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Installation of a heavy king pile using driving guidance

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Abstract. Combined walls are built out of heavy king piles and lighter sheet piles to protect site jumps up to 30 m of quay walls. Few recommendations exist on how to install the king piles so that the sheet piles can absorb the deformations coming from the location slippage of the king piles. As such the installation process of king piles needs to be regulated. By measuring the installation process on a construction field in Rostock in Germany, the dynamical influence on the king pile's position at the end was investigated. For that purpose, a large king pile with a length of about 30 m was equipped with acceleration, strain and inclination sensors. The driving guide and the installation machine were equipped with acceleration sensors as well. The data was saved with a frame rate of 200 kHz. Next to these analogical sensors the hole driving process is visually recorded by a high-speed camera and a drone. The movement of the king pile during driving derived from the measurement data and compared with the numerical video analyses. The influence of the driving guide was then analysed. Further, the end position of the king pile was measured with an inclinometer.

1. Introduction

The installation of combined sheet steel pile walls is still challenging, because the interaction between the installation devices, the ram guide, the pile and the soil are not well known yet. Few recommendations exist on how to choose the driving hammer and guiding suitable for the soil and installed pile. Currently the calculation for combined walls is only done for the final state. Hence a calculation for the combined walls which takes the installation process into account and a guideline for choosing the correct guiding for the installation of king piles are required.

The installation process of a large king pile (height $h > 1000$ mm, length $l \approx 30$ m) is investigated on a construction site at the harbour of Rostock by measuring the acceleration, change in length and inclination at the profile. The influence of the ram guiding on the acceleration and the movement of the king pile was then analysed. The following change in the position at the foot of the king pile was derived.

2. Installation process of combined walls

According to [1], heavy ramming is to be expected when installing in stiff clay or clay as well as densely stored fine sand or gravel. With increasing driveability, the stress on the profile increases, so that larger vibrations can be expected. Common practice is to use vibration to denser storage or stiffer consistency and, moreover, by means of hammering. Vibration after previous ramming should not take place according to [2].

When installing by vibration, the profile is driven as a result of dynamic excitation, which is generated by eccentrically arranged vibrating masses in the vibrator. This leads to a harmonious vertical displacement. According to [3], the excitation frequency should approx. correspond to one and a half times the resonance frequency of the "vibrator profile soil" system ($\sim$10 to 28 Hz). The aim is to achieve the most efficient installation of the profile without additional compaction [4]. In the case of cohesive soils, cohesive and adhesive forces must be overcome with the largest possible vibration range of the vibrator (see [3] and [5]). In the close range, ground displacement and shear wave formation occur and, as a result, the horizontal stresses increase. In the case of loose storage of noncohesive soils, the soil next to the profile shows a contracting behaviour (compacting) and a dilating behavior (loosening) in the case of previously dense storage. In the case of saturated soils, this can lead to excess pore water pressure due to the dynamic excitation. This is accompanied by a lowering of the effective tensions up to a liquefaction [6]. The cyclical loading of the grain structure favors the reduction of the shaft resistance. As a result of increasing load cycles, there is an accumulation of the deformation increments and a cyclical failure in the transition area from the profile to the soil [1].

During hammering, the pile is driven in by an impulse-like action due to a mass falling on the pile head. According to [7], the compaction in the near area when installing a round tube pile by vibration is greater than by hammering, whereby the area of influence for the compaction during hammering extends to greater depths. The horizontal tensions increase significantly more when hammering than when vibrating. The studies of [8] confirm that this influence increases with increasing storage density. However, according to [1], the intensity and range of the changes in soil condition-related changes depends on the pile and the entire system.

According to [9], the horizontal profile movement can be greater than the vertical profile movement and is influenced in particular by the excitation initiated, the clamp or ram hood, the ram guide, the profile rigidity and length as well as the current embedment length in the soil. Since the lock friction does not apply for king piles, the influence of the profile movement through the ram guide increases. To ensure the planned position of the trusses, the EAU makes requirements for the introduction of trusses to the parallelism, the escape, twisting as well as the distance between the king piles. For this purpose, the king piles should be "conveniently placed with a double guide" and brought in with an adequate, rigid piling device.

