Measuring Time Dependent Stress-Changes around a Driven Pipe Pile in Medium Dense Sand

Mussie Kidane [i)], Philipp Stein [i)]

[i)] Scientific Staff, Federal Waterways Engineering and Research Institute (BAW), Wedeler Landstrasse 157, 22559 Hamburg, Germany.

ABSTRACT

Time dependent changes of pile capacity in sands are often attributed to a decrease of arching effects in the surrounding soil following pile driving. This effect is assumed to lead to a gradual increase of radial stresses acting on the pile shaft and thus on an increase in pile capacity. This time dependent increase is referred to as pile setup. As part of an R&D project of Germanys Federal Waterways Engineering and Research Institute (BAW) one open ended pipe pile was equipped with combined total stress and pore water pressure sensors in order to investigate effective stress changes over a measurement period of almost 5 years. Additionally, after 28 months, two pairs of strain transducers and accelerometers were installed at the pile head and toe for stress wave measurements during pile installation and re-driving. The pile was driven at a harbour site that is subject to tidal water level changes. The measurements revealed a decrease rather than an increase in radial stresses, all though the pile capacity increased over time following evaluation of the stress wave measurements.

Keywords: pipe piles, setup effect, soil stress measurements, pile driving monitoring

1 INTRODUCTION

A number of case studies on driven piles have reported a marked increase of the load bearing resistance with time (Tavenas and Audy, 1972), (Fellenius et al., 1989), (York et al., 1994), (Long et al., 1999), (Bullock et al., 2005) and others. This time dependent increase is referred to as pile setup. This effect is often associated with the dissipation of driving induced pore water pressures for cases in fine grained soils. Its main cause in coarse grained soils however, still remains unclear. A number of theories do exist but currently lack clear evidence from field test data. One theory suggests that a progressive decrease of arching effects following driven pile installation is associated with the increase of the piles load bearing resistance (Chow et al., 1997). (Alawneh and Sharo, 2018) link these arching effects to the phenomenon of friction fatigue (Heerema, 1980) taking place at pile penetration.

The arching effects are assumed to act in tangential direction to the pile length axis and are induced by the pile driving process. They shield the radial stresses from acting onto the piles shaft. Other theories point towards a tendency of strength and stiffness increase following driving induced soil disturbance or other phenomena related to chemical processes (Suarez, 2012).

As part of an ongoing R&D project of the German Federal Waterways Engineering and Research Institute (BAW) one open ended pipe pile (D = 0,711 m) was equipped with combined total stress and pore water pressure sensors as well as accelerometers and strain transducers. The pile – used as a dolphin – was installed at the naval port of Wilhelmshaven, Germany. Pile driving monitoring was performed during pile installation and during re-driving after a waiting period of approx. 28 months. The combined total stress and pore water pressure sensors have generated recordings within and after the waiting period for a total duration of approx. 54 months.

2 SITE CONDITIONS AND PILE SETUP

The port of Wilhelmshaven is Germanys biggest naval port. It is located in the north west within the state of Lower Saxony towards the North Sea. The port is undergoing a substantial overhaul associated with major construction works including a 2,2 km quay wall and the installation of dolphins and piles for its floating bridges (Matthiesen and Eickmeyer, 2015).

The ground conditions are primarily governed by alluvial mud (silt) underlain by coarse grained soils (sand) within the penetration depth of the pile. The sand has a loose to medium density which was explored by cone penetration tests, see Fig. 1.

An open-ended tubular pile with a diameter of 0,711 m was instrumented with combined earth pressure/pore water pressure sensors by GLÖTZL, see Fig 4.

