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On-site measurements - Dynamic analysis of existing pile response induced by driving of adjacent piles

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ABSTRACT: Franki piles are in-situ concrete driven piles that are installed by driving a heavy steel pipe into the ground with the aid of a pile driver. This causes considerable vibrations, which lead to wave propagation in the ground. When installed in groups, pile driving vibrations transmitted through the ground may impair the curing process of the young concrete of neighbouring piles that have already been installed. In order to investigate this problem, a large-scale field study was carried out. This study presents metrological investigations into the production of in-situ concrete piles (Franki pile type) with different lengths and diameters in a test field in Hamburg, Germany. Several Franki piles were installed in groups within the investigated construction area. The reinforcement of the piles was instrumented with strain gauges and accelerometers at different depths as part of an accompanying metrological investigation to record the impact of vibrations on the existing piles as a result of a neighbouring pile installation. The measurement results are presented and discussed focusing on the wave propagation through the subsurface and the vibrations affecting the concrete of the adjacent pile.

1 INTRODUCTION

Among various foundation installation techniques, pile driving remains one of the most effective methods for ensuring deep load transfer in challenging soil conditions. In the impact pile driving process, a heavy tool (i.e., hammer) is dropped on the pile or ground to drive the pile into the unexcavated ground. As a result, the soil particles are displaced in a limited area around the installed pile depending on the installation method chosen (Fleming et al., 1992). Several studies and practical examples (Nataraja and Cook, 1986, Hwang et al., 2001, Siegel et. al., 2007, Stuedlein, 2016, Rooz and Hamidi, 2019) can be found stating that pile driving also improves the ground condition around the pile.

2 PROBLEM STATEMENT

Franki piles are driven cast-in-situ piles with an enlarged base. They are designed and manufactured in accordance with Eurocode 7, DIN EN 12699 and the recommendations of the 'Piles' working group (EA piles). The diameter typically ranges between 42 and 71 cm with common pile lengths from 10 to 25 m. Depending on the existing soil conditions, the piles can bear loads of up to 6000 kN (PORR GmbH & Co. KGaA, 2017). Such piles are usually best suited for installation in granular soils, where the load-bearing capacity is achieved by compaction around the pile base (Prakash & Sharma, 1990).

During the installation of Franki piles the pile driver transfers dynamic forces directly into the ground via a so-called internal pile driving inside a pile driving pipe. After reaching the pile setting depth, the pile-driving pipe is fixed at the head with the help of the carrier, and a concrete seal is hammered out at the base of the pipe. The resulting vibrations can affect the young concrete of the neighbouring piles by disturbing the strength development during curing. Bonzel and Schmidt (1980) found that if concrete is exposed to prolonged vibrations, the degree of strength increase is lower than expected. As piles cannot be visually inspected for possible damage, it is likely that defects caused by such dynamic disturbances during the curing process will remain undetected.

Several studies have been conducted on physical modelling of driven piles to evaluate the evolution of displacement and stresses of the surrounding soil mass (Jardine et al., 2013; Arshad et al., 2014; Jardine, 2014; Doreau-Malioche et al., 2018). There have also been multiple metrological investigations regarding installation of various driven piles (Henke and Grabe 2013, Henke, 2012, Henke and Fischer, 2011, Henke and Grabe, 2007, Henke and Grabe, 2011) to examine the wave propagation in the surrounding soil and in adjacent piles as a result of the driving process.

However, there are limited studies addressing the effect of vibrations on curing of young concrete on a newly installed pile. Most vibration assessments are limited to buildings, civil engineering structures, buried pipes, etc. In principle, vibration measurements are only carried out if there is a particular need for protection of a structure (Kopf, Garbers and Söllhuber, 2015).

To predict vibrations during pile driving, Massarsch and Fellenius (2008) developed a concept and analysed the complex dynamic system of source, medium and receiver (see Figure 1). This concept was, however, only validated for the far field and under the assumption of elastic subsoil behaviour. Furthermore, due to a lack of sufficient experimental investigations in the near field, no standardized regulations on vibration propagation in the subsoil can be made (see DIN 4150-1).

In order to gain a detailed understanding of the effects of pile-driving vibration on early-age concrete, a large-scale field study was conducted. The details of the geotechnical investigation and the results are described in the following sections.