Nevertheless, a reduced ram guide is often used for economic reasons, so that the actual influence of the rigidity of the ram guide must be checked. Their geometry itself has another major influence on the final position of the king piles. Since the installation tolerances for intermediate screeds according to [10] can be exceeded even if the delivery tolerances are observed due to the large profile lengths, stricter tolerances should be contractually agreed according to [11].

3. Measearement of the installation prcoess of a king pile

3.1. Location and Installation Setup

For the investigation of the dynamics of the pile driving process, the installation of a king pile during the construction work at berth no. 23 of Rostock overseas port was equipped with measurement technology. The Rostock Port GmbH, as client, contracted out the construction of the new quay wall to the joint venture "New Building Berth 23 seaport Rostock". They had to build a new, back-anchored quay wall in front of the existing quay wall as a combined sheet pile wall consisting of the HZ 1180M A 12, S 430 GP as king pile and the AZ 20-700, S 355 GP as intermediate pile. The new quay has an inclination of 1 : 18 in order to reduce the width of the waterway as much as possible. Due to the dense sands in the area of the quay wall track, replacement drillings were performed. The measurement was done during the installation of an almost 30 m long king pile during the construction process. Fig. 1 gives an overview of the construction site with the pontoon for the vivratory installation, the installed piles of the new quay wall and above the tested king pile during the installation of the sensors. After the replacement drills were made up to one meter above the planned settling depth of the king pile, the king pile was set in the pile driving guide, which guides the king pile above the top plate on three sides (cf. Fig. 4). Then the pile was vibrated from a pontoon up to three meters above the planned settling depth.

Figure 1. Aerial photograph of the construction site with the test king pile

A high-frequency vibratory pile driver of type *PTC 30 HFV* with a *Sennebogen 3300E cable excavator* from the company *TAGU Tiefbau GmbH Unterweser* was used for the vibratory pile driving (cf. Fig.2). The vibrator achieves a maximum frequency of 38 Hz at a maximum centrifugal force of 1600 kN. The static moment can be varied between 0 and 27 kgm to prevent the passage of the resonance frequencies of the system "vibrator profile soil" during start-up and shut-down. The impact ramming was done with the *Sennebogen S 655 R - HD crawler excavator* with the *Nyblad* supporting leader mast and the hydraulic free-fall hammer from the company *Ed. Züblin AG* (cf. Fig.3). The IHC S-90 hydro hammer with a maximum impact energy of 90 kNm and an impact rate of 46 blows per minute was used as the pile driver. The hammer weight for pile driving above water was 9.65 t according to the manufacturer's specifications.

3.2. Measurement concept

For the schematic investigation of the installation process, the pre-deformation of the profile was first determined. Since the pile can deform in a horizontal position due to its own weight, the initial deformations were measured after the pile has been placed from a passenger cage. For this purpose, square profile tubes were welded to the profile, which enable measuring the deformation using an inclinometer probe. By arranging two axes eccentrically from the neutral phase (cf. Fig. 5), it was also possible to calculate twisting. For each inclinometer measurement (before as well as after installation), the head of the king pile was measured in order to determine the absolute positional deviations. The arrangement of the measuring points was presented in [12], Fig. 8. As the individual sensors have different local reference systems, a global, left-handed coordinate system (geodetic ally positive direction of rotation) and origin on the neutral phase in the sectional plane of the profile head was determined.

Figure 2. Vibratory driving

Figure 3. Impact driving

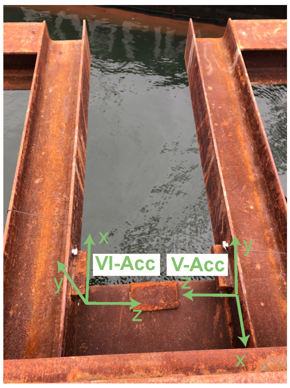

Figure 4. Ramm guiding with two acceleration sensors

Figure 5. Detail view of the eccentric installed squared profile steel pipe for the inclination measurements

Figure 6. Sensor equipped measurement point I

During vibration, the accelerations at the pile driving guide were also recorded (see fig. 4). During impact driving, the accelerations were measured at the leader suspension of the pile driving device.