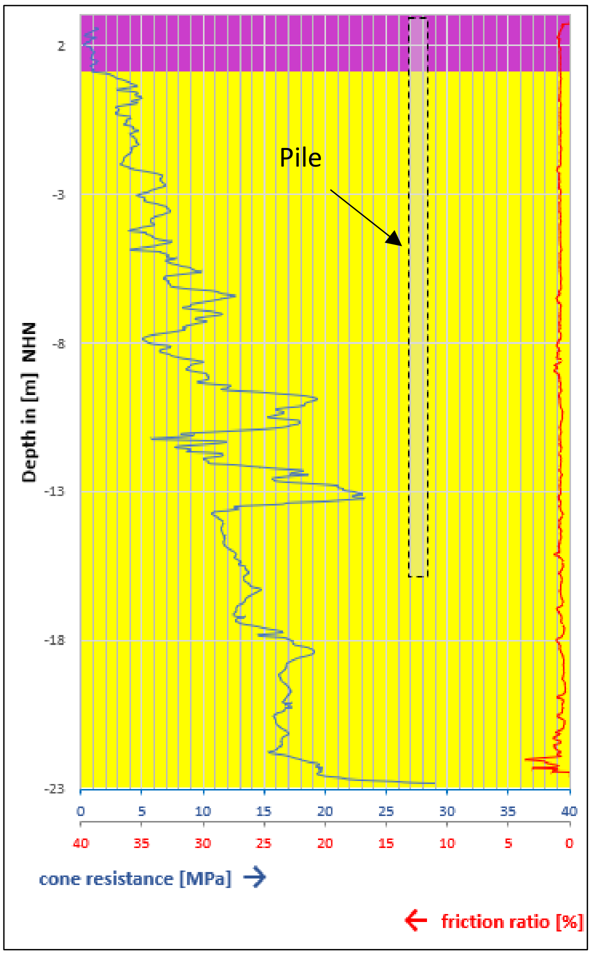

Fig. 1. Readings from cone penetration test as well as ground conditions – silt in purple and sand in yellow colour.

The pile was driven to an embedment depth of 15,15 m below ground. The pile had a constant outer diameter but varying pile wall thickness ranging from 16 to 30 mm.

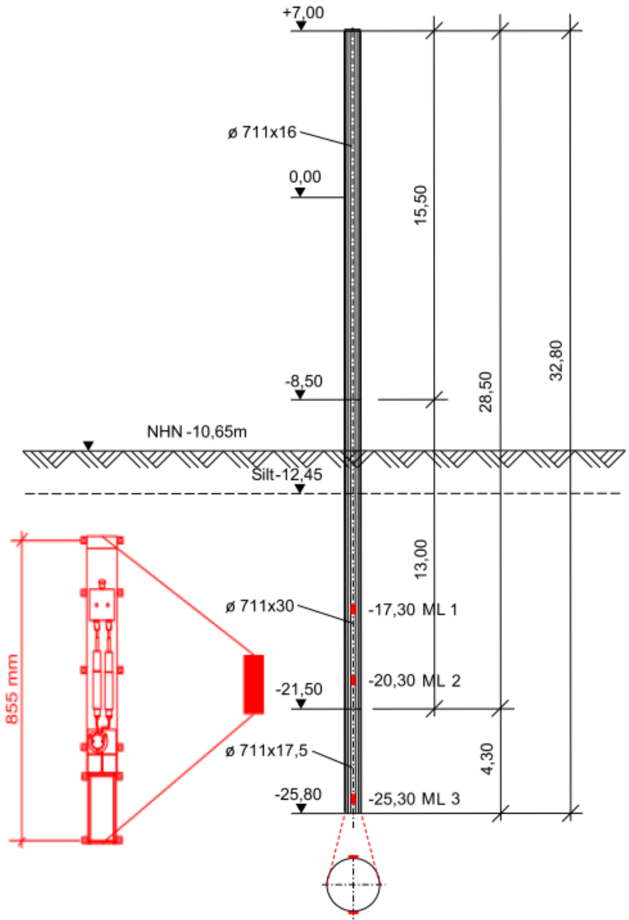

Fig. 2. Pile including combined earth pressure/pore water pressure sensors (6 outside and 4 at the inner pile shaft).

3 MEASUREMENT SETUP

During pile installation and a restrike test, pile driving monitoring was carried out using the Allnamics Pile Data Recorder (PDR) with two pairs of strain sensors and accelerometers at the pile head and pile toe, each.

After pile installation, a long-time monitoring of total radial soil stresses and pore water pressure was carried out on the inside (ML 2 and ML 3) and outside (ML 1-3) on opposite sides of the pile's shaft. Therefore, combined sensors supplied by GLÖTZL were used. The sensor cables and an inclinometer tube for later lateral testing were protected using a screwed-on steel profile, see Fig. 4 (picture at the bottom). The following figure shows an exemplary drawing of a sensor mounted on the outside (convex) pile wall.