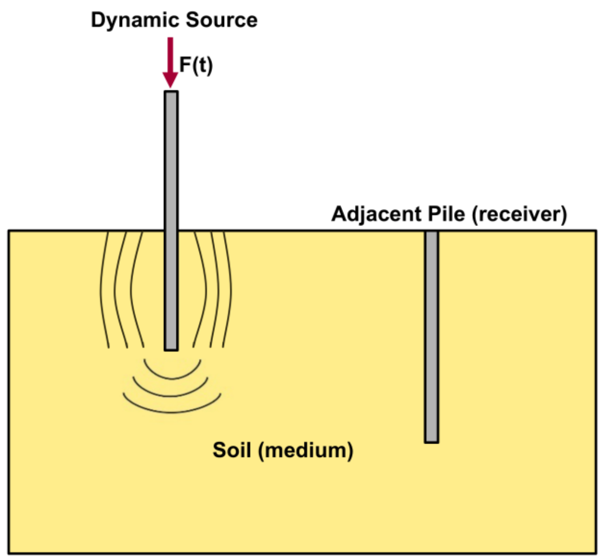


Figure 1. System of impact driven cast-in-situ pile with adjacent pile

3 FIELD TEST DESCRIPTION

The test field under consideration is located at the site of an existing pile load test field, within which various pile systems have been systematically investigated as part of the expansion project for the A26 Hamburg passage in Northern Germany. The piles have been installed by PORR (former Stump-Franki Spezialtiefbau GmbH) GmbH. The vibration propagation tests were carried out as part of this construction project.

3.1 Ground Condition

According to the ground survey, the construction area is characterized by deep deposits of sands, which are overlaid by soft clay layers.

Figure 2 shows a soil profile and the results of cone penetration test (CPT) surrounding the area of the measurements starting from a depth of +2.7 m NHN. It can be seen that, cone resistance value ranges from 14–24 MN/m^2 regarding the sand layer.

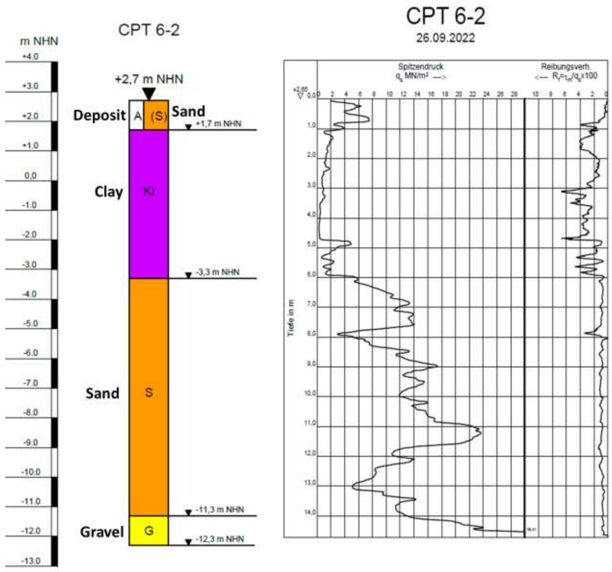


Figure 2. Soil profile and associated Cone penetration test (CPT) results

3.2 Pile installation and layout plan

13 Franki piles have been installed in three different groups (see Figure 3) and with a varying clear distance of 2 m to 5 m between neighbouring piles. The piles contained in each group are listed below:

- Group 1: FP-M.1, FP-D.1 to FP-D.4, FP-S.1 and FP-S.2
- Group 2: FP-M.2, FP-D.5 and FP-D.6
- Group 3: FP-M.3.

In addition, 12 sheet pile walls have been installed in group 3, so that the vibration effects of other pile systems on the young concrete of neighbouring concrete piles are also investigated but these effects are out of scope for the current publication.

3.3 Instrumentation and Measurements

Vertical geophones (HG-6HS) with a natural frequency of 4.5 Hz, and a sensitivity of 78.9 V/m/s were installed on the ground to measure the vertical vibration propagation around the driven piles. The geophones were positioned in two rows at varying distances around the piles (see Figure 4). Since most of the area around the pile installation site was covered with a structural deposit, it was only possible to place the first geophone at 15 metres from the pile.

