Real-time quality monitoring and result verification by static and dynamic trial loading of piles in marine clay

Monitoring de qualité en temps réel et vérification par essais de chargement statiques et dynamiques de pieux dans l'argile

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ABSTRACT A construction project in the city of Konstanz, on Lake Constance, provided a rare opportunity to install several test piles of different types and test these with regard to their bearing capacity. This opportunity was used to investigate full-displacement bored piles (FDP), vibro-concrete columns (VCC) and vibro-mortar columns (VMC). During pile installation, an on-line quality monitoring and verification system was used to monitor productivity. The results of this installation process were verified by static and dynamic axial load tests, with which it was hoped to show to what extent these agree with the results of the quality monitoring and the static tests and are therefore suitable for these foundation elements.

The difficult foundation soil presented a particularly interesting challenge. An approximately 3 m-thick fill overlays a fine-sandy lacustrine clay with a very soft to, at the best, soft consistency; this is underlain by a semi-solid boulder clay as from a depth of about 25 m. The foundation concept therefore envisaged a combined pile-raft foundation with approximately 15-m long piles as the technically and economically optimum solution.

Despite the very unfavourable conditions, unexpectedly high individual loads were measured for the floating-installed columns. For the vibro-concrete column, the limit settlement was not achieved until an axial load of 1,000 kN had been reached. The full-displacement bored pile "failed" at a load of 720 kN, and the 4 m-shorter vibro-mortar column still required a load of 680 kN to reach its limit settlement. In comparison, the dynamic-loading tests confirmed the limit load-bearing capacities thus determined with a deviation of only about 5 %. However, a deviation of about 33 % from the statically determined bearing capacity of the full-displacement pile was less than satisfactory, and this remains to be investigated in detail with the results of future loading tests.

RÉSUMÉ Dans le cadre d'un projet de construction situé à Constance, au bord du lac de Constance, plusieurs pieux de types différents ont pu être testés en termes de capacité portante, occasion qui se présente rarement. Ceci a permis d'analyser des pieux forés à refoulement total, des pieux vibroforés vibrobétonnés et des colonnes ballastées injectées. Lors de la mise en œuvre du pieu, un système de monitoring de qualité et de vérification a été utilisé pour suivre la productivité. Les résultats obtenus lors du processus d'installation ont été vérifiés par des essais de chargement axiaux statiques et dynamiques, grâce auxquels la concordance entre le monitoring en cours d'exécution et les essais statiques pour ce type de fondation peut être démontrée.

Le sol de fondation, particulièrement difficile, a présenté un défi particulièrement intéressant. Un remblai d'épaisseur environ 3 m repose sur une argile finement sableuse lacustre de consistance très molle à, au mieux, molle. Ce terrain repose sur une argile moyennement ferme à blocs à partir d'une profondeur de 25 m. Le concept de fondation envisagé a consisté de ce fait en une fondation mixte avec des pieux d'une longueur de 15 m environ, représentant la solution optimale des points de vue technique et économique.

Malgré les conditions très défavorables, des charges unitaires inattendues très élevées ont été mesurées pour les colonnes flottantes. Pour le pieu vibroforé vibrobétonné, le tassement limite n'a pas été atteint avant une charge axiale de 1000 kN. Le pieu foré à refoulement a atteint la "rupture" pour 720 kN, et la colonne ballastée injectée, d'une longueur de 4 m inférieure aux autres a également nécessité une charge de 680 kN pour atteindre son tassement limite. En comparaison, les essais de chargement dynamiques ont confirmé ces résistances maximales avec un écart de 5 %. Cependant, une différence d'environ 33 % en comparaison avec la résistance mesurée de manière statique sur le pieu à refoulement n'a pas apporté satisfaction, ce qui doit encore être étudié plus en détails avec de nouveaux essais de chargement.

1 QUALITY MONITORING IN REAL TIME

Digital networking makes it possible to provide fleet, fleet management and process data. The system is available around the clock, 24 hours a day, 7 days a week for use worldwide. The aim is to provide the responsible persons with a tool that allows optimization of the operating costs and productivity using real-time data.