Fully encapsulated, waterproof strain gauges (DMS) were used. The accelerations at the supporting pile were measured with triaxial piezoelectric accelerometers with a maximum measuring range of ±2000g in order to cope with the high accelerations expected during impact driving. In addition to the inclination probe measurements at the beginning and end of the installation process, the inclinations were measured at measuring points I and III the whole time. For that purpose sensors in the MEMS (Micro Electro Mechanical System) standard were intended to provide information on the rotation of the king pile between dynamic loads when measurement by means of an inclinometer probe was not possible. The characteristics of the sensors used are shown in Table 1 of [12].

The sensors of the lower three measuring points were protected by means of welded-on protective boxes which guided the soil past the sensors and minimized water ingress. Since the uppermost measuring point I was only exposed to low external loads, the arrangement of a protective box was not not necessary here. Between the protective boxes, tubular steel profiles were welded to the king pile to prevent them from vibrating and protect the cable routing. The strain gauges were attached directly to the profile with a spot welder. The acceleration sensors as well as the inclination sensors were attached to welded-on steel plates with fixed threaded screws. From measuring point III upwards, the cables were bundled and led to the measuring computer on the land side of the quay. The strain relief was realized by fixing the cable bundle to a climbing rope, which was attached to welded eyes.

The transition from the protective boxes to the pipes was filled with construction foam to keep the possible movement of the cables as small as possible. During the installation process all data was measured with a frequency of 200,000 Hz by using an SBOX-System of *DEWESOFT*.

4. Results

The first measurement with the inclinometer probe demonstrated that the maximal deformation of the profile in the weak axis was approx. 2 cm which means 0,6 % of the profile length. The graphs can be found in [12]. By the use of a pixel tracking method described in [13] the driving progress over the time was derived. The level of the sensors could then be explored continuously during the installation concerning the water, soil and ram guiding level. The result was a driving depth of 15.80 m in 262 s by vibration and 2.82 m in 337 s by impact driving. The pause of the vibrator during the slope check between 60 s and 80 s was observed. Between the end of the vibration driving at approx. 200 s and the impact driving there was a delay of approx. 2 h due to the dismantling of the pile driving guide and the changing of the pontoons. Vibrating in leads to a harmonious course of the vertical movements. In contrast, the impulse-like excitation during impact driving resulted in a step-like course of penetration, the shape of which indicated a decrease in pile driving efficiency with increasing depth.

4.1. Influence of the ram guide on the dynamics of the king pile during the vibro driving

The recorded accelerations were evaluated directionally. For this purpose, the measurement signals were first analysed. When evaluating the normalized amplitude spectrum of the vertical accelerations at the four measurement points using Fast Fourier Transformation (FFT), the resonance frequency of the entire "Vibrator-Supporting Screed-Driving Soil" system was 31.2 Hz. This was very close to the planned excitation frequency of 30 Hz. The time-dependent application of the FFT to the individual signals allowed the relevant frequency ranges to be identified. During vibration, the low-frequency oscillations below 1 kHz were especially dominant. An influence from harmonics was not recognized.

At the beginning of the vibration, the profile at the base oscillated in the transverse directions with a phase shift to the axial oscillations (see Fig. 7). This phase shift occurred with increasing bedding by the soil. Since the profile was able to move between the beams of the ram guide, there was no continuous contact to all sides of the guide. During the periods in which, according to the recording of the high-speed camera at the level of the pile-driving guide, there was contact between the pile and its right side, the accelerations at the pile-driving guide increased as expected to a maximum of 600 m/s^2 axially and transversely to the pile-driving guide beam. In the longitudinal direction of the beam the accelerations were about 40 % lower. Qualitatively, the course of the accelerations was the same in all spatial directions, so that it was assumed that the entire pile driving guide was excited, which was dominated by the profile installation in axial profile direction and by the horizontal bearing of the profile.