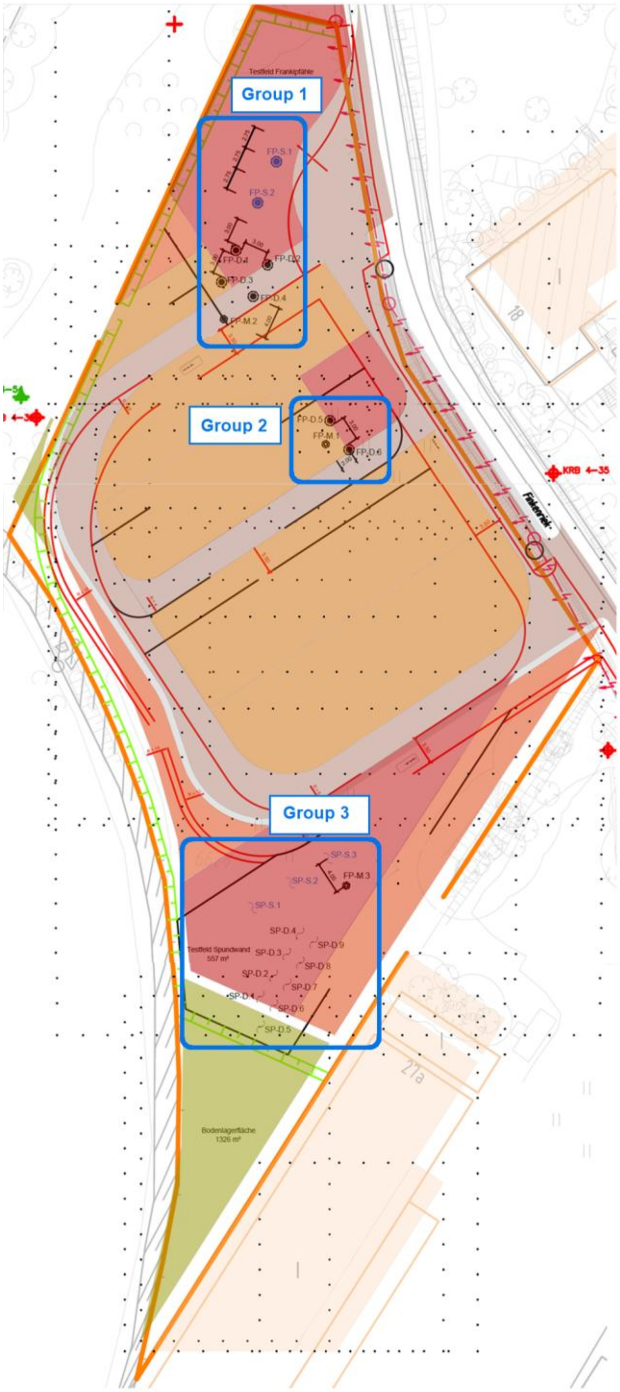


Figure 3. Site plan of the measuring field with layout of the pile groups

In order to measure the vibration effects on the adjacent piles, accelerometers and strain gauges were attached to the reinforcement inside the piles. Each of the pile reinforcement was equipped with a triaxial piezoelectric accelerometer (type KS943B.100), which has a maximum measurement capability of 60g. Furthermore, three uniaxial strain gauges were installed at varying heights to quantify the development of vertical stress in the existing pile during the driving of neighbouring piles.

In addition, the driving pipe head was instrumented with a triaxial piezoelectric accelerometer (type KS943B.10) with maximum measuring capacity of 600g. The schematic design including instrumentation of the piles and the sensors used in field are presented in Figure 5.