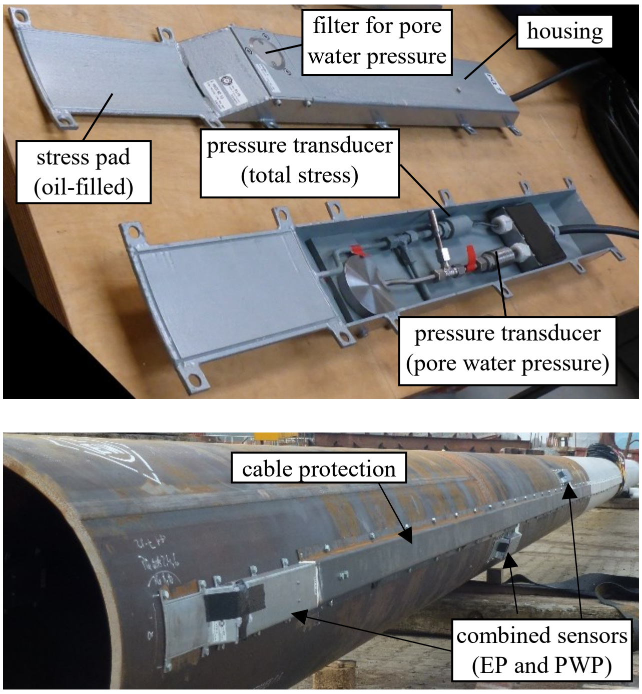

Fig. 3. Combined earth pressure and pore water pressure sensor (GLÖTZL Gesellschaft für Baumesstechnik mbH).

For the data acquisition, a Sisgeo OMNIAlog datalogger was used. On top the solitary dolphin, the power supply of the data acquisition unit was ensured over a period of 5 years by a solar panel in combination with a 100 Ah battery, see Fig. 5.

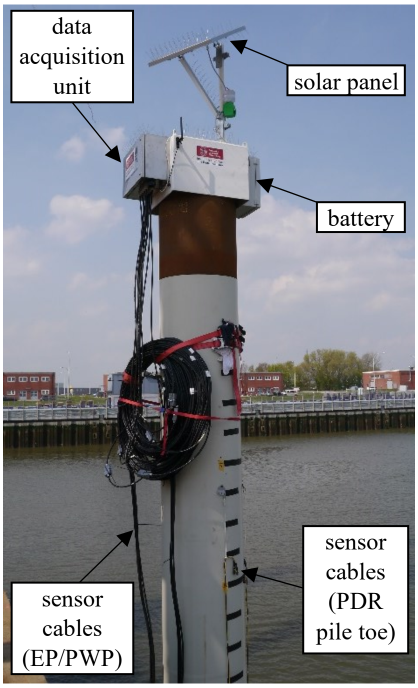

Fig. 4. Monitoring equipment on dolphin after pile installation.

During penetration a plate inside the pile that was tied to a rope was used to measure the plug length during driving.

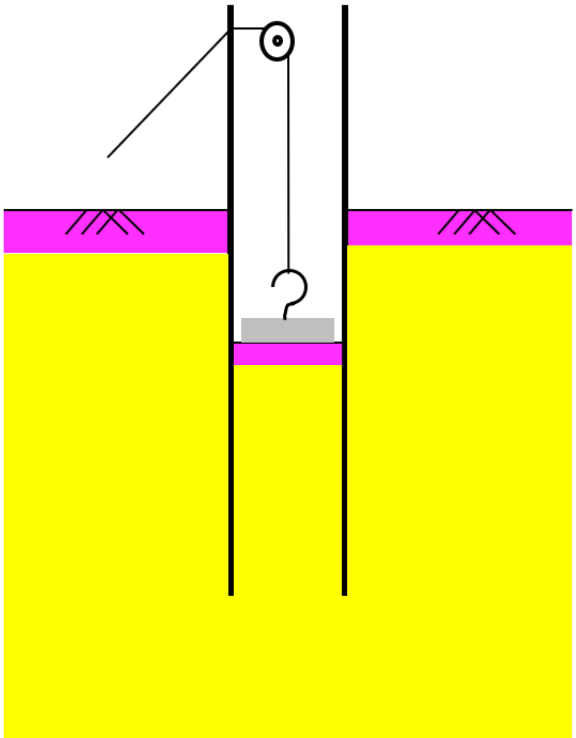

Fig. 5. Pile including plug length measurement

Instrumentation and measurements were conducted by the Institute of Foundation Engineering and Soil Mechanics of Technische Universität Braunschweig (IGB-TUBS).