The basic technical configuration (on-board unit) consists of the RigController and the M5. The software application "**Q**uality **P**roduction **M**anager "(QPM) serves as the user interface. This software allows Internet access to fleet data. A PC, tablet or smartphone supporting one of these browsers can be used as a terminal.

Basic functions were realized for different users to allow interpretation of the data from an economic and technical point of view the. Some examples:

Device management:

- Easy finding of the devices, see Figure 1.

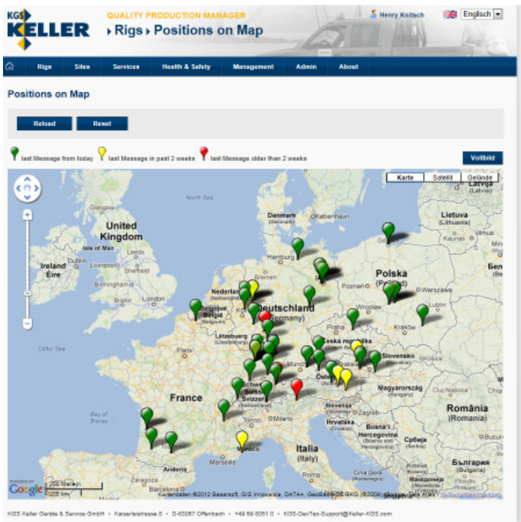

Figure 1. Device overview in Europe

- **Remote maintenance** enables our service technicians to carry out actions on remote devices at any time. The service technician and the device operator simultaneously see the activities on the screen.
- Effective use of disposition of construction plant.
- Monitoring of maintenance intervals and assistance in maintenance planning.
- Identification of idle and incorrect usage times to reduce operating costs.
- Reduction in rental costs of third-party devices.
- Theft protection: Establishment of geofence sectors for areas.

Site management:

- Automatic generation of accurate reports for site-relevant accounting purposes.
- Automatic documentation of installation protocols.
- Checking and warning of production parameters.
- Generation of CAD plans for the visualization of achieved construction progress.
- In **Quality Management** it is possible to check any production parameter such as depth, pressure, quantity, etc. A range of values for the checks can be defined for the site. The alarm can be sent via the email system.
- For **Claim management,** evaluations can be provided of downtime, unnecessary transfer operations resulting from obstruction on site, or documentation on obstacles encountered during drilling.

Today's construction industry faces enormous demands. Increasingly complex construction projects must be implemented in ever shorter time spans. At the same time, intense competition in the industry is generating significant pressure on costs. These demands can only be met by universal use of digital technologies.

2 RESULT VERIFICATION

2.1 Background and scope of testing

In Constance, within the framework of a planned construction project, the opportunity arose to construct test columns and examine these with regard to their bearing capacity. We examined full-displacement concrete piles (FDP), vibro-concrete columns (VCC) and vibro-mortar columns (VMC), which differ mainly in terms of their manufacturing process and material quality. In addition to the axial static loading tests, dynamic loading tests were conducted on the columns, and these were summarised, evaluated, and compared in separate reports. In addition, a static axial tensile test on a FDP was planned to provide information on the ratio of the column skin friction to the total bearing capacity.

2.2 Soil conditions

The test site is located approximately 120 m north of the Rhine bank of the lake in a mixed industrial estate with residential development to the north. It is mostly flat. The ground surface is partly sealed with asphalt and concrete residues. An approximately 3 m-thick fill layer overlies fine sandy clays with soft to very soft consistency (Eisele 2008). Boulder clay of stiff to hard consistency is not encountered until a depth of about 25 m below ground level. Groundwater was encountered near the surface because of sandy strata embedded in the clays.

The following figure shows the result of a cone-penetration test conducted in the area of the test field. The undrained cohesion is in excess of 20 kPa.