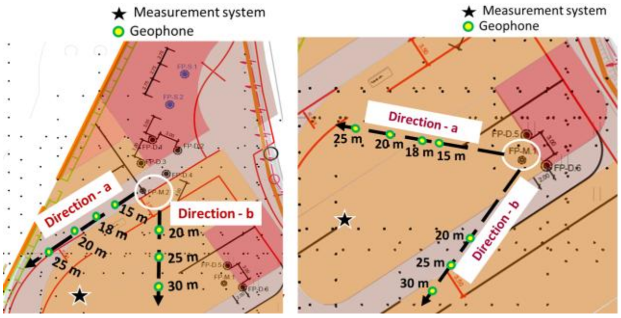


Figure 4. Position of geophones around the piles FP- M.1 and FP-M.2

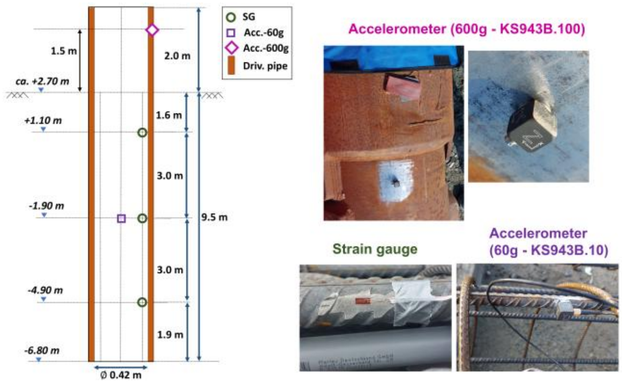


Figure 5. Schematic description of sensor position in piles (left), exemplary pictures of different sensors used (top: driving pipe-head, bottom: reinforcement) (right)

The DeweSoft system was utilised to conduct continuous measurements at all sensors, with a measurement frequency of 2000 Hz. The measurements were taken throughout the entire driving operation, which had an approximate duration of one hour.

3.4 Results

In the context of the present investigation, some exemplary results of group 1 and group 2 (exclusively containing Franki piles) will be discussed.

3.4.1 Driving energy

The preliminary evaluation process can be obtained from the pile-driving report, in which the quantity of impacts necessary per metre of pile penetration during driving is documented. During the first 1 to 2m, the drop height was 3 m and 4 m respectively and was afterwards increased to 6.5 m until the desired depth was reached. The reference piles (FP-M.1 and M.2) were driven with a 2.2-ton hammer, while a 4.5-ton hammer was used for the neighbouring piles (installed in second phase). The difference in ramming energy due to the heavier ramming hammer is clearly noticeable. Compared to the neighbouring piles, a higher number of blows was necessary to install the reference piles. The development of the stroke counts per meter for the piles investigated in group 1 and group 2 can be seen in Figure 6.

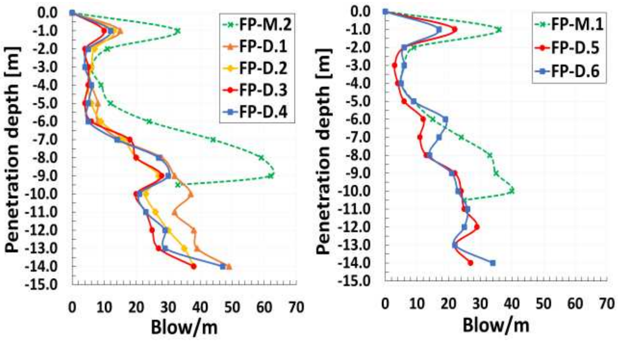


Figure 6. Blow counts according to the pile driving protocol (left: group 1, right: group 2)

3.4.2 Vibration velocity at subsurface

Figure 7 shows the measured vertical velocities of the ground at different distances around the reference piles during driving of neighbouring piles for discrete hammer blows for group 1 and group 2. In both directions 'a' and 'b', the vibration velocity decreases with increasing distance from the source as anticipated, due to soil material and geometric damping. Hammer impact generates a combination of waves (compression wave, shear wave, surface wave etc.), which are transmitted and propagated into the surrounding soil depending on the layer and material properties. With each impact, the driving pipe penetrates into the ground, resulting in an increase in compaction of the soil and a decrease in the amplitude of the ground vibration.

The maximum vibration velocities at the ground surface in the two investigated directions are determined using the measurement data. In addition, a frequency analysis of the vibration velocity is carried out using Fast Fourier Transformation (FFT) for both pile groups. The estimated frequency range of the waves falls within 4–12 Hz.

The attenuation of energy can be proved using the formula provided in internationally recognized German design code DIN 4150-1 which is setting guidelines for vibration effects on structures.

