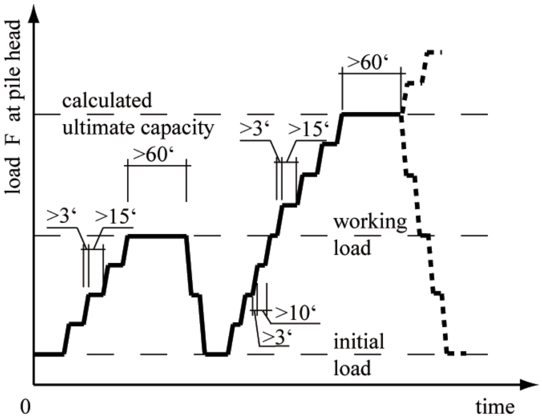

Figure 7. Recommended load steps F_i on the based on EA-Pfähle (2007).

To prepare the dynamic testing, a steel casing will be placed on the pile head (see Figure 8). By filling concrete around the starter bars inside the casing, the connection between case and pile will be achieved. The sensors for the measurement of strains and accelerations during the impact of the drop weight shall be installed by each testing engineering consultant individually, at about 1.5-times the pile diameter below the top of the steel casing. The acquisition of the measuring signal shall also be performed individually by each testing engineering consultant.

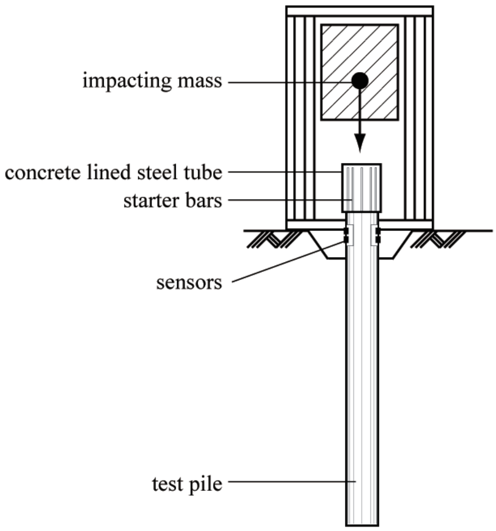

Figure 8. Dynamic load test set-up.

6 NORMATIVE REGULATIONS AND DEFINITION OF PILE CAPACITY

The design resistance of pile foundations $R_{c,d}$ is calculated from characteristic values $R_{c,k}$ and the partial safety factor for resistance γ_t, as specified in DIN EN 1997:2004 and AC:2009.

$$R_{c,d} = R_{c,k}/\gamma_t \quad (1)$$

However, different design methods for piles are allowed in DIN EN 1997:2004+AC:2009. As a first option, the calculation can be done with empirical or analytical methods whose validity is verified with static load tests at comparable boundary conditions. The second option is to perform either a static load test or a dynamic load test. A further option is the use of the observed performance of comparable pile foundations, supported by soil investigation and testing.

The dynamic load tests should be calibrated by means of static load tests with comparable boundary conditions (soil conditions, time between installation and testing, activated resistance...). Klingmüller (2011) provides a discussion on the calibration of DLTs by means of SLTs: The calibration gets more difficult if creep effects occur during the static testing. In our tests this influence is expected to be small. Static and dynamic tests should also be performed with minimum time delay to avoid the influence of ageing effects. Furthermore, the drop weight has to be chosen large enough that the full pile capacity can be predicted from the tests. Another aspect is the change in measured pile capacity due to the impact testing itself. This has to be assessed in the posterior analysis of the testing data.

The DLT and SLT differ in their consideration of characteristic values. In the frame of the European and German Standards scattering factors have to be included to calculate the design capacity, which are larger in the case of a DLT. However, the consideration of the established design standards will be only one single aspect of the comparative evaluation. Generally, the test results from dynamic and static load tests have to be compared in a precisely defined way. Due to the fact that it is difficult to define failure by means of load settlement curves, the European and German standards DIN EN 1997 and DIN 1054 define the maximum pile capacity in compression as the load corresponding to a settlement of 10 % of pile diameter D. On the other hand, Likins and Rausche (2004) found in their comparative study the Davisson's offset limit method (Davisson 1972) to be the most appropriate. See also the discussion in Fellenius (1980), which also gives a good summary of pitfalls in performing SLTs.

Davisson's method is a widely used method for predicting the ultimate pile capacity from static load test results. It defines the failure load as the load which causes a displacement equal to the elastic compression of the pile as a free standing column without soil plus an offset (see Fig. 9). The ultimate capacity of the pile is defined as the intersection of the result of Davisson's method with the load-settlement curve.

