Observation of Pile-Soil-Interaction during Cyclic Axial Loading using Particle Image Velocimetry

Hans-Georg Kempfert[1], Sebastian Thomas[2], Berhane Gebreselassie[3]

Institute of Geotechnics and Geohydraulics, University of Kassel, Germany
[1]geotech@uni-kassel.de; [2]sebastian.thomas@uni-kassel.de; [3]berhaneg@uni-kassel.de

ABSTRACT: Two phenomena characterize cyclic axial loaded piles: accumulation of plastic pile displacements and degradation of pile capacity with increasing load cycles. The reason for this complex pile-soil-interaction is still not well understood. Hence, load and displacement controlled small-scale model pile tests were performed to investigate pile and soil behaviour from a qualitative point of view. Particle Image Velocimetry (PIV) was used to visualize the grains movement near the pile. A volume change was generally observed in all the tests depending on the mode of cyclic load. Shear localization appears in a small shear zone parallel to the pile shaft and remains approximately constant with increasing load cycles. Next to the shear zone a shear band can be observed which expands outwards with increasing load cycles. Moreover, a different pile and soil behaviour was observed under cyclic load compared to the static load test.

INTRODUCTION

The phenomena of accumulation of plastic displacements and degradation of pile capacity with increasing load cycles is observed in many field and model tests, e.g. Kempfert/Lauffer (1991), Lehane et al. (2003) and LeKouby et al. (2004). It is known that the reduction in pile skin friction is a reason for the degradation of pile capacity. In this research work, small-scale model pile tests on bored piles were performed to identify the mechanisms of pile-soil interaction during cyclic axial loading based on Particle Image Velocimetry (PIV). The program VidPIV (ILA 2004) was employed to visualize grain movement near the pile.

PIV was developed originally for flow field measurement of gaseous and fluid media in the field of hydromechanics. In geotechnical engineering it has been successfully employed to assess deformation fields in granular soils (White/Bolton 2004, Hauser 2005).

The quality of the test results obtained by PIV analysis depends on the accuracy of the measurement. However, it must be noticed that exact measurements are not possible due to systematic and random errors as defined in DIN 1319-1:1995-01. These errors were studied systematically with a different testing program and the error is estimated to be about 0.03 mm. This seems sufficient enough for a qualitative analysis of the small-scale model test results.

EXPERIMENTAL PROGRAM

Testing setup and procedure

Small-scale model pile tests were performed using a 60 cm high, 40 cm long and 20 cm deep box. The front side of the box is made of 15 mm thick Plexiglas wall whereas all the other sides are made of steel sheets. A groove of 3 mm was cut into the Plexiglas to avoid intrusion of sand grains between the wall and the pile. A quadratic model steel pile (7.5 x 7.5 cm) with rough surface (surface injected with model sand) was used. A void was left below the pile tip in order to avoid the influence of base resistance. After inserting the pile, a dry silica model sand with grain size of 0.064 to 4.00 mm ($d_{50} = 0.5$ mm, $e_{min} = 0.48$, $e_{max} = 0.84$) was placed and compacted by tamping to reach a medium density ($I_D \approx 0.5$). A surcharge of 20 kPa was applied on the surface using a rigid wooden plate. The cyclic axial load had been applied using a hydraulic press at a loading frequency of 1 Hz. After every 10 load cycles, the cyclic loading was stopped and a picture had been shot using a digital camera with a resolution of 3456x2304 pixels. It is assumed that the observed grain movement around the pile (spatial) are the same as that on the front wall (plane condition).

Testing program

One static displacement-controlled tension test (PIV-01) was performed to evaluate the ultimate static pile resistance R_{ult} and the corresponding pile displacement in order to allow a comparison of grain movement with cyclic tests. Furthermore, one displacement-controlled test (PIV-02) was carried out with cyclic amplitude of $s' = 0.25$ mm and up to 100,000 load cycles. Finally, five load-controlled tests with cyclic load level of $F_{cycl} = 0.4$ kN (double amplitude) and different average load levels F_{avg} from -0.2 kN to 0.2 kN were conducted to identify pile and soil behaviour under different cyclic loading modes (Table 1).