4 PILE DRIVING MONITORING AND ANALYSIS

The following table gives details on the pile installation and Restrike test (IGB-TUBS, 2019). For the Restrike, the same hammer setup and similar driving energy was used.

Table 1. Pile installation and Restrike test parameters.

pile	S202	
type	dolphin	
diameter	711 mm	
wall thickness	16 – 30 mm	
total pile lengths	33.8 m	
type testing	PDM	Restrike
date testing	2016-05-02	2018-09-06
hammer	IHC S-90	
recorded blows	858	8

Signals from one of the last hammer blows of the pile installation (end of initial driving, EOID) and one of the first blows of the Restrike test were analysed using the TNOWAVE (e.g. Middendorp, 2004) method by two independent experts. The following table gives an overview over the signal matching results of EOID and Restrike of different experts (IGB-TUBS, 2016; 2019; Allnamics, 2019).

Table 2. Pile installation and Restrike signal matching results.

test		EOID	EOID	Restrike	Restrike	Restrike
blow		846	852	1	2	3
expert		B	A	B	A	B
W_{msrd}	kJ	28	34	58	47	28
u_{set}	mm	5.3	7.0	1.5	2.5	1.5
R_{shaft}	MN	1.05	1.09	1.98	2.99	1.30
R_{toe}	MN	0.41	0.35	0.57	0.82	0.42
R_{tot}	MN	1.46	1.44	2.55	3.82	1.71

While the EOID results are almost identical, even on the breakdown of shaft and toe resistance, the results of the restrike differ greatly depending on the chosen hammer blow and possibly the assumptions of the analysing expert. This leads to an assessment of the pile setup after 28 months of 18% (expert B, blow 3) to 163% (expert A, blow 2).

The densification adjacent to the pile due to pile plugging was assumed to be very limited due to the results of the measurement from the plug length. The measurement showed almost no relative movement of the soil mass inside the pile compared to the seabed level.

5 EARTH PRESSURE MEASUREMENT AND ANALYSIS

The combined earth and pore water pressure sensors had to undergo large stresses during the dynamic installation process of the pile. The validation of the readings from the sensors was challenging as approx. 50 % of the sensors did not survive the installation procedure itself. The other sensors could not be validated using the original calibration sheets from the manufacturer. Instead they had to be compared with the tidal water level changes. The following Fig. 6 shows a good agreement between water level measured through a buoy externally (dotted black line) and the tidal fluctuations in the measured total stresses as well as pore water pressures. For the visualisation, measurements were corrected for long-time trends (see below) and converted to meters of water level change.

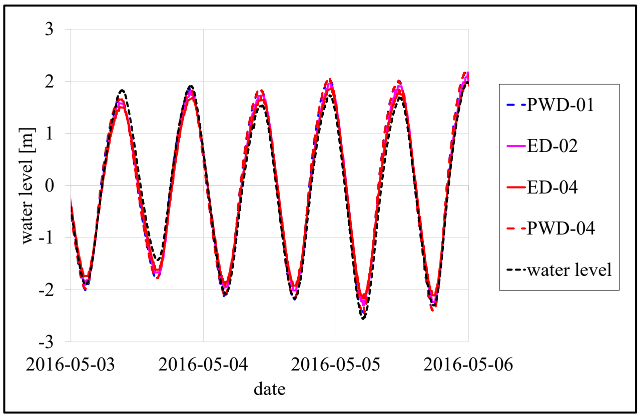

Fig. 6. Results of measured total stresses (ED), pore water pressures (PWD) and water level (black dotted line) over the first few days after pile installation.