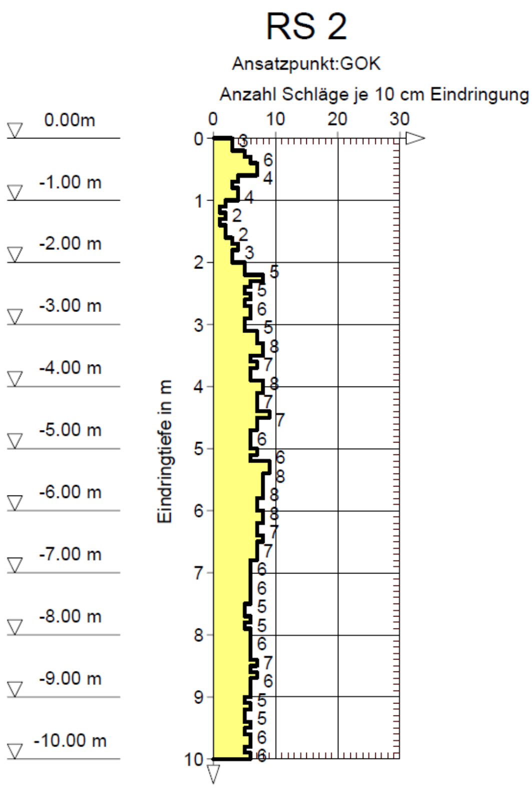

Figure 2. Result of a heavy-cone penetration test near the test field (extract from the geotechnical report)

2.3 Column systems

The static axial loading tests were performed on 3 different types of columns.

1. Displacement concrete pile (FDP)
2. Vibro-concrete columns (VCC)
3. Vibro-mortar columns (VMC)

All types of columns are constructed as unreinforced concrete elements with full soil displacement. A "full-displacement auger" is used in the construction of the displacement concrete piles according to DIN EN 12699, also named rigid inclusions; this displaces the in-situ soil laterally and subsequently fills the resulting void with a pumpable concrete. The norm requires a minimum spacing between columns of 6 to 10 times the column diameter, a minimum reinforcement for unplanned loads, and an undrained soil cohesion of at least 15 kPa.

Both the vibro-concrete columns and the vibro-mortar columns are made using a depth vibrator in accordance with a permit issued by the Deutsche Institute für Bautechnik (German Institute for Construction Technology, Agrement Board). The concrete for the vibro-concrete columns is pumped in via a side-mounted pipe, whereas the vibro-mortar columns use a lean concrete "tamped" by a bottom-feed vibrator.

In contrast to non-displacement pile systems, such as bored piles, the achievable column diameter depends significantly on the ease with which the in-place soil can be laterally displaced. This effect can lead to fairly large diameter differences within a column, especially in the case of VMC. For the FDP and the VCC, column diameters are taken as being not greater than the diameter of the full-displacement auger or of the depth vibrator. As a rough check, the column diameter can be back-calculated from the volume of material used.

Overview of the column systems				
	FDP	FDP (tension)	VCC	VMC
chosen average column diameter [m]	0.35	0.35	0.45	0.55
Column length [m]	15.00	18.00	15.00	11.00
Column material	C20/25, F3, 32 mm, XC3			240 kg/m³ binder, CEM I-III 32,5, Particle size 2/4-32

Table 1. Details of the various pile/column systems

2.4 Static test set-up

The test load was applied using a manual hydraulic press. The reaction beam is a traverse of steel girders, see Figure 3.

In addition to the hydraulic-press pressure, with which the respective test load is controlled, the applied load can also be monitored at two load cells. The settlement or heave of the pile head is registered by electronic transducers. Measuring beams are installed as a reference system for the displacement measurement.

The ultimate limit state (GZ1) is considered to be achieved when one of the following criteria is met:

a) The settlement limit of 0.1 times the column diameter is reached.
b) The creep k_s exceeds 2 mm.
c) The ultimate limit state of the pile material is achieved.

Figure 3. Static loading rig

2.5 Dynamic test set-up

To verify the static axial bearing capacity, impact tests were performed by GSP Ltd. on seven test columns using the "High-Strain" method; these were evaluated according to the "CAPWAP" procedure (CASE Pile Wave Analysis Program) with system identification ("Extended procedure" or "procedure with complete modelling" in accordance with EAPfähle 2012). The results of the static loading tests were not available at the time of evaluation of the dynamic load tests.

In the dynamic load testing, the bearing capacity is determined separately for skin friction and tip load from the measurement of strain and acceleration at the pile head by applying the one-dimensional wave theory. In addition, the loading of the piles or columns, and the applied energy, are recorded.