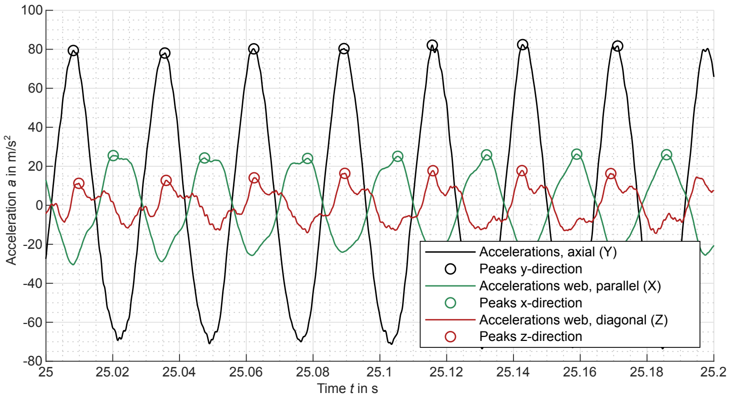

Figure 7. Segment of the accelerations at the end of the vibration phase in the three directions

The section of the accelerations at the lowest measuring point I in Fig. 7 at the beginning of the installation showed that the harmonic, axial excitation of the vibrator was transferred to the profile and the axial accelerations increased accordingly from top to bottom in the profile. These were on average about 150 m/s^2 and increased briefly to about 400 m/s^2. The transverse oscillations parallel to the web corresponded to about 20 % and transverse to the web to about 30 % of the axial oscillations.

For classification of the influence of the pile driver, the accelerations in the xz-plane on the right-hand beam of the pile driving guidance (cf. Fig. 4) as well as the accelerations orthogonal to the web are shown in profile for three time sections in Fig. 8. The axial accelerations are similar to those of Fig. 7 for the three time sections. At the beginning of the vibrating in, a time section with one-sided guidance, only at the flange (section A) and a directly following section B with contact to the lateral support of the pile driver guide were selected. The comparison showed that with two-sided guidance, the accelerations across the web in the profile were reduced by up to 40 %. This was accompanied by a doubling of the accelerations in the transverse direction in the pile driver guide. As the driving depth increased, the accelerations in the transverse direction in the profile increased again, which was associated with the distance of the measuring point I from the pile-driving guide and the reduced guide. If the profile was already further integrated, as in section C at a distance of 4 m from the pile-driving guide, the transverse vibrations were reduced further in succession, which was due to the increasing lateral bedding of the soil.

The further movement of the king pile was derived after validation by use of the pixel tracking method by integrating the acceleration results. For that purpose the acceleration signals were first processed with a low pass filter (< 1 kHz). Additionally the signals were integrated twice using the trapezoidal method in order to calculate the oscillation paths from the accelerations.

4.2. Accelarations and movement during the impact drving

As expected, impact pile driving resulted in signals with significantly higher accelerations and a higher harmonic content than with vibration. Furthermore, the waves were reflected by the sea soil. The propagation velocity calculated from the phase shift and the known running length between the sensors was about 5200 m/s. This coincided with the velocity of propagation calculated equally from the strain measurement signals and was in the order of magnitude of 5172 m/s expected for steel. With regard to the upward accelerations due to reflected waves, values of up to about 5000 m/s^2 were obtained for the lower three measuring points. At the uppermost measuring point IV, less continuous signals were recorded, which showed accelerations of up to 12000 m/s^2. In the direction of displacement, the accelerations were on average between 2000 m/s^2 and 5000 m/s^2 in the lower three measuring planes. At measurement point IV, there were temporary accelerations of up to 28500 m/s^2. Accelerations of a comparable magnitude were also measured at measuring points II and III, which occasionally led to overloading of the sensor. The break value of the sensors of 5000 g was not exceeded and no signal changes were recorded after these events. The accelerations parallel to the web were greater than transverse to the web and corresponded to about 10 to 20 % of the axial accelerations. These transverse