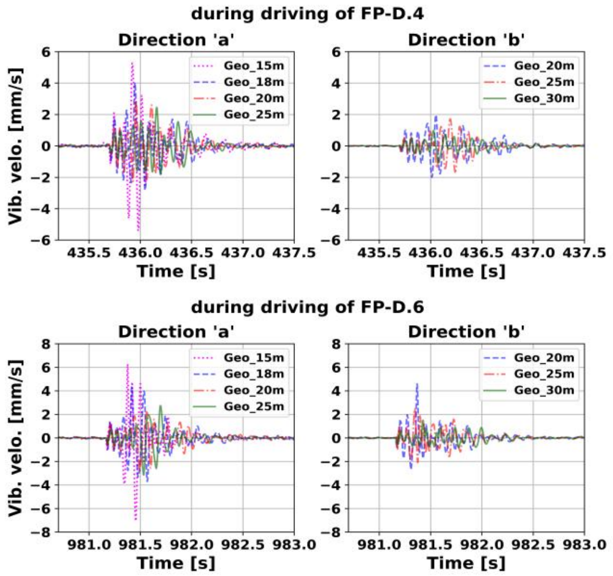


Figure 7. Measured vibration velocities at the subsurface at various distances in direction "a" (left) and direction "b" (right) for a discrete hammer blow during the driving of pile FP-D.4 (top) and pile FP-D.6 (bottom)

In DIN 4150-1, the following equation (1) is given for assessing the propagation of vibrations:

$$v = v_1(\frac{R}{R_1})^{-n} exp[-\alpha\ (R - R_1)] \qquad (1)$$

with,
v = vibration velocity amplitude, (mm/s)
v_1= vibration velocity amplitude at R1, (mm/s)
n = exponent (-)
α = coefficient of attenuation (m^{-1})
R = actual distance from the source, (m)
R_1 = reference distance, (m)

Equation (1) describes the decrease in the amplitude of the vibration velocity v in the far field (R > R1). Figure 8 represents the decay of maximum vibration amplitudes during pile driving in group 1 and group 2. It is clearly demonstrated that an approximation of the vibration velocities as a function of the distance to the source for the far field seems reasonable and fitting in both cases.

According to Bonzel and Schmidt (1980), vibrations with vibration velocities of up to approx. v = 20 mm/s generally have no detrimental effects on the strength of the young concrete. The diagrams show that all measured vibration velocity values are below 20 mm/s. However, if the decay curve approximated in accordance with DIN 4150-1 is compared with the experience of Bonzel and Schmidt (1980), an impairment of the young concrete cannot be ruled out for piles that are located close to the newly constructed pile.

In this case, the critical distance would be within 4-8 m from the vibration source.

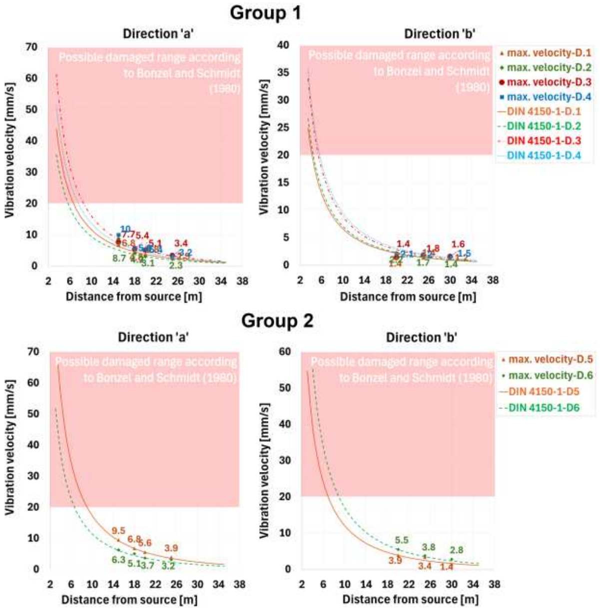


Figure 8. Decay curve of maximum ground vibration for group 1(top) and group 2(bottom)

3.4.3 Acceleration in neighbouring piles

Some exemplary results of measurements on the neighbouring piles during driving of the new pile are presented based on two different parameters: a) distance from the newly installed pile and b) age of the concrete.

a) Distance from the newly installed pile (hardened concrete):

Group 1 consists of six newly installed piles (four of which are instrumented) and one reference pile FP-M.2. Figure 9 shows an example of the accelerations in the horizontal axes in piles FP-M.2, FP-D.4 and FP-S.4 during the construction of the neighbouring pile FP-D.2 for three discrete driving impacts. The acceleration curve at the pile-driving pipe head is shown for comparison. The concrete of these piles can be considered to be hardened, as they have been installed at least more than 3 days earlier. Since they are placed at different distances from the driving source, the acceleration is fluctuating accordingly. Similar to the vibration velocity on the subsurface, the acceleration also decreases with distance.

b) Concrete age (same distance):

The findings indicate that the vibration caused by driving has a noticeable effect on different concrete ages (curing time), when the distance between the newly driven pile and neighbouring piles are similar.