Table 1. Testing program of the load-controlled tests

Test no.	Load mode	F_{avg} (kN)	F_{cycl} (kN)
PIV-03	symmetric two-way	0	0.40
PIV-04	unsymmetric two-way tension	0.1	0.40
PIV-05	unsymmetric two-way compression	-0.1	0.40
PIV-06	one-way tension	0.2	0.40
PIV-07	one-way compression	-0.2	0.40

TEST RESULTS

Soil behaviour in displacement-controlled test

Fig. 1a shows velocity vectors after 100 load cycles evaluated using PIV analysis for the test PIV-02. Different grain movement along the pile causes strain localization near the pile. These shear strains (Fig. 1b) are derived from the velocity field shown in Fig. 1a. Hence, they can be positive or negative depending on the direction of the velocity field in global coordinate system. It can be seen from Fig. 1b that there is a development of a thin shear zone near the contact area between pile and soil. Next to it, a shear band can be observed. There is a high concentration of shear strains in the shear zone and relative a small concentration in the shear band. Outside these two regions no shear strains are observed. The width of the shear zone remained constant at $d_{SZ} = 10\,d_{50}$ with increasing load cycles, whereas the width of the shear band increased with the number of cycles and reaches 100 d_{50}.

Segregation of grains was observed after 100,000 load cycles in the shear zone in the upper third part of the pile as indicated in Fig. 2a. This might be the result of particle breaking and migration of fine grains downwards. Such segregation of particles may be the reason for the different stress-strain relationship during cyclic loading. Even at low stress level in the small-scale tests, the breaking of particle seems possible, in particular by large number of load cycles. A similar phenomenon was observed from results of cyclic triaxial tests by Donohue et al. (2009). The influence of abrasion seems to be not relevant, since a washed rounded model sand was employed.

The net grain movements after every ten load cycles were evaluated and shown in Fig. 2b. The accumulation of the grain movement results in decreasing void ratio which in turn causes compaction of the soil.

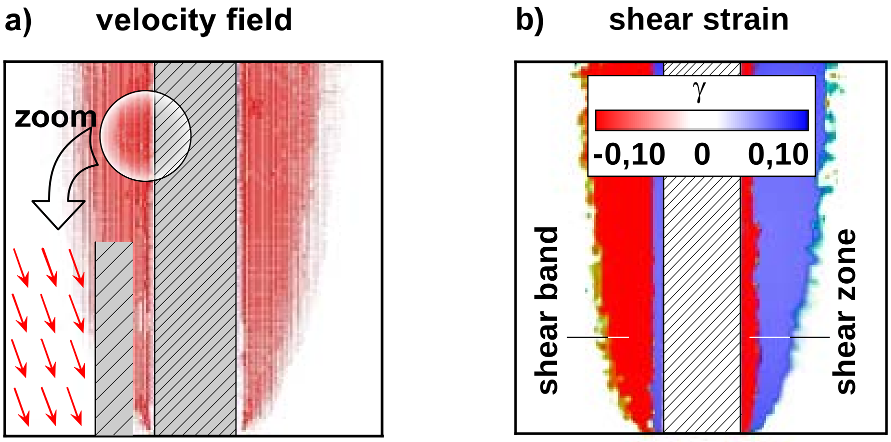

**FIG. 1. a) Velocity vectors after 100 load cycles for test PIV-02,
b) shear strains derived from velocity vectors**

Soil behaviour in load-controlled tests

Similar soil behaviour was also observed in the load-controlled tests. The cyclic loading results in soil compaction near the pile in the tests PIV-03 to PIV-05 and PIV-07. A shear zone was developed during the first 10 load cycles and remained constant with further load cycles. The width of the shear zone was approximately 4 to 12 mm (Fig. 3b), and depends on the mode of cyclic loading. The width of the shear zone is smaller in one-way tests than in two-way tests. The shear band extends further with the number of load cycles but it also remains smaller in one-way test.

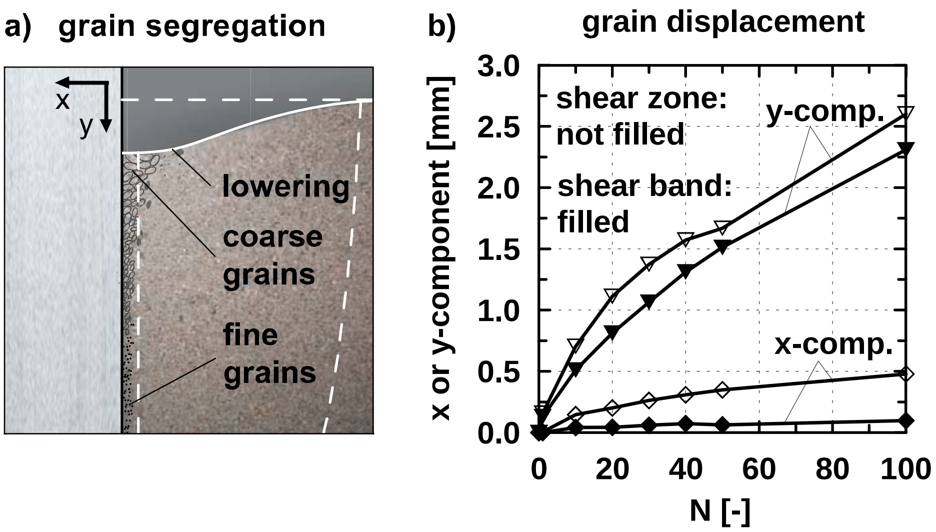

FIG. 2. a) Grain segregation in the shear zone, b) grain movement parallel or perpendicular to the pile shaft