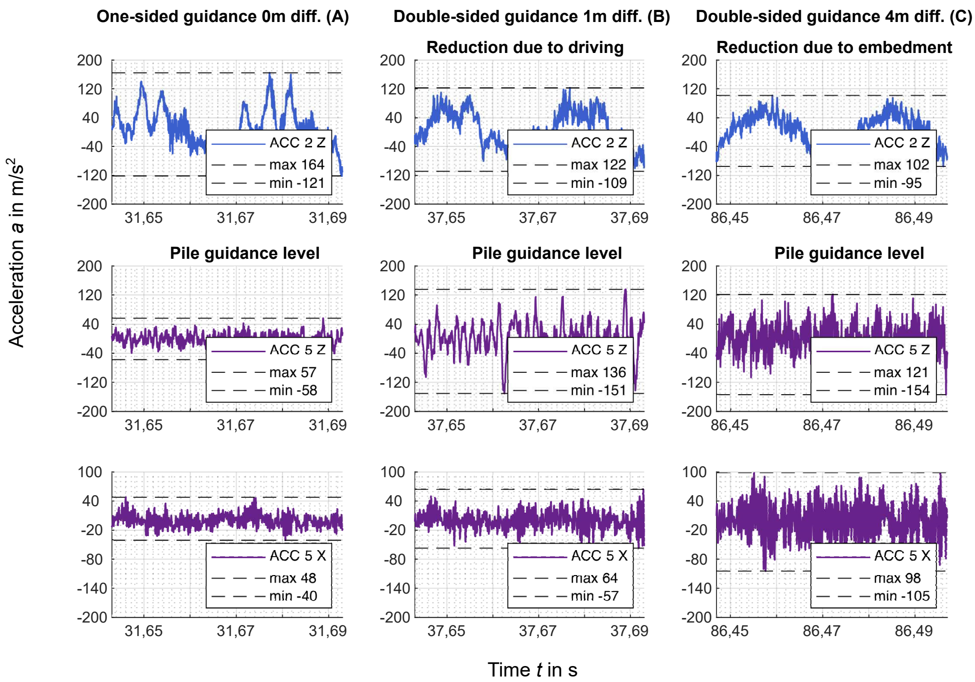

Figure 8. Accelerations of the ram guide during the vibration phase

oscillations decreased with increasing embedment depth.

The signal in upper part of Fig. 9 shows the axial accelerations at the measurement point I for the first ten hits. For the calculation of the axial movement another method was necessary than for the continuous signal of the vibratory installation. Due to the discrete acceleration signals, the signals were not directly duplicated, as was the case with single-vibration, but integrated section by section. First, the peaks in the signal from $2000\,\mathrm{m/s^2}$ were read out with their associated time values. The respective integration section was defined with a start of 0.05 s before and 0.2 s after the peak in order to acquire the main signal of each individual beat. Then the original signal was averaged with the Savitzky-Golay filter (order 1, window length 37). Then the signal was integrated with the cumulative trapezoidal method, the result was processed again with the Savitzky-Golay filter and integrated again. The result obtained was interpreted as axial displacement which was about 0.2 m for the first ten hits.

By applying this method to the first three measurement points (at the pile head the variation of the accelarations was too high) the axial movement was compaired to the movement that was derived by the video analysis. As it can be seen in Fig. 10 the integrated displacement concurred well with the directly derived displacement. Despite the low lateral vibration sensitivity of the acceleration sensors, this procedure led to overestimated movements when applied to the lateral accelerations.

4.3. Deformation and position at the end

In comparison with the initial inclinometer measurements, the deformations in the final state are shown in Fig.12 for the measurement axis "z1-incl". The deformations in the x-direction or in the direction of the strong axis have changed only slightly. In contrast to this, plastic deformation in the negative z-direction clearly occured as a result of the installation in the axis z1-incl after the first few meters. This was a maximum of 1 cm at about -25 mHN. Due to an assumed deformation of the inclinometer tube, the last 2.5 m were not possible in comparison to the measuring axis "z2-incl". In this axis deformations of less than 0.3 cm occurred and in