The surviving earth pressure sensors all showed a decrease of the radial stresses acting on the pile throughout the entire measurement period. Fig. 7 shows the progression of total stresses measured at ML 1 (ED-02 at the outer pile shaft) and ML 2 (ED-04 outer pile shaft, ED-07 and ED-08 at the inner pile shaft), for location of ML see Fig. 2. (see Fig. 2 for location). All measurements show a general decrease of total stresses. In case of sensor ED-08, a stable value is reached after about 100 days, in other cases the development continues over the whole monitoring period. Some sensors show temporary failures and leaps after the restrike and other unassignable events.

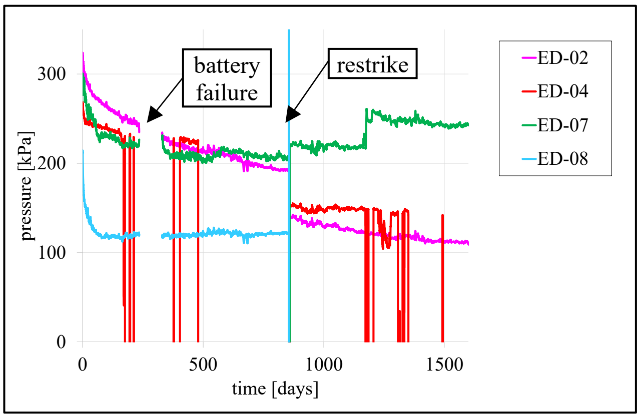

Fig. 7. Results of measured total stresses over the complete measuring period

Fig. 8 shows the development of measured pore water pressured over the same monitoring period. Despite certain scatter and temporary sensor failures, the overall stable course of the pore water pressure is evident. Thus, the abovementioned decrease in total soil stresses can be attributed to the effective stresses and is not a reversal of possible pore water pressure build-ups during pile driving.

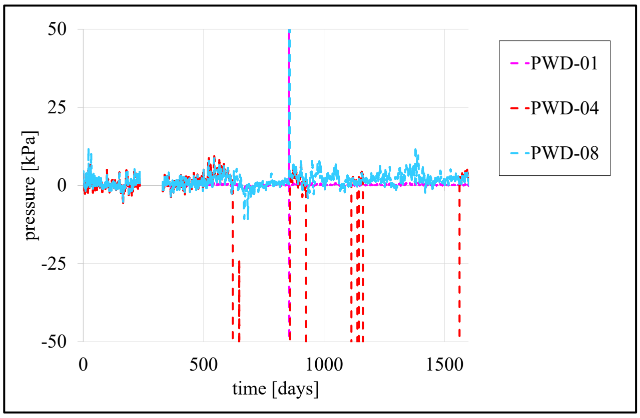

Fig. 8. Results of measured pore water pressures over the complete measuring period

6 DISCUSSION OF RESULTS AND OUTLOOK

The results of the pile driving analyses were compared to estimated pile capacity from Table 2. Here, three different methods were used to predict the characteristic pile capacity based on the empirical relations.

From the three methods used here – NGI-05 (Clausen et al., 2005), UWA-05 (Lehane et al., 2005) and EAP-14 (Moormann and Kempfert, 2014)) the UWA-05 method seems to best fit the results from the dynamic load test during pile installation while the EAP-14 method seems to fit the results from the restrikes best despite the large scatter of the results of these latter load tests.

Table 3. Estimated pile bearing resistance $R_{char,calc}$ based on empirical methods.

Method	NGI-05	UWA-05	EAP-14
$R_{char,calc}$	2.025	1.081	2.509

Looking at the soil stress measurements in comparison to the results of the pile driving analyses after pile installation and restrike, one can state that even though the radial stresses acting on the pile wall decreased over time, the pile capacity increased. Thus, even though a setup effect was witnessed, a decrease of arching effects can be disproved in this case study. This generally challenges the theory attributing a progressive decrease of arching effects following pile installation to pile setup. In contrast to this theory, a decrease of radial stresses acting on the pile was measured. This shows that a clear explanation for the driving mechanism of pile setup in coarse grained soils is not available to date.

A preliminary study on other possible mechanisms that could be used to find explanations for the observed earth pressure measurements and the results from the dynamic load tests based on the Finite Element Method is presently being conducted. A publication on this subject is currently being prepared.

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