A free-falling weight with a mass of approximately 10 t was used to apply the impact loads in the dynamic-load testing (Figure 4). Using different drop heights, several blows were applied and the permanent settlement from each impact was recorded on site.

Figure 4. Free-falling weight for dynamic loading tests

To measure the strains and accelerations generated by the impacts, two transducer pairs were mounted on opposite sides of the prepared column heads. The strain gauges and accelerometers used were supplied by Pile Dynamics Inc., Cleveland, USA, and are designed for high dynamic loading; they have a measuring range of ± 3,000 µm/m and 5,000 g and are calibrated at 2-year intervals.

At the time of testing, the column concrete was cured and 36 - 42 days old.

2.6 Test results

To capture the load behaviour in the dynamic testing, a column-soil model was made for each column using the CAPWAP procedure. Here, the soil was divided into 1 m-thick layers. The activated static bearing loads are given in Table 2 as mean values per column type and compared with the values measured during static testing.

	VBP	**BRS**	**BSS**
Mean column diameter	0.35 m	0.45 m	0.55 m
Column length	15.00 m	15.00 m	11.00 m
Static limit load-bearing capacity (limit value)	720 kN	1,000 kN	680 kN
Static limit load-bearing capacity (creep value)	560 kN	850 kN	560 kN
Dynamically activated load-bearing capacity	840 kN	830 kN	595 kN
Column length (dynamic test)	15 & 18 m	15 & 16 m	11 m

Table 2: Test columns and determined loads

2.7 Comparison of column systems, calibration and geotechnical evaluation

For the displacement concrete pile FDP, the difference between the dynamic and static load capacity of about 10% (same column length) to about 30% (3 m longer column in the dynamic test) is not satisfactory. In contrast, the differences for the vibro-concrete columns (VCC) and the vibro-mortar columns (VMC) of max. 5 % dynamic/static load were very good. Presumably, the excess pore-water dissipates faster with the dynamic installation method, and this therefore leads to realistic loads.

The following figures show first of all the load-displacement curves of the FDP and the VMC from the static test (dashed lines). In addition, the curves reduced by the creep settlement (solid lines) are shown, and in each subsequent figure the comparable load-displacement curves computationally determined from the dynamic test by complete modelling. Furthermore, the loads corresponding to the two limit-load definitions from the static test are indicated numerically.