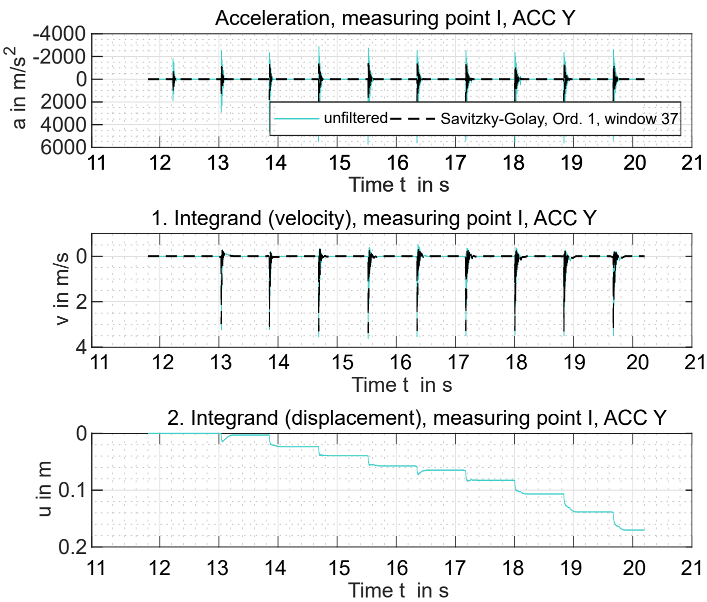

Figure 9. Vertical acceleration, integrated speed and integrated swinging path for the first ten ramming strokes at the lowest measuring point I

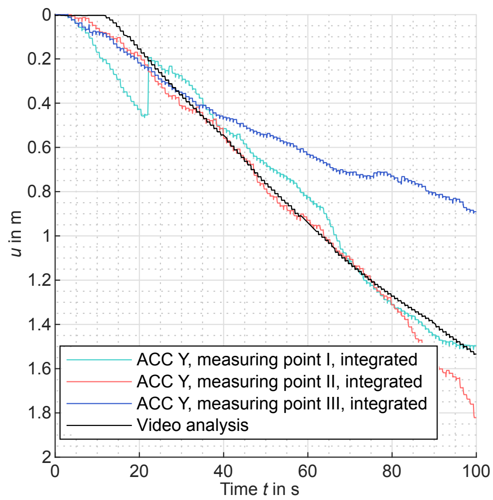

Figure 10. Vertical acceleration, integrated speed and integrated swinging path for the three lowest measuring points

some areas no additional plastic deformations occured as a result of the installation.

More significant than the plastic deformation of the supporting pile was the resulting deviation from the planned position. This was limited by the distance from the existing quay wall at its base by 30 to 40 cm in positive x-direction. The target position was determined by linear interpolation with an inclination of 1:18, assuming that the head was in the correct position. The deviation of 22 cm in the x-direction at the foot resulted in an inclination of 1:21 (see Fig. 11, left). In the z-direction, in which no inclination was provided, there was also a positional deviation which was a maximum of 5 cm at the foot of the soldier pile, resulting in an average inclination of 1:530 (see Fig. 11, right). The resulting position of the base of the support pile on the settling depth of the intermediate piles is illustrated in Fig. 12, where, assuming the same deformation of the neighbouring support pile, it was mirrored in order to visualise the possible change in the system distance, which according to the manufacturer's specifications may not deviate by more than 200 mm at the base (cf. [14]). In comparison to the nominal position, there was a difference from the system dimension of about 4 cm in longitudinal direction. In the lateral direction, no difference can be determined due to the unknown position of the adjacent supporting plank. In the present case, it should be noted that the selected driving technique does not result in the planned system dimensions being exceeded in the longitudinal direction, but does result in a deviation from the planned inclination.

5. Concluding Remarks

By measuring the installation process of a heavy driving process on a construction field in Rostock in Germany, the dynamical influence of the installation process on the king pile's position at the end was investigated. For that purpose, a large king pile with a length of about 30 m was equipped with acceleration, strain and inclination sensors. The driving guide and the installation machine were equipped with accelerations sensors as well. The measurement was done in February 2019. First of all, the dynamic response due to driving with vibration differed

