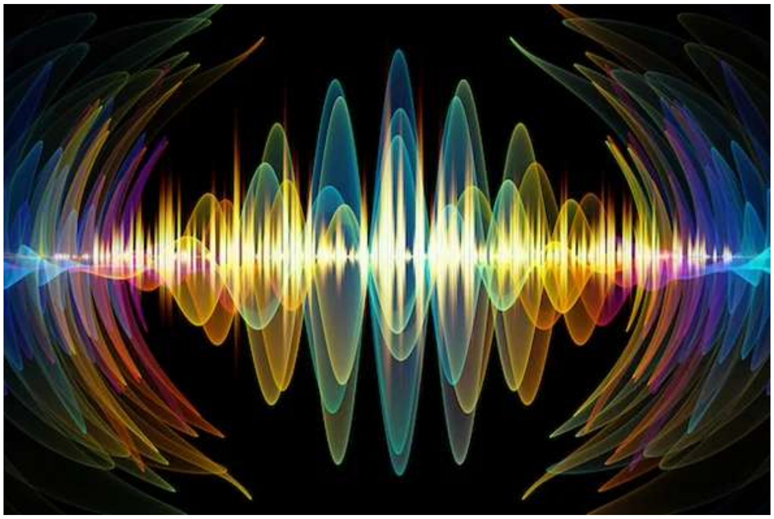

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Dynamic Ground Response during Vibratory Sheet Pile Driving

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Abstract: Vibratory sheet pile driving is a widely used foundation method. In order to investigate the effect of different operational parameters, such as vibration frequency and eccentric moment on sheet pile to ground interaction, carefully monitored and documented field tests were performed. A single sheet pile was vibrated into a sandy soil deposit (esker) and different operational parameters were varied. The interaction between the vertically oscillating sheet pile and the surrounding ground was studied, using sensors on the vibrator and on the ground in the vicinity of the sheet pile. The effect of vibration frequency and eccentric moment on sheet pile penetration speed and emitted ground vibrations is presented. When the sheet pile is vibrated at the resonance frequency of the vibrator–sheet pile–soil system (system resonance), ground vibrations increase significantly and sheet pile penetration speed decreases. It is concluded that the vibration frequency is an important parameter for the efficient and environmentally safe installation of sheet piles. These tests provide insight into the interaction of a vibrated sheet pile and the surrounding ground. Based on these results, guidelines for the efficient and environmentally friendly installation of piles and sheet piles are proposed. **DOI: 10.1061/(ASCE)GT.1943-5606.0002520.** *© 2021 American Society of Civil Engineers.*

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Introduction

Heavy construction vibrators are widely used in the foundation industry, especially for the installation of sheet piles. Another growing application is deep vertical vibratory compaction (DVVC) of granular soils. Although it is generally assumed that, especially in granular soils, vibratory driving is more efficient than impact driving, its practical application for the installation of piles is often limited in practice. This is due to several reasons. First, it is difficult to estimate the vertical bearing capacity of vibratory driven piles. Therefore, static or dynamic loading tests are frequently required to verify pile bearing capacity. The so-imposed additional cost has often prevented the choice of vibrators for pile installation. A second reason, which has limited the use of vibrators especially in vibration-sensitive areas, is the common opinion that vibratory driving can cause excessive ground vibrations. However, as shown, modern vibrators offer new opportunities for efficient and environmentally safe driving when carried out considering the significance of vibration frequency and eccentric moment.

Modern construction vibrators are among the most sophisticated machines in foundation engineering (Warrington 1992; Gavin and Doherty Geosolutions 2015). Major improvements in the design, operation, and control of vibrators have been achieved during the past decades (Warrington 1989; Massarsch and Westerberg 1995; Viking 2002; Holeyman 2002; Massarsch et al. 2017). In the past, investigations have focused primarily on the dynamic interaction between the vibrator and the sheet pile (Rodger and Littlejohn 1980; Holeyman 2000; Viking 2002) and the dynamic response of the vibrator system including the powerpack (Whenham and Holeyman 2008; Whenham 2011). The dynamic interaction between a vibrating sheet pile and the surrounding soil deposit has only been considered in a few cases (Massarsch 2002; Whenham and Holeyman 2008; Deckner 2017). It has been shown that the vibration frequency is of critical importance for all aspects of vibratory driving, such as drivability, vibration transmission into the soil, and bearing capacity (Hartung 1994; Massarsch et al. 2017).

A major advancement was the introduction of hydraulic vibrators where the frequency can be varied without affecting the hydraulic power supply. One of the key advantages to hydraulic vibrators is that the rotational speed of the vibrator can be varied by changing the flow to the motor and thus the speed. This decouples the vibrator speed from synchronous motors used in electric machines. which are essentially fixed. However, an even more significant step was the introduction of vibrators with variable eccentric moment. Such vibrators can be started up and shut down at zero eccentric moment, thereby avoiding vibration amplification due to resonance. With such variable vibrators, driving can be adapted to the site-specific conditions. In order to utilize vibrators effectively for different applications, it is necessary that the project planner (who selects the vibrator type) and the machine operator (who executes the work) are familiar with the fundamental concepts of vibratory driving and can adjust the driving to the project-specific conditions.

Progress regarding the understanding of vibratory driving has been made in the area of vibratory compaction (DVVC), where the interaction between the vibrating probe and the surrounding soil has been studied extensively (Massarsch and Fellenius 2005). An important step has been the introduction of the resonance compaction concept, in which the vibration amplification effect on soil

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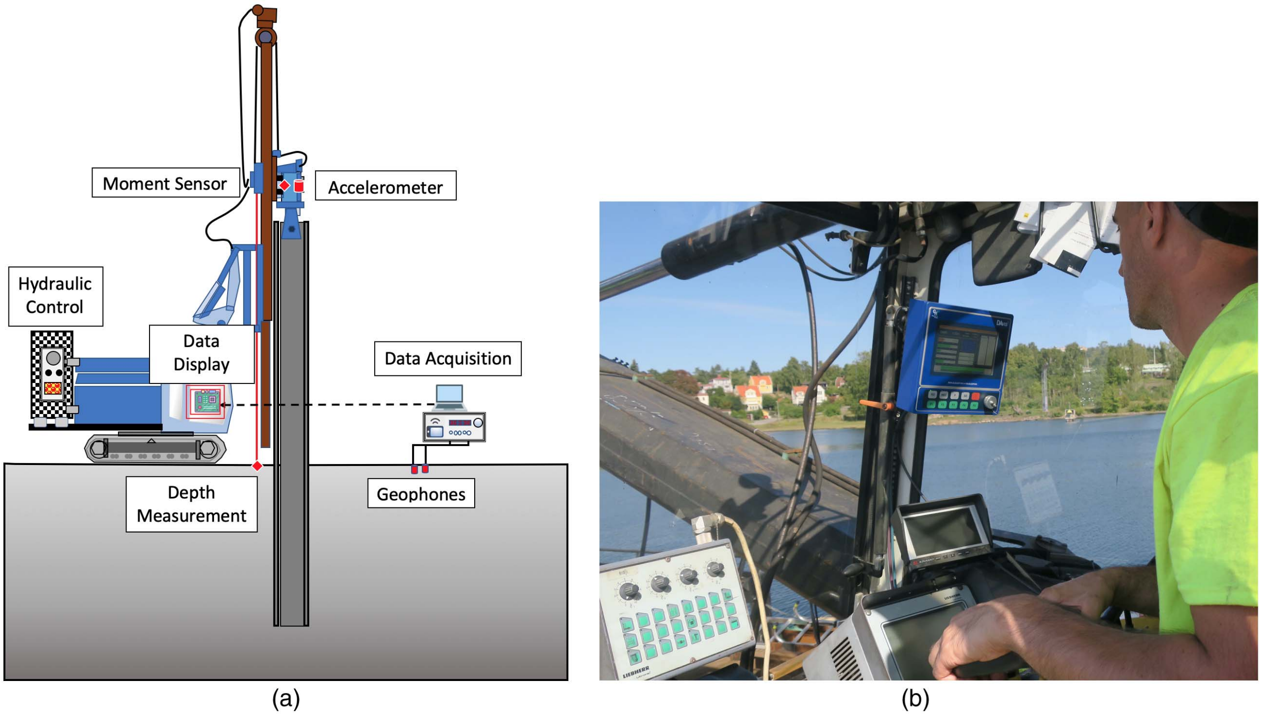

Fig. 1. (a) MPCS sensors; and (b) MPCS display in the operator cabin.

compaction was used to enhance soil densification (Massarsch 1991; Massarsch and Fellenius 2017).

The objective of this investigation was to study the dynamic response of the ground during vibratory driving of sheet piles. To verify the machine criteria supplied by the manufacturer, the test program started with a test run without connecting the vibrator to the sheet pile. Thereafter, three driving tests were performed and the influence of changing operational parameters (frequency and eccentric moment) on drivability and ground response were measured. These tests provided insight into the interaction of a vibrated sheet pile and the surrounding ground. Based on these results, guidelines for the efficient and environmentally friendly installation of piles and sheet piles are proposed.

Monitoring and Process Control System

Case histories of vibratory sheet pile driving projects documenting the installation process in detail are scarce. This is surprising because electronic equipment is now used on a routine basis in connection with other types of foundation works, such as impact pile driving or ground improvement. To allow the optimization of vibratory driving of piles and sheet piles, a user-friendly monitoring and process control system (MPCS) was developed for controlling, optimizing, and documenting the entire vibratory driving process. The system was initially conceived for DVVC projects using the resonance compaction concept (Massarsch 1991; Massarsch and Westerberg 1995). The most recent MPCS development can be used for a wide range of vibrator applications, such as driving or extracting piles and sheet piles, resonance DVVC, and surface resonance compaction using a vibratory plate (Massarsch and Wersäll 2020). The following parameters are directly measured by the MPCS:

- Position of pile/sheet pile (GPS coordinates) (optional);
- Date and time (hh:mm:ss);
- Depth of sheet pile (m);
- Acceleration of vibrator (cm/s^2);
- Hydraulic pressure of power supply (MPa);
- Ground vibration velocity (mm/s), three components (triaxial);
- Eccentric moment (kgm) (optional); and
- Static force (kN) (optional).

From the preceding measurements, the following parameters are derived:

- Frequency of the vibrator (Hz);
- Frequency of the ground vibrations (Hz);
- Vector of vibration velocity (mm/s);
- Root mean square (RMS) of vibration velocity;
- Displacement amplitude of vibrator (mm);
- Pile penetration speed (cm/min);
- Centrifugal force (kN); and
- Vibration cycles per depth interval (cycles/cm).

The practical application of the MPCS has been described by Massarsch and Wersäll (2019). The configuration of the different sensors is shown in Fig. 1(a). When developing the MPCS, emphasis was placed on guiding the vibrator operator during the different phases of vibratory driving or soil compaction. All relevant information (measured and derived parameters) can be displayed on a screen to the machine operator; see Fig. 1(b). In addition, limiting values can be indicated, as well as visual guidance (arrows, bar diagrams, or dials), to assist the machine operator in optimizing the installation process.

The MPCS can also be programmed to optimize the driving process. The vibration frequency can be varied manually or automatically to avoid resonance effects in the surrounding area. An important aspect is to fully document the entire vibratory driving process. All parameters can be transmitted wirelessly to a central office where the data can be stored and further evaluated.

An important practical consideration when selecting the vibrator is the estimation of the driving resistance, which depends on the dynamic soil properties. A concept was proposed by Massarsch et al. (2017) by which the resistance is expressed by the number of vibration cycles per depth interval. If the sheet pile is vibrated at a constant frequency, it is possible to determine the number of penetration cycles as a function of depth, similar to a dynamic

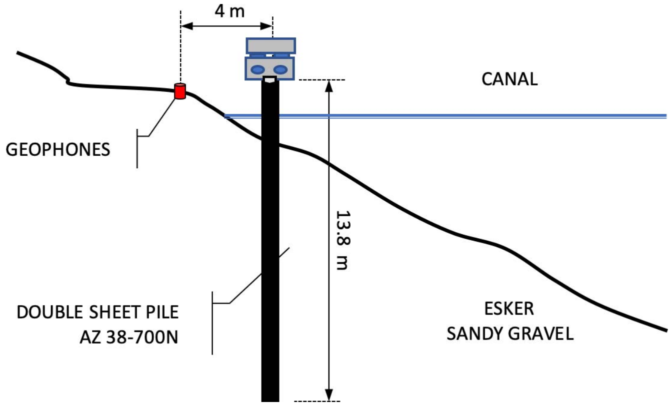

Fig. 2. Cross section and view of test area.

penetration test. If the vibrator operating frequency of the vibrator, f, is kept constant, the sheet pile penetration speed, v_P, can be measured and converted to an equivalent number of penetration cycles, which represents the driving resistance. The equivalent number of penetration cycles, c_e, per depth interval (cycles/cm) can be calculated according to the following relationship:

$$c_e = \frac{f}{v_P} \tag{1}$$

where f = vibration frequency; v_P = sheet pile penetration speed; and c_e = number of equivalent vibration cycles (e.g., cycles/0.2 m). The c_e parameter can be correlated to the penetration resistance of, for instance, the superheavy dynamic penetrometer (DPSH-A) test or the cone penetration test (CPT). This concept was successfully used on DVVC projects, for instance, in connection with underwater compaction of a hydraulic fill inside sheet pile caissons (Massarsch et al. 2017).

In the subsequent sections, three driving tests are described, where relevant driving parameters and the dynamic ground response were monitored. The measurements are interpreted to determine which parameters are important for efficient driving of sheet piles, and at the same time minimizing vibration transmission to the surroundings. Recommendations are given that can serve as guidelines for planning and execution of vibratory driving of piles and sheet piles.

Project Description

A more than 4-km-long sheet pile wall was installed to a depth of 8–15 m along Södertälje Canal located 30 km south of Stockholm, Sweden. Due to complex project conditions, such as potential for slope instability and settlement hazards, field trials were performed at the start of the project. The sheet piles were installed at the shoreline of the slope with the vibrator and powerpack operating from a barge. Fig. 2 shows a cross section with the location of the sheet pile next to the shoreline and the geophones installed at a distance of 4 m.

The tests were carried out in an esker, consisting of sand and sandy gravel. For the sheet pile installation, a vibrator with variable frequency and variable eccentric moment was chosen. Two types of triaxial geophones were used to monitor vibration response of the ground during driving: MPCS standard geophones (manufactured by Loster: GM3D-17, MItterfels, Germany) and wireless geophones (Sigicom: INFRA C12 triaxial vibration monitor, Stockholm, Sweden) for monitoring of slope stability. The frequency range of interest was 5–500 Hz. Fig. 3(a) shows the positioning of the double sheet pile at the shore of the canal. Vibration sensors were installed at 4-m distance from the sheet pile, about 1 m above the water level in the canal (Fig. 2). Fig. 3(b) shows details of the vibrator instrumentation, including the accelerometer and the moment sensor, which measured the movement of the piston that controls the eccentric moment.

Vibrator Characteristics

A Dieseko PVE 40VM vibrator with variable frequency and variable eccentric moment (Sliedrecht, Netherlands), with the nominal parameters specified by the manufacturer in Table 1, was used. The vibrator was mounted on a Liebherr HS853 (Ehingen, Germany) HD Litronic crawler crane with a set of leads. The operating weight of the rig was approximately 800 kN. The Power Pack PVE 800 (Dieseko Group, Sliedrecht, Netherlands), mounted piggyback on the rig, had a maximum power of 565 kW with an oil flow of 800 L/min. The vibrator was operated by remote control (MPSC) from which the frequency and the eccentric moment (and thus the

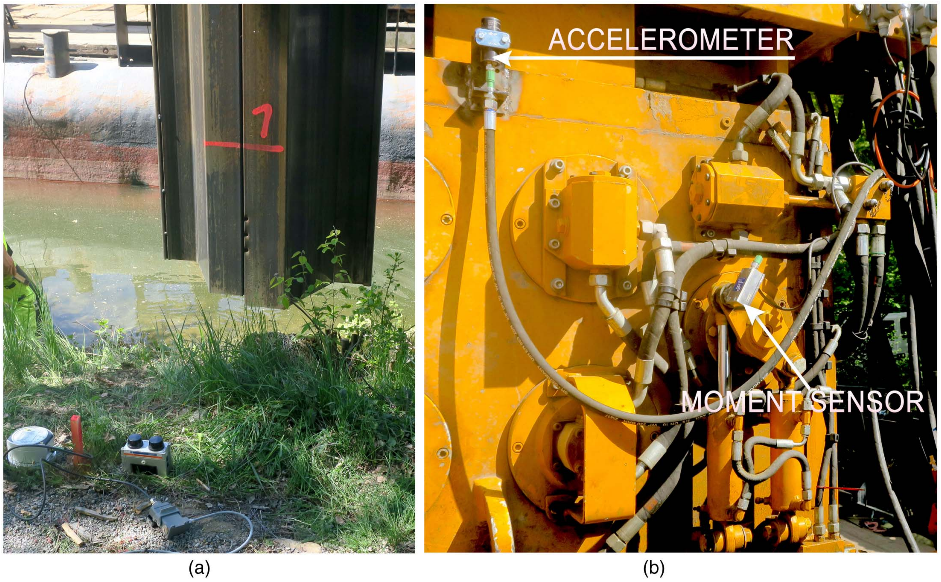

Fig. 3. Installation of double sheet pile in trial area; see Fig. 2: (a) view of geophones; and (b) instrumented vibrator.

Table 1. Dieseko PVE 40VM vibrator characteristics according to manufacturer

Parameter	Value	Unit
Dynamic mass excluding clamp	4,300	kg
Dynamic mass including clamp	6,900	kg
Eccentric moment	0–40	kgm
Maximum centrifugal force	0–1,775	kN
Maximum frequency	38 (33[a])	Hz
Maximum amplitude excluding clamp[b]	19	mm
Maximum amplitude including clamp[b]	11.6	mm
Maximum operating pressure	35	MPa

[a] Specified by manufacturer.
[b] Peak-to-peak amplitude.

vibration amplitude) could be varied. Fig. 3(b) shows the vibrator with the accelerometer and the sensor used to measure the eccentric moment.

Sheet Piles

Double sheet piles of type AZ 38-700N were used in the initial driving test; see Fig. 3(a). The mass of the 13.8-m-long sheet pile was 3,500 kg. The cross-sectional area of the sheet pile toe was 322 cm^2 and the coating area (one side, excluding inside of lock) was 2.05 m^2/m. The nominal displacement amplitude of the vibrator without the sheet pile but with clamp was 11.6 mm; see Table 1.

Site Conditions

The geotechnical conditions of the site are characterized by an esker, deposited during the latest glacial period. At the test location, the water level in the canal, and thus the groundwater table, was located approximately 1.5 m below the ground level at the trial pile location. The sheet pile was installed at the shoreline of the slope. The inclination of the more than 10-m-high slope was approximately 2 (H):1 (V). The esker comprises mainly sand and gravel deposited in a postglacial river about 10,000 years ago. Extensive soil investigations were carried out before the start of the project, using different types of penetration tests and soil sampling. The grain size d_{10} ranged from 0.3 to 1.7 mm. The coefficient of uniformity C_u ranged between 5.5 and 9.2 mm. Layers of dense gravel and boulders or granite blocks occurred locally. Thus, the driving conditions can differ significantly within a short distance. For the sheet piles, a drivability investigation in the form of dynamic penetration tests by superheavy dynamic probing, HfA (a Swedish dynamic penetrometer equivalent to DPSH-A), was carried out. The HfA test measures the number of blows to penetrate 0.2 m (N_{20}) by a 63.5-kg mass falling free from 0.5-m height onto a 32-mm-diameter rod. Three dynamic penetration tests were performed in the vicinity of the trial area and the results are shown in Fig. 4. The penetration resistance, N_{20}, typically ranged between 5 and 20, indicating a gravelly sand of medium-dense to dense sand. The N_{20} values exceeding 25 are due to the probe encountering stiff gravel layers and stones. Two tests were located in the channel (where canal bottom was at 5-m depth) and one test at the foot of the slope. Unfortunately, the closest test to the sheet trial was located at a distance of approximately 15 m. Therefore, the results need to be considered as indicative only of the soil conditions.

Swedish experience about the relationship between HfA and CPT results are summarized in Table 2 (TK Geo 13 2013).

Referencing also a large number of HfA and CPT investigations in other areas of the project site, the following is an average relation between HfA and CPT: q_c (MPa) = $0.9N_{20}$ was obtained, which is in reasonable agreement with Table 2.

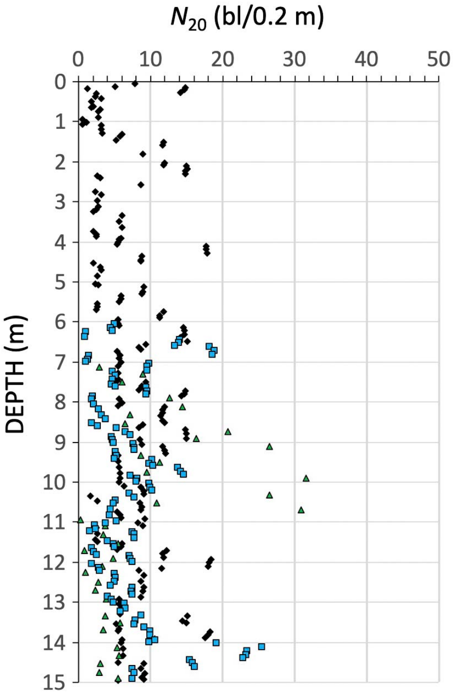

Fig. 4. Results of three dynamic penetration tests near trial area.

Table 2. Density classification of granular soils according to HfA and CPT

	HfA	CPT[a]	CPT[b]
Density	N_{20} (blows/0.20 m)	q_c (MPa)	q_c (MPa)
Very loose	0–4	0–2.5	<2
Loose	4–8	2.5–5	2–4
Compact	8–12	5–10	4–12
Dense	12–25	10–20	12–20
Very dense	>25	>20	>20

[a] TK Geo 13 (2013).
[b] International classification.

Test Run of Vibrator

Few case histories of vibratory driving have been reported where the performance of the vibrator was checked against the specifications provided by the manufacturer. However, such data are important in order to verify the characteristics of the vibrator power pack and to assure that the measuring system works as assumed. Therefore, before the start of the driving tests, the freely suspended vibrator equipped with clamp but not connected to a sheet pile was test run. The vibrator was run at five levels of eccentric moment: 10%, 30%, 60%, 75%, and 85% of the maximum eccentric moment ($M_{e,\max} = 40$ kgm). The measurements compared with the specifications are given in Table 1. The specifications indicated a maximum frequency of 33 Hz. However, the power pack, which was used to activate the vibrator, enabled operating at the slightly higher maximum flow, achieving a maximum frequency of 38 Hz. Fig. 5 shows the results of the test run for different values of the eccentric moment, M_e; the effect of vibration frequency, f, on the displacement amplitude, S ($2s$); hydraulic pressure, p; and the centrifugal force, F_v. Due to the added mass of the sheet pile and sheet pile–soil interaction, the centrifugal force developed by the vibrator does not necessarily correspond to the dynamic force actually transferred to the sheet pile (e.g., as measured with strain gauges).

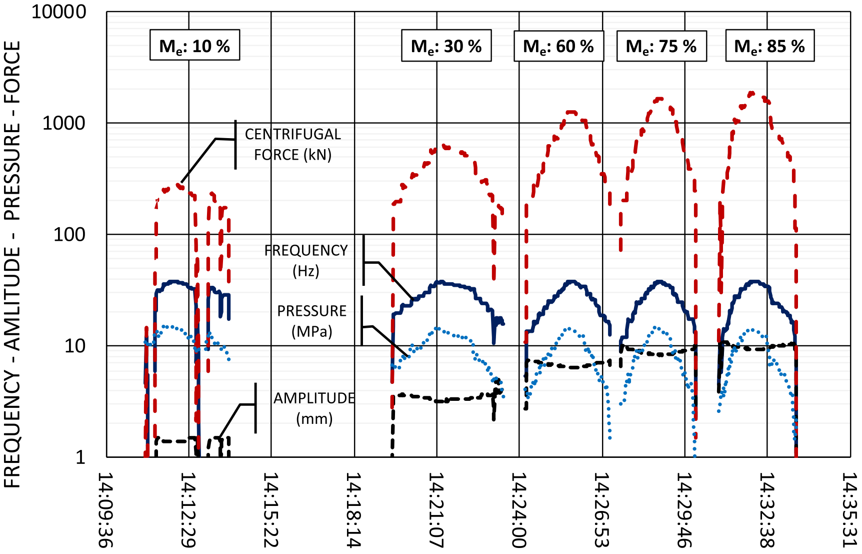

Fig. 5. Calibration test of free-hanging vibrator (with clamp) showing the effect of the stepwise increase of eccentric moment (%) and variation of vibrator frequency on centrifugal force, pressure, and displacement amplitude; see Table 1. The ordinate is in logarithmic scale.

This aspect is important when performing detailed drivability studies and has been discussed in detail by Whenham and Holeyman (2012).

The centrifugal force developed by the vibrator depends on the eccentric moment and the vibration frequency. However, the centrifugal force does not necessarily correspond to the dynamic force actually transferred to the sheet pile (as measured with, e.g., strain gauges).

At each level of the eccentric moment, the frequency was varied between 15 and 38 Hz, but the displacement amplitude was almost unchanged. However, because the centrifugal force is a function of the vibration frequency and the eccentric moment, at a maximum frequency of 38 Hz, the measured maximum centrifugal force was 1,840 kN. This value is slightly higher than the nominal value of 1,775 kN given in the specifications provided by the vibrator manufacturer. Different displacement amplitudes may be observed between the sheet pile head and sheet pile toe, in particular during hard driving (refusal), as has been described by Whenham and Holeyman (2008).

Three driving tests were performed to investigate the influence of vibration frequency and eccentric moment on sheet pile penetration and ground vibrations. Test 1 focused on the influence of eccentric moment and frequency, Test 2 on the resonance frequency of the vibrator-pile-soil system, and Test 3 on the performance of a less powerful vibrator.

Driving Test 1: Constant Frequency and High Eccentric Moment

Test 1 was performed with the 13.8-m-long double sheet pile. MPCS sensors were used to monitor the performance of the vibrator, the sheet pile, and the dynamic response of the ground. Triaxial geophones were used to measure the vertical, radial, and tangential vibration velocities. The time history of vibrations was recorded, from which RMS values of vibration velocity were determined. The geophones were installed on the ground at the top of the slope at a 4-m horizontal distance; see Fig. 2. To take into account the influence of the sloping ground surface near the sheet pile, which can amplify horizontal vibrations, the resultant of the three vibrations component, called the *R* vector, was determined. The sheet pile was installed using 85% (35 kgm) of maximum eccentric moment (40 kgm).

Installation of the sheet pile to 7.7-m depth took 1 min, leaving 5.1-m aboveground. Driving was stopped without reaching refusal. A summary of the 60-s driving time record is shown in Fig. 6. The penetration depth of the sheet pile is shown along the negative ordinate. For operational reasons, measurements started at 1.5-m depth and the sheet pile was vibrated to 7.7-m depth with a constant frequency of 38 Hz. The vibrator acceleration (17*g*), and displacement amplitude (6 mm) were constant. This observation is important because it indicates that the shaft resistance, which affects the displacement amplitude, was negligible during driving. The hydraulic pressure ranged between 14.2 and 15.5 MPa, suggesting that only about 50% of the maximum pressure was required to install the sheet pile. The driving records show that the sheet pile

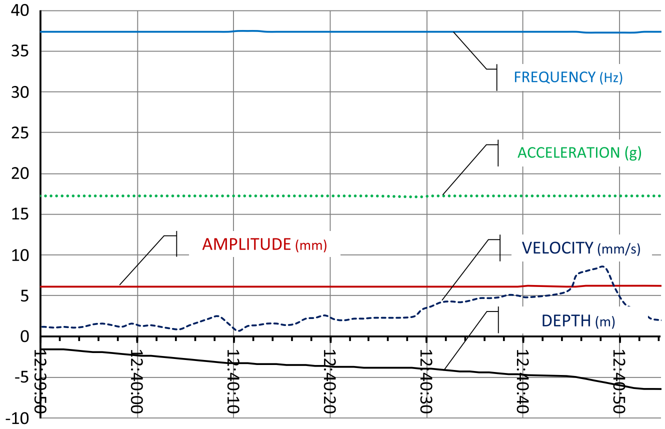

Fig. 6. Time record of Driving Test 1 with constant frequency and maximum eccentric moment: frequency, acceleration, displacement amplitude, and ground vibration velocity (*R* vector) as a function of time. Also shown is the penetration depth of the sheet pile.

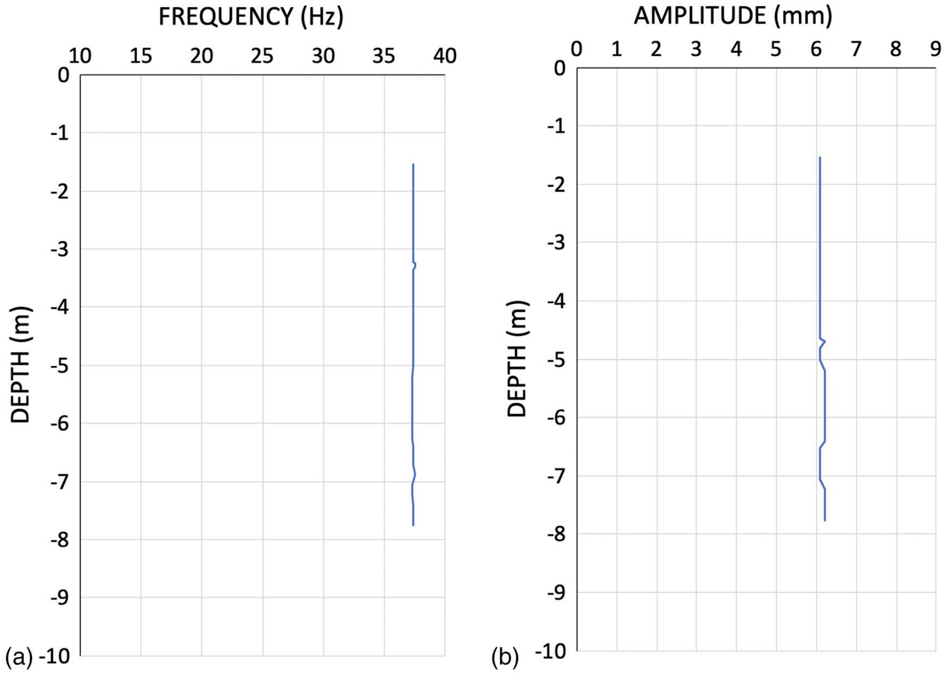

Fig. 7. Driving Test 1: (a) vibration frequency; and (b) sheet pile displacement amplitude during driving; see Fig. 6.

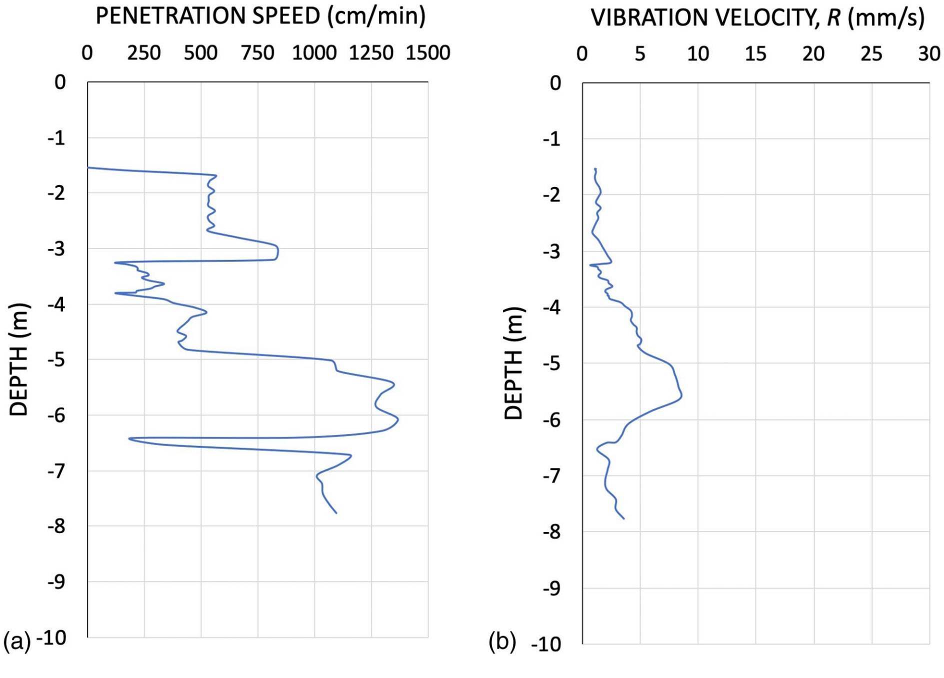

Fig. 8. Driving Test 1: (a) sheet pile penetration speed; and (b) vector of ground vibrations; see Fig. 6.

could be installed in the medium-dense to dense sand without activating the full power of the vibrator; see Fig. 4.

Fig. 7 shows the variation of the vibration frequency and the displacement amplitude as a function of depth.

The vibration frequency was kept constant at 38 Hz; see Fig. 7(a). The displacement amplitude was practically constant during the penetration phase, indicating that at a high vibration frequency (38 Hz), the shaft resistance was negligible; see Fig. 7(b). From the depth measurement and the time record, the sheet pile penetration speed v_P was derived according to Eq. (1). Fig. 8(a) shows that v_P ranged mostly between 500 and 1,300 cm/min. A sheet pile penetration speed higher than 500 cm/min is typical for efficient driving (5 min to reach 10-m depth). However, between 3.2- and 3.8-m depth, the penetration speed decreased to 250 cm/min, indicating that the sheet pile had to penetrate a dense layer.

Ground vibrations were measured in three directions and the resulting velocity vector (R) was determined. Fig. 8(b) shows that

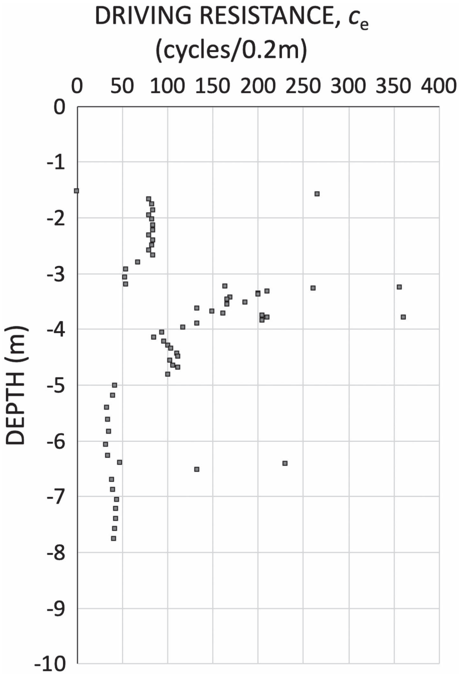

Fig. 9. Driving Test 1: equivalent number of vibration cycles at constant frequency (38 Hz).

at 4-m distance, ground vibrations were generally low (<2 mm/s), but increased when the toe of the sheet pile penetrated into the dense layer between 3.2 and 3.8 m and below 6 m. Because the displacement amplitude of the sheet pile did not change during driving [Fig. 7(b)], it can be concluded that ground vibrations originated primarily from the toe of the sheet pile and that the increase was due to the presence of a denser layer. Ground vibrations decreased again below about 6-m depth, indicating that the toe penetrated looser soil.

The driving resistance based on the equivalent number of vibration cycles, c_e, can be determined according to Eq. (1); see Fig. 9. The sheet pile was vibrated at 38 Hz and at a constant eccentric moment. Therefore, the sheet pile driving resistance, expressed as cycles/0.2 m, can be compared to the HfA N_{20} penetration resistance; see Fig. 4. The dense layer encountered in the HfA test at about 2.2-m depth is probably the layer with increased driving resistance identified between 3.2- and 3.8-m depth in Fig. 9. The depth difference is likely due to the about 15-m distance between the HfA penetration test and the test pile location.

Driving Test 2: High Eccentric Moment and Resonance Test

The objective of Driving Test 2 was to determine the resonance frequency of the vibrator–sheet pile–soil system. Sheet pile installation was at 1-m distance from the previously installed but not extracted sheet pile. At the start, the same vibrator settings as during Test 1 were used. Fig. 10 summarizes the driving record of measured parameters (frequency, velocity, amplitude, and depth) versus time. The vibrator was started at 38 Hz and operated at an eccentric moment of 35 kgm, the same vibrator settings as during Test 1. The vibrator acceleration was initially $16g$ and the displacement amplitude was 6 mm. At 4.5-m depth, the vibration frequency was gradually lowered from 38 to 24 Hz and kept at this frequency for a period of 10 s. The ground vibration velocity and the displacement amplitude reached a maximum value and it was concluded that the system resonance frequency was around 24 Hz. Thereafter, the frequency was increased back to 38 Hz.

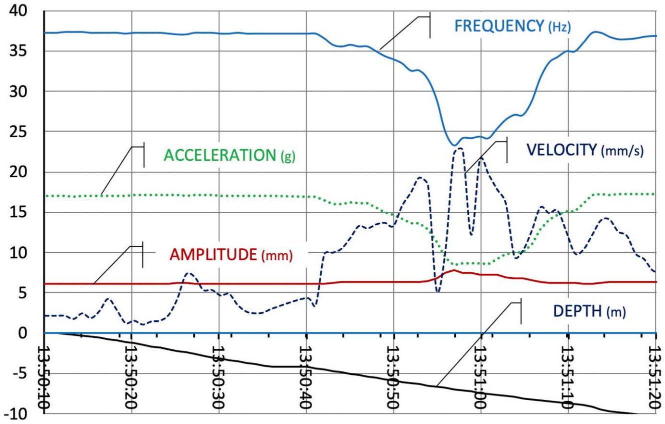

Fig. 10. Time record of Driving Test 2 to 10-m depth with eccentric moment of 35 kgm.

The objective of the test was to investigate the effect of frequency variation on displacement amplitude and ground vibration (R vector) when the system operated close to resonance. The variations of the vibration frequency and the displacement amplitude with depth of penetration are shown in Fig. 11. Down to 4.5-m depth, at a vibration frequency of 38 Hz, the displacement amplitude was 6 mm and almost constant, similar to that during Driving Test 1. However, when the vibration frequency was gradually lowered to 24 Hz from 4.5- to 7-m depth, the displacement amplitude increased to 8 mm. Thus, at the 24-Hz resonance frequency, the sheet pile and the surrounding ground were vibrating in phase and the sheet pile acted as an antenna for emission of vibrations. When the vibration frequency again reached 38 Hz, the displacement amplitude returned to 6 mm and vibration velocity decreased.

Figs. 12(a and b) show the distribution of sheet pile penetration speed and ground vibration velocity with depth, respectively. The penetration speed was initially high, but decreased when the vibration frequency was lowered. At the 24-Hz frequency from 6- to 9-m depth, the penetration speed reduced from about 1,200 to 750 cm/min. The effect of a boulder on the penetration speed can be observed at 4.2-m depth. Below 9-m depth, when the frequency was again increased, the penetration speed also increased. At resonance (24 Hz), the ground vibration velocity increased from about 4 to 22 mm/s. Thus, at system resonance, ground vibrations were amplified by a factor of 5.5.

The sheet pile driving resistance was calculated according to Eq. (1) and is shown in Fig. 13. Because the sheet pile penetration speed was high, the number of vibration cycles was low and almost constant with depth. The number of vibration cycles, c_e, ranged between 50 and 80 cycles/0.2 m, with the exception of locally higher values probably due to boulders in the sand deposit. The c_e values can be compared with the dynamic penetration resistance, N_{20}, which ranged between 5 and 10 blows/0.2 m; see Fig. 4. The c_e value was not visibly affected by the change in frequency.

Driving Test 3: Low Eccentric Moment and Resonance Test

Test 3 was carried out 3-m farther away, next to Test 2. The objective was to simulate a less powerful vibrator using a lower eccentric moment. The eccentric moment of the vibrator was reduced to 15 kgm (30% of the maximum value). Driving started with a

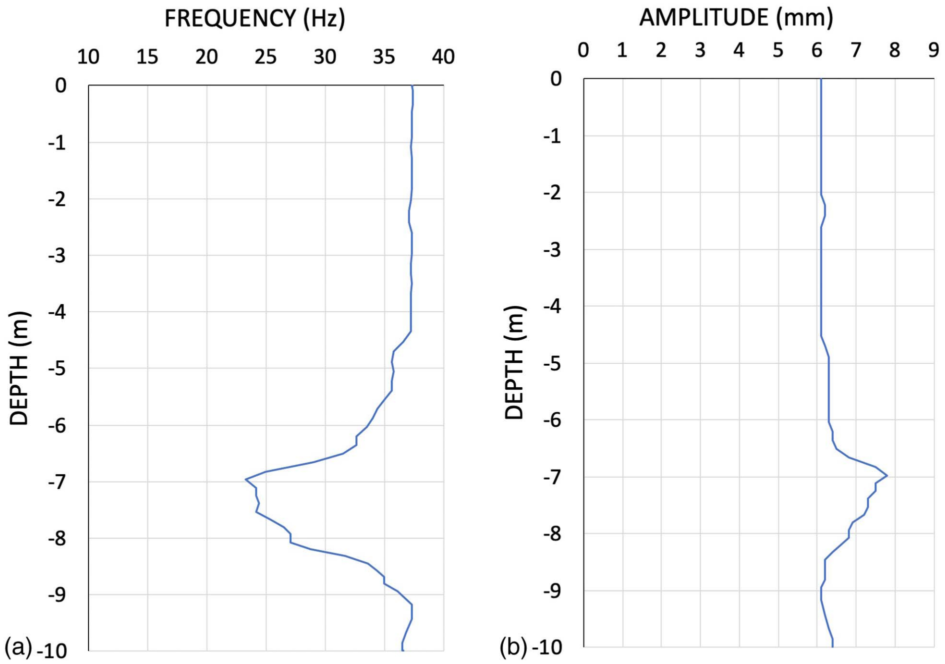

Fig. 11. Driving Test 2: (a) vibration frequency; and (b) sheet pile displacement amplitude during driving with variable frequency; see Fig. 10.

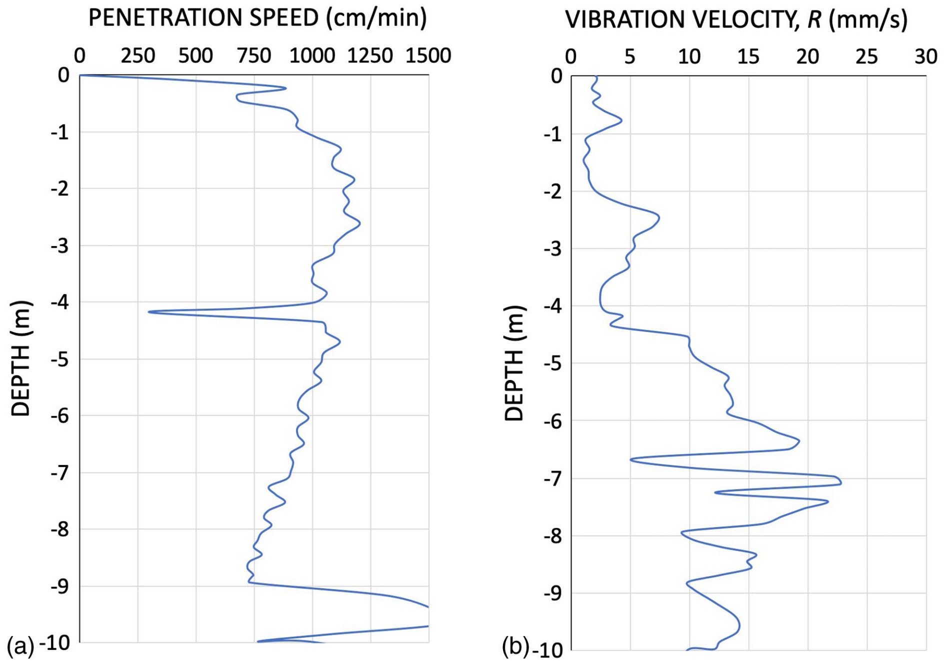

Fig. 12. Driving Test 2: sheet pile penetration speed and ground vibrations (*R* vector); see Fig. 10: (a) penetration speed; and (b) ground vibration velocity.

maximum frequency of 38 Hz. The sheet pile was installed to 10-m depth. The time record of measurements is summarized in Fig. 14. The vibrator acceleration was initially $4g$ and the displacement amplitude 1.5 mm. These lower values are due to the reduced eccentric moment. At 4.8-m depth, the vibration frequency was reduced to zero from 38 Hz and then increased to 24 Hz, which corresponded to the resonance frequency recorded during Driving Test 2. Thereafter, the vibration frequency was again reduced to 2 Hz and then returned to 38 Hz. The ground vibration velocity (*R* vector) was measured at a horizontal distance of 4 m.

The variation of the vibrator frequency and the sheet pile displacement amplitude with depth are shown in Fig. 15. During the initial driving phase at 38 Hz, the sheet pile displacement amplitude was approximately 1.5 mm. This low displacement amplitude is due to the reduced eccentric moment (15 kgm). Between 4.8- and 8.2-m depth, the system resonance frequency was determined by two tests, varying the frequency between 38 and 2 Hz, 2 and 25 Hz, and, finally, 38 Hz. When the frequency was reduced to below 10 Hz, the vibrator started to slow down and the displacement amplitude decreased. Around 24 Hz, resonance occurred, the

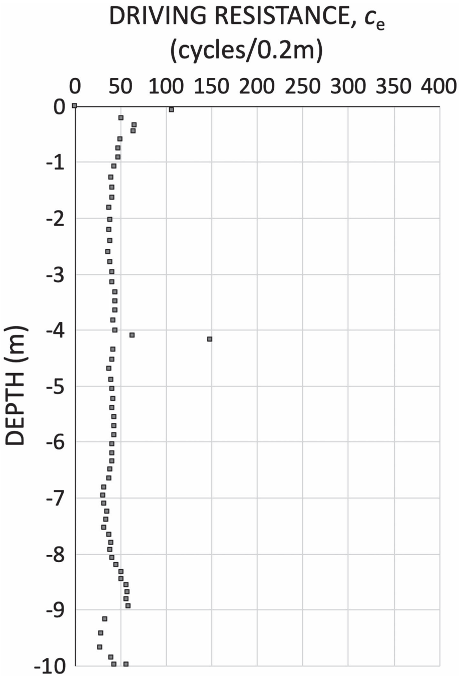

Fig. 13. Driving Test 2: equivalent number of vibration cycles during vibratory driving with frequency varied between 38 and 24 Hz.

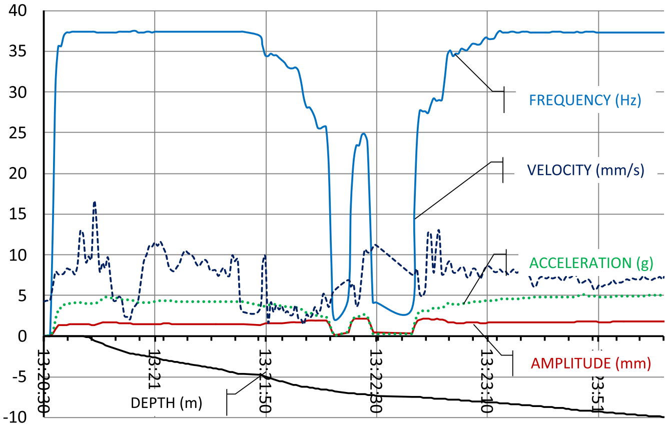

Fig. 14. Time record of Driving Test 3 to 10-m depth with reduced eccentric moment of 15 kgm. The vibration frequency was lowered between 5 and 7.5 m to determine system resonance. The effects of frequency variation on displacement amplitude and ground vibration (R vector) are shown.

frequency of which was approximately the same frequency as the resonance frequency of Driving Test 2. Again, the displacement amplitude increased at resonance from 1.5 to about 2.1 mm, corresponding to a 40% amplification.

Fig. 16(a) shows the sheet pile penetration speed and the ground vibration velocity as a function of depth. Initially, in spite of the reduced eccentric moment, the penetration speed was high but decreased with depth. Below 4.5 m, when the vibration frequency was lowered, the penetration speed decreased to very low values; at resonance (24 Hz), the penetration speed had reduced from about 750 to about 200 cm/min.

Fig. 16(b) shows the variation of the ground vibration velocity as a function of depth. Although the vibrator was initially run at a high frequency (38 Hz), the ground vibration velocity was relatively high (8–12 mm/s), with the exception in the loose layer between 1.5 and 2 m. There is a slight increase of ground vibration velocity during the resonance test, but the data are affected by the vibrator shutting down at two instances.

During the resonance test, the ground vibration velocity increased from about 5 to 12 mm/s. Thus, as a result of system resonance, ground vibrations were amplified by a factor of about 2.5.

The sheet pile driving resistance was determined from the sheet pile penetration speed and the vibration frequency. The driving resistance calculated according