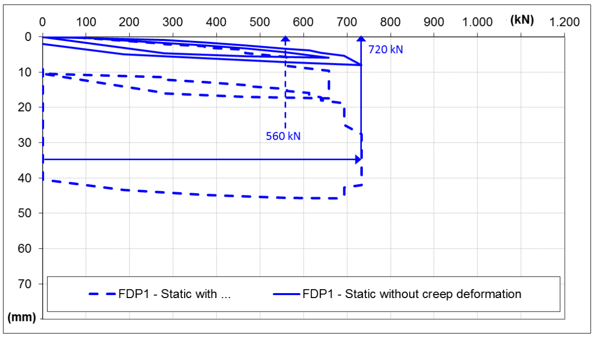

Figure 5. FDP static with and without creep deformations

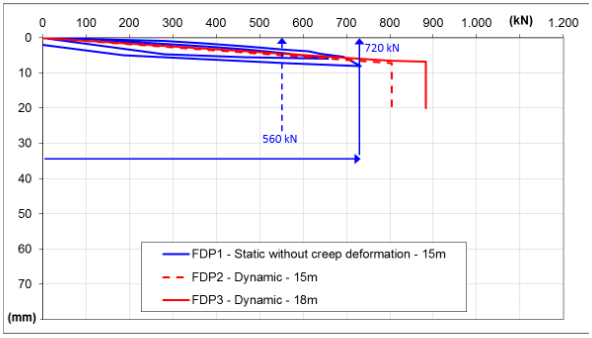

Figure 6. FDP dynamic and static without creep deformations

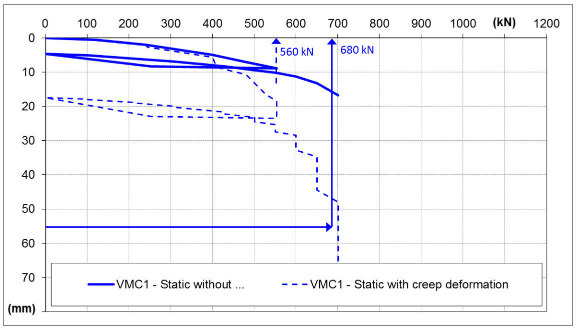

Figure 7. VMC static with and without creep deformations

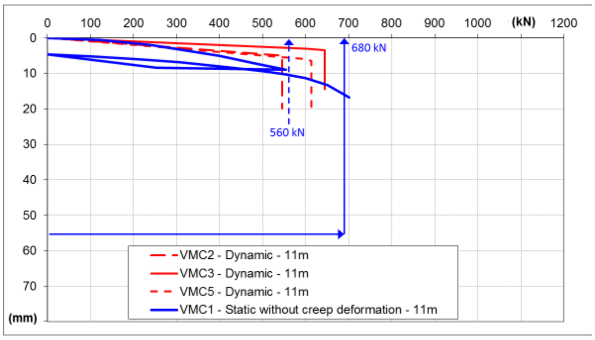

Figure 8. VMC dynamic and static without creep deformations

The complexity in the calibration of the results of dynamic loading tests with those of static loading, as required by the Standards, is described in illustrative examples by Klingmüller, O., Schallert, M. (2012) and Klingmüller, O. (2013). In this project

- ✓ the limit load was reached with both methods (static and dynamic),
- ✓ creep under static load was taken into account mathematically,
- ✓ comparable deformations at service load were reached and
- ✓ generally, good agreement between the results was achieved.

In addition, several dynamic tests in a single construction area show inhomogeneities in the soil and thus contribute to an increase in the safety of the structure. In future, this additional safety should be taken into account when discussing the updating of standards in respect of the scatter factors to be applied for static and dynamic tests on a construction project.

3 SUMMARY AND OUTLOOK

In Konstanz, full-displacement concrete piles (FDP), vibro-concrete columns (VCC) and vibro-mortar columns (VMC) were installed and tested for their load-bearing capacity in the lacustrine clay. In their manufacture, an on-line quality monitoring and verification system was used during installation to monitor productivity.

Using floating construction of the columns/piles, high axial limit loads of up to 850 kN were achieved. This shows amazing potential in comparison with previously estimated loads of only half this figure.

For vibro-concrete columns and vibro-mortar columns, axial static and dynamic test loads agree very well, with a deviation of only 5 %; they are thus suitable for these foundation elements. And this example also demonstrated that dynamic load testing is also applicable in cohesive soils.

The fairly large difference to the statically determined load on a full-displacement pile was unsatisfactory.

Further research will have to determine whether the excess pore-water pressure dissipates faster during dynamic installation due to the tumbling motion of the depth vibrator, and thus leads to realistic loads. To this end, a comparison of static and dynamic analysis with the Finite Element Method is planned soon. This will allow the influence of pore water in cohesive soils to be considered. The results of this research, which will require validation by field tests, should provide useful information for further development of the recommendations of the Working Group on piles regarding dynamic load testing as a function of the evaluation method for cohesive soils.

4 REFERENCES

Eisele 2008. *Baugrund- und Gründungsgutachten*. Dr. Eisele Ingenieurgesellschaft mbH. Konstanz, 31.01.2008, internal report.

Klingmüller, O., Schallert, M. 2012. Resistance factors for high-strain dynamic testing regarding German application of Eurocode 7 and correlation of dynamic and static pile tests, *Proceedings of IS-Kanazawa 2012: The 9th International Conference on Testing and Design Methods for Deep Foundations, Kanazawa, Japan*, 18-20 September, 2012.

Klingmüller, O. 2013. Vorgaben des EC7 für Dynamische Pfahlprobebelastungen und Regelungen im Deutschen Normenhandbuch - Vorschlag zur Vereinfachung, *Geotechnik,* Volume 36, Issue 1, 3-9. March 2013.