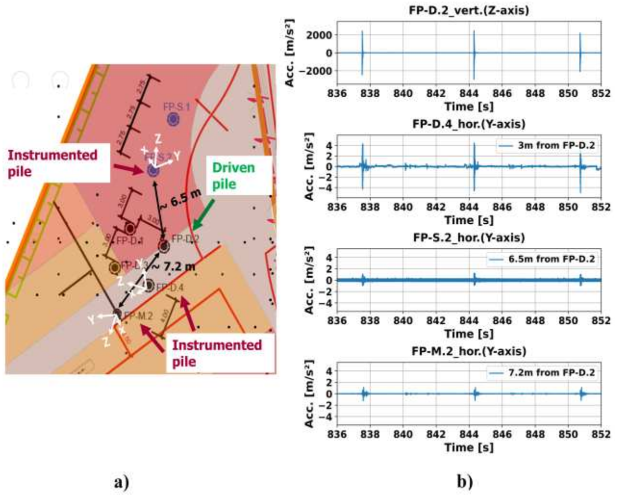
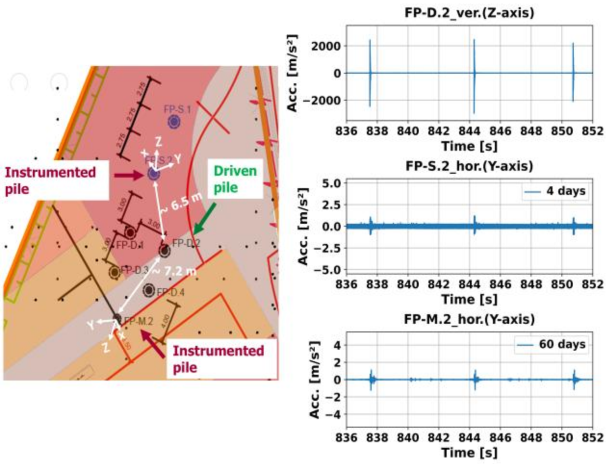


Figure 9. a) Position of the investigated piles FP-D.4, FP-S.2 and FP-M.2 during driving of pile FP-D.2; b) accelerations in the horizontal axis in piles FP-D.4, FP-S.2 and FP-M.2 during driving of pile FP-D.2 and comparison signal (in vertical axis) at the driving pipe head of pile FP-D.2

In Figure 10, the comparison of the accelerations in piles FP-S.2 and FP-M.2 is illustrated, both of which are placed within 6.5 to 7.5 meters distance from pile FP-D.2. Pile FP-M.2 was installed approximately two months, and FP-S.2 was installed four days prior to installation of FP-D.2. Since the concrete in both of these piles are assumed to be hardened, it can be concluded that the discrete impacts on the neighbouring piles are distinctly recognizable. Both of the piles show an acceleration ranging within 2 m/s^2 which is not very high, considering the distance between the neighbouring piles and the installed piles.

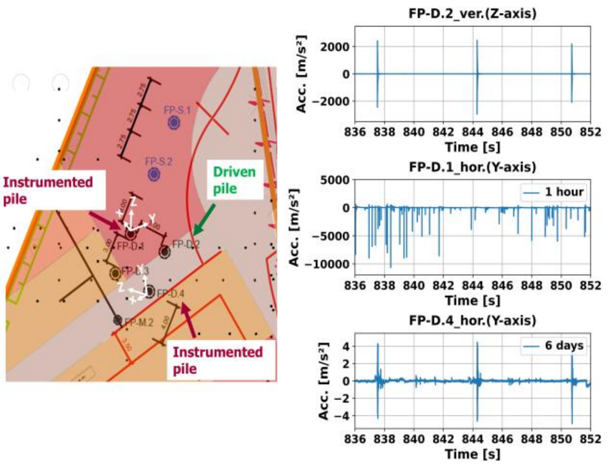
Figure 11 demonstrates the comparison between the acceleration in the horizontal direction in piles FP-D.1 and FP-D.4, both of which are placed around 3 meters from pile FP-D.2. The results obtained in this case significantly differ due to varying concrete age. Pile FP-D.4 was installed six days earlier and FP-D.1 was installed approximately one hour before installation of FP-D.2. Considering concrete age, the hardened pile FP-D.4 shows clear driving impacts with an acceleration of around 5 m/s^2.