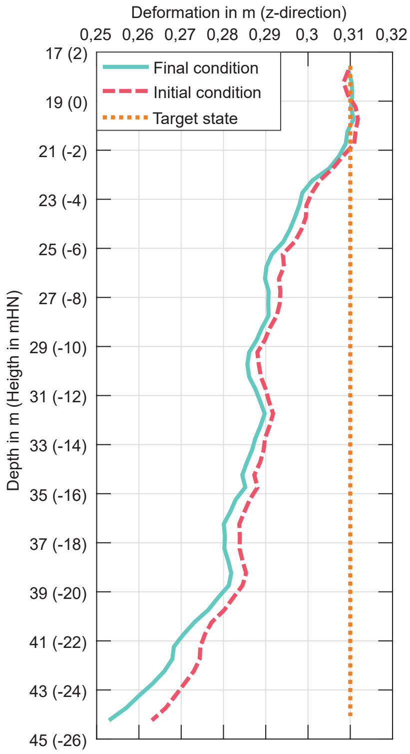

Figure 11. Difference of the planed position at the end in the measuring axis Z1 (different axis scaling)

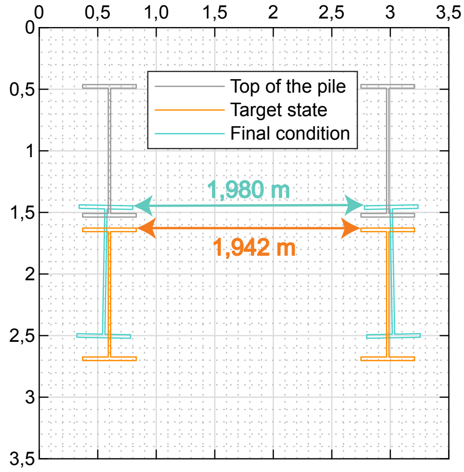

Figure 12. Position of the head of the king pile (grey) and the foot of the king pile in set position (orange) and in the final state (blue)

fundamentally from that due to impact pile driving. Accordingly, vibration was dominated by low-frequency components and impact pile driving by higher-frequency components, which were identified as harmonics in particular. The axial accelerations during vibration were on average $150\,\mathrm{m/s^2}$ and increased briefly to about $400\,\mathrm{m/s^2}$. During pile driving, the average axial accelerations were between 2000 m/s2 and 5000 m/s2. At the uppermost measuring point IV less continuous signals were recorded, with accelerations of up to $28500\,\mathrm{m/s^2}$ occurring. At the pile-driving guide during driving by means of vibration, accelerations of up to $600\,\mathrm{m/s^2}$ were recorded as a result of the transfer of dynamic energy, which were thus greater than those at the support pile. Accelerations of up to $400\,\mathrm{m/s^2}$ were measured at the pile driver during impact pile driving, which were directly dependent on the individual pile driving strokes. When the pile driver was in contact with the profile, the lateral accelerations in the profile were reduced. The oscillation paths determined on the basis of the integrated acceleration signals can be validated on the basis of the camera recordings at the level of the pile-driving guide. It was observed that with increasing distance from the ram guide, the lateral oscillation paths increased and the influence of the ram guide decreased. The inclinometer measurements in the steel pipes eccentrically welded to the profile allowed the determination of an initial deformation before driving and the position and deformation in the final state. As a result of the installation, the profile inclination from the head in the direction of the water was 1:21 instead of the planned 1:18 and in the direction of the quay wall route an unplanned inclination of 1:530. This results in a deviation of the system dimension with an assumed similar, mirrored positional deviation of the adjacent pile of 4 cm, which had the capability to be considerably greater depending on the position of the adjacent pile. In the accompanied construction project was shown that with previous replacement drilling, even a simple pile-driving operation can be sufficient to install the support pile within constructional tolerances. With less preparatory work, significantly larger deviations would have been expected in the subsoil. Overall, it can be stated that a clear influence of the pile-driving guide and the installation equipment used can be worked out on the basis of the measured values. This provides the basis for further numerical simulations to determine the influence of the pile driving on the final condition in order to develop holistic design criteria. Furthermore, a schematic optimisation of the design procedure for combined sheet pile walls was to be carried out in order to take the driving procedure into account and to be able to make recommendations regarding driving.

6. Acknowledgements
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