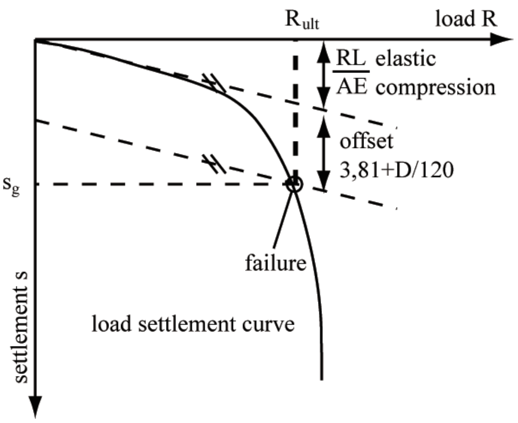

Figure 9. Interpretation of load settlement curve with offset limit method (after Davisson, 1972).

7 TEST PROGRAM

The preliminary test program for the static and dynamic load tests can be seen in Table 2. There, the acronyms D1 to D5 represent the five different testing engineering consultants. It is planned to perform dynamic tests within a period of about two weeks. Once all DLTs have been finished, two SLTs will be performed by an independent contractor at two additional piles. No testing will be carried out earlier than 30 days after construction of the bored piles.

The testing engineering consultants (D1 to D5) have to interpret their DLTs twice: Firstly, without knowing the results of the SLT, only based on the soil investigation report and the DLTs, and a second time with the results from SLT.

Table 2: Testing scheme for the pile tests.

pile No.	1st test	2nd test	3rd test	4th test	5th test	6th test	static test
P1							S1
P2							S1
P3	Reserve						
P4	D1	D2					
P5		D2	D3				
P6			D3	D4			
P7				D4	D5		
P8					D5	(D1)	

The aim of the test is to assess the quality of the dynamic load testing for bored piles and to eventually find out the reasons if the result is not as convincing as hoped for. Since it is expected to achieve piles with a comparatively similar capacity, in the case of an unexpected variety in test results, an intensive discussion with all participants will be part of the program. Since it is foreseeable that eventual deviations in pile capacity will be attributed to the design of the individual piles, all the information of local CPTs, low strain testing, construction reports etc will be looked at carefully in the discussion.

The test procedure can be summarized as follows:

(1) Individual DLTs and analysis of pile capacity at piles P4 to P8;
(2) SLTs at pile P1 and P2;
(3) New analysis of DLTs in light of the SLT-results;
(4) Additional DLTs at the previously tested piles P1 and P2.

Further instrumentation of the piles as well as of the adjacent soil is planned. A distributed temperature sensor network will give additional quality information during the concrete curing. In addition, it is also intended to install fibre optic strain sensors as well as ultrasonic transducers. The pore water pressures in the surrounding soil will also be monitored during the static and dynamic testing.

8 CONCLUSION AND OUTLOOK

Dynamic load tests are known as a cost effective alternative to static load tests, but the resulting signals are analyzed by specialists and not necessarily by the geotechnical expert. In order to evaluate the quality of the analysis and the pitfalls in assessment, a pile testing event has been planned. Instead of just supplying the same tested signals to each analyzer but by giving them the full responsibility for the whole test individually, it is aimed to evaluate the result that could be expected in a standard project specific for bored piles.

The new test site at the BAM TTS at Horstwalde has shown to be suitable for the evaluation of static and dynamic load tests. The combination of conventional boreholes, sampling and lab analysis with several CPT soundings has given a complete and reliable overview on geotechnical parameters.

The performance of the tests had to be delayed to spring 2012, while the preparation of the piles already started at end of 2011. The installation of piles and ground anchors will be executed by BAUER Spezialtiefbau, who also will perform the static load tests. The test results of our testing evaluation will be presented at the IS-Kanazawa 2012 conference.

9 POSTSCRIPT ADDENDUM

Meanwhile, as of May 2012 most of the load tests have already been performed. The integrity of all piles was verified prior to the load testing. For the piles P4 to P8 the bearing capacities as evaluated from the DLTs were in a range of 2.3 to 3.7 MN. On the other hand, the static load tests for the piles P1 and P2 showed values of approximately 2.7 MN and 3.2 MN.

In this respect, the preliminary character of the results added here to conclude this paper has to be stressed. Currently the testing consultancies are preparing their full reports on the tests. Furthermore, the aim of the project is not just the simple comparison of the evaluated pile capacities but also the careful examination of any deviations. After producing the initial predictions, a second stage is envisaged where the following issues will be discussed:

- While the piles were planned to be identical, certain deviations in their local soil profiles and in the piles themselves have to be taken into account.
- Given the results of the static load tests, a comparison with the DLTs in terms of shaft friction distribution and tip resistance is necessary, also discussing the calibration of DLTs at the SLTs in general.
- The individual analysis of pile capacities will be discussed with the testing consultancies to understand better the influence of the personal experience.
- Apart from the evaluated maximum pile capacity, the comparison of the load-displacement-curves will also be looked at.

A full report of the findings will be published in the near future.

ACKNOWLEGDEMENTS

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