In contrast, the concrete in pile FP-D.1 is still in fluid condition, such that there was no significant support or bond between concrete and reinforcement. Therefore, it is likely that the signals could not be dampened before reaching the accelerometer at the reinforcement, leading to continuous high vibrations at the sensor. As a result, the reinforcement was stimulated to vibrate with a high amplitude. It should be noted that, the recorded signals contain high-amplitudes with directional asymmetry that may partly originate from local sensor–mounting or instrumentation effects, are therefore considered not to be a part of structural vibration.



a) b)

Figure 10. a) Position of the considered piles FP-S.2 and FP-M.2 during driving of pile FP-D.2; b) accelerations in the piles FP-S.2 and FP-M.2 during driving of pile FP-D.2 and comparison signal (in vertical axis) at the driving pipe head of pile FP-D.2

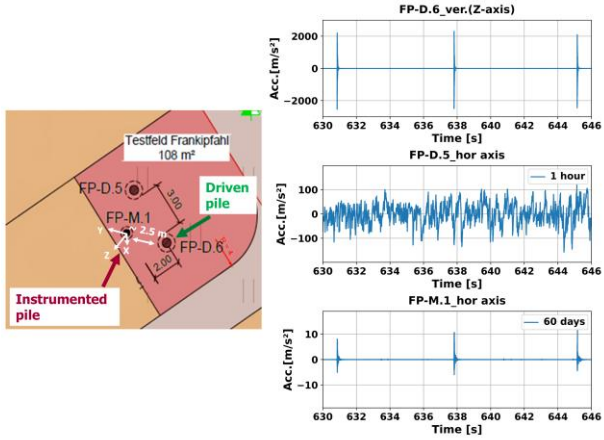


a) b)

Figure 11. a) Position of the investigated piles FP-D.1 and FP-D.4 during driving of pile FP-D.2; b) accelerations in the horizontal axis in piles FP-D.1 and FP-D.4 during driving of pile FP-D.2 and comparison signal (in vertical axis) at the driving pipe head of pile FP-D.2

Similar outcome can be noticed in group 2 (Figure 12) as well. The fresh concrete in FP-D.5 provided little stiffness and damping, resulting in higher vibration amplitudes but unclear measurements during adjacent pile driving, whereas pile FP-M.1 exhibited clear, well-defined acceleration responses due to fully hardened concrete.

Although the amplitudes of the accelerations are not exactly similar (given the difference in pile geometry), vibration behaviour in fresh and hardened concrete aligns with the observed trend.



a) b)

*Figure 12. a) Position of the investigated piles FP-D.5 and FP-M.1 during driving of pile FP-D.6***;** *b) accelerations in piles FP-D.5 and FP-M.1 during driving of pile FP-D.6 and comparison signal at the driving pipe head of pile FP-D.6*

3.4.4 Vertical strain in neighbouring piles

The recorded strain measurements in reference piles from both groups are discussed in this section. Three strain gauges were installed at 1.6 m, 4.6 m and 7.6 m depth of the piles.

The associated changes in loads can be approximated from the measured strains as follows using equation (2):

$$\Delta\sigma = E \cdot \Delta\epsilon_{max}$$
$$\Delta F = A \cdot E \cdot \Delta\epsilon_{max} \qquad (2)$$

Here,
A= Pile area (m^2)
E= Standard concrete stiffness module (MPa)

The changes in loads in all the neighbouring piles with hardened concrete are determined using the above-mentioned formula. The load changes were not calculated for the piles with fresh concrete, since the concrete still behaved fluid-like and therefore was not suitable for load estimation.

Figure 13 shows the calculations of dynamic loads for reference pile FP-M.2 during installation of pile FP-D.2 placed at a distance of approximately 7.2 m. The trend of changes in each of the strain gauges is easily recognizable. The strain gauge at the top (1.6 m) experiences higher dynamic loads (≥ 50 kN) in the beginning of driving, whereas at the lowest strain gauge (7.6 m) the highest dynamic loads (≥ 40 kN) occur at the end of the ramming process.