Different soil behaviour was observed in the one-way tension test PIV-06. Like in the static tension test a dilatant soil behaviour was observed. No shear zone was developed near the pile. However, the width of the shear band is slightly larger than from the static test at pile failure. The shear strains registered are also larger as compared to the shear strains in static tests as well as two-way tests. Similarly, the width of the shear band is smaller than in two-way tests (Fig. 3b).

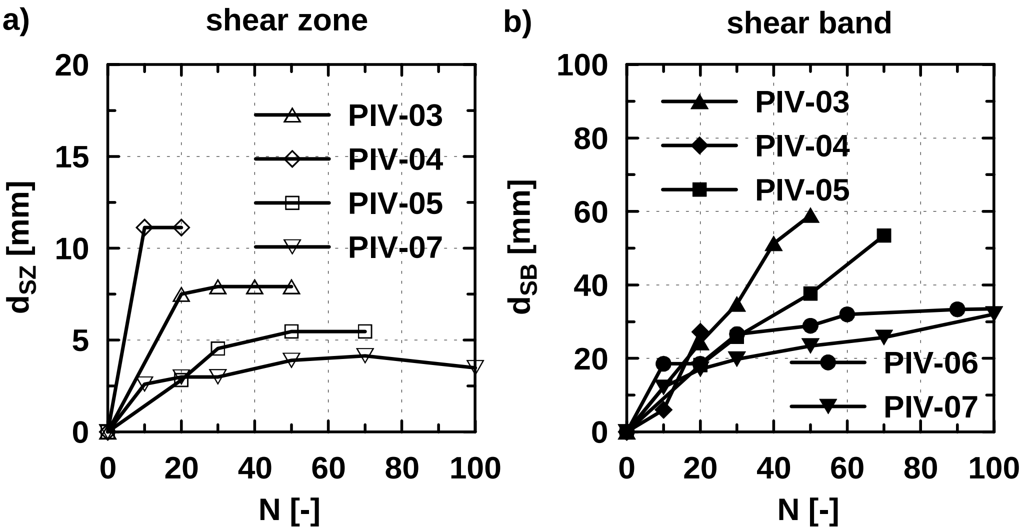

FIG. 3. Development of a) shear zone and b) shear band

Pile behaviour under cyclic loading

The ultimate pile resistance (in tension) in the static test PIV-01 was determined to be R_{ult} = 0.53 kN and the corresponding pile displacement is s = 1.5 mm. It is assumed that the pile failed under the cyclic loading if the pile displacement exceeds s = 1.5 mm. The number of load cycles N_f at failure depends on the mode of cyclic load as indicated in Table 2. All tests failed by pull out except test PIV-07 which is not failed after 1,000 load cycles. As it can be seen in Table 2, the two-way tests failed generally earlier than one-way tests.

Table 2. Pile failure at load cycle N_f in load-controlled tests

Test No.	Load mode	N_f
PIV-03	symmetric two-way	50
PIV-04	unsymmetric two-way tension	20
PIV-05	unsymmetric two-way compression	80
PIV-06	one-way tension	90
PIV-07	one-way compression	not failed after 1,000

There is an accumulation of plastic pile displacements in one-way tests (Fig. 4a). The test PIV-07 shows a cyclic stability and it was not failed after 1,000 load cycles, while test PIV-06 shows a cyclic failure after approximately 90 load cycles. The elastic pile displacements s_{el} are constant with increasing load cycles. Therefore, the cyclic pile stiffness ($k = F_{cycl}/s_{el}$) remains constant (Fig. 4b).

The rate of increase of plastic pile displacements s_{pl} is slower at the beginning in two-way tests than one-way tests. However, after only a few load cycles the plastic displacements are increased rapidly until pile failure. The elastic pile displacements were getting larger in these tests and hence a decrease in cyclic pile stiffness with increase of load cycles (Fig. 4b). Such pile behaviour was also observed from field tests by Karlsrud et al. (1986).

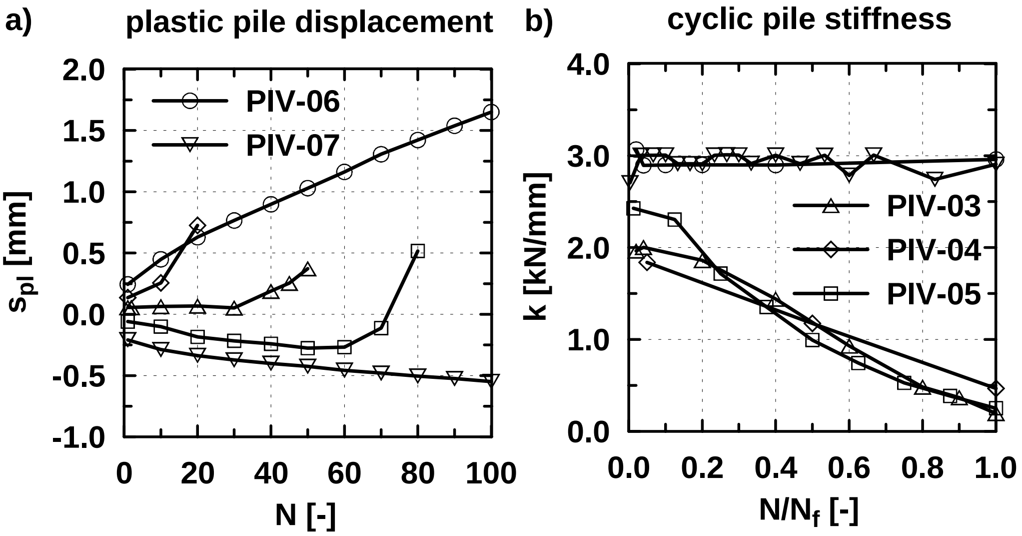

FIG. 4. Pile behaviour in one-way and two-way tests: a) plastic pile displacement and b) cyclic pile stiffness (Note: the legends are for both diagrams)

CONCLUSIONS

The paper presents some results of displacement and load controlled cyclic small-scale model pile tests in medium dense dry sand. The grain movement was visualized using PIV. It was observed that the pile and soil behaviour depends mainly on the mode of the cyclic load. Moreover, a compaction of soil near the pile mostly occurs during cyclic axial loading. Only during one-way tension test a dilatant soil behaviour was observed. Shear localization occurs in a small shear zone near the pile shaft, whose width remains constant with the number of load cycles. Next to the shear zone a wider shear band was observed, whose width grows further with increasing cyclic loading.

The investigation in this research work helps to better understand the different hypothesis in the literature regarding the pile-soil interaction behaviour under cyclic axial loading. Furthermore, the paper shows that there is no a single conceptual model for the pile behaviour under cyclic loading. The research project is not yet concluded and new findings will be published in the future.

ACKNOWLEDGMENTS

The authors would like to thank the German Research Society (DFG) for the financial support of this research.

REFERENCES

DIN 1319-1:1995-01. "Grundlagen der Messtechnik - Teil 1: Grundbegriffe." *Deutsches Institut für Normung*.

Donohue, S., O'Sullivan, C. and Long, M. (2009). "Particle breakage during cyclic triaxial loading of a carbonate sand." *Geotechnique*, Vol. 59 (5): 477-482.

Hauser, C. (2005). "Boden-Bauwerk-Interaktion bei parallel-wandigen Verbund-systemen." *Berichte des Lehr- und Forschungsgebietes Geotechnik, Bergische Universität Wuppertal*, Nr. 29, Dissertation.

ILA (2004). "Introduction to VidPIV - User Manual." *ILA - Intelligent Laser Applications GmbH*, Juelich.

Karlsrud, K., Nadim, F. and Haugen, T. (1986). "Piles in clay under cyclic axial loading - Field tests and computational modelling." *Proceedings of the 3rd International Conference on Numerical Methods in Offshore Piling:* 165-190.

Kempfert, H.-G. and Lauffer, J. (1991). "Pfahlprobebelastung in weniger tragfähigen Böden unter statischer und wechselnder Belastung." *Geotechnik*, Nr. 14: 105-112.

Lehane, B.M., Jardine, R.J. and McCabe, B.A. (2003). "Pile group tension cyclic loading: Field test programme." *Imperial College Consultants (ICON)*, Research Report Nr. 101.

LeKouby, A., Canou, J. and Dupla, J.C. (2004). "Behaviour of model piles subjected to cyclic axial loading." *Proceedings of the International Conference of Cyclic Behaviour of Soils and Liquefaction Phenomena*, Bochum: 159-166.

White, D.J. and Bolton, M.D. (2004). "Displacement and strain paths during plane-strain model pile installation in sand." *Geotechnique*, Vol. 54 (6): 375-397.