In case of group 2, Figure 14 provides a detailed overview of driving impacts at the top sensor (at 1.6 m) of reference pile FP-M.1, at the beginning, middle and near the end of the driving process of pile

FP-D.6. It is clearly visible that the resulting changes in dynamic loads decrease from ≥ 130 kN to ≥ 50 kN as the driving source further passes the sensor.

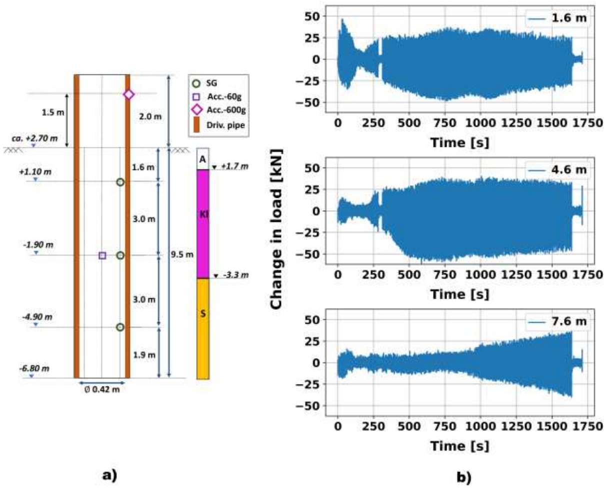


Figure 13. a) Position of the strain gauges in Pile FP-M.2 compared to soil layering, b) changes in vertical dynamic loads based on the measured vertical strains in pile FP-M.2 at 3 depths during driving of pile FP-D.2

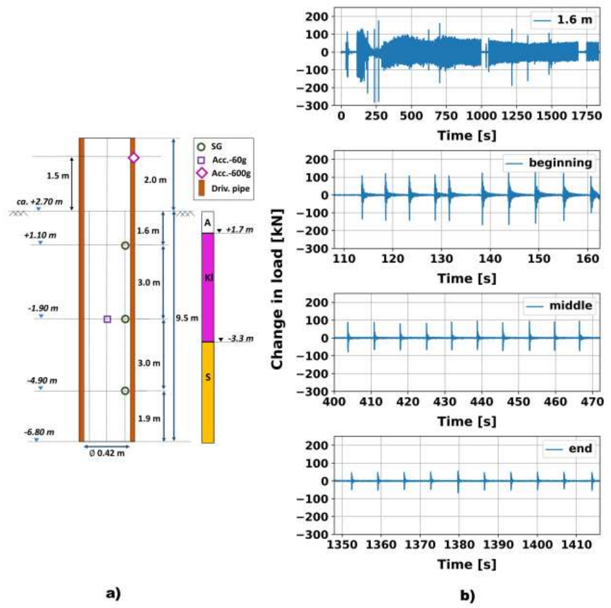


Figure 14. a) Position of the strain gauges in Pile FP-M.1 compared to soil layering, b) changes in vertical dynamic load at pile FP- M.1 at 1.6 m depth during driving of pile FP-D.6 for whole driving duration (top) and for 10 impacts at various driving depths (beginning, middle, and near the end)

4 CONCLUSION

In this study, wave propagation during the pile installation process including the impact on neighbouring concrete piles was investigated through large-scale field investigation. The findings derived from the measurements of pile driving effects on ground as well as adjacent piles reveal some interesting aspects. The main observations are outlined below:

- The results confirmed that vibration velocities decrease with increasing distance from the driving source and are affected by subsoil conditions and driving energy.
- Accelerations and dynamic loads on adjacent piles were strongly influenced by both the age of the concrete and their horizontal and vertical proximity to the vibration source.
- Measurements indicated that freshly cast concrete piles exhibit lower and less consistent response signals, suggesting incomplete sensor bonding and material interaction during early curing stages (Gasser et al., 2024).
- Freshly cast concrete piles are more susceptible to high vibration caused by adjacent pile driving, which may negatively affect the curing process.
- Regarding the present field test conditions (soil characteristics etc), it was possible to make an initial approximation of a critical distance between piles based on the German design code DIN 4150-1 (geophone measurements).

Future work will include the remaining sheet pile installations to assess the influence of different pile installation methods on adjacent piles. Additionally, numerical analyses will be employed to examine energy transfer mechanisms more precisely. The findings from this approach will help to evaluate the impact of vibrations on early-age concrete and serve as the basis for further concrete technology investigations to assess the effects of the vibrations on strength and stiffness development of the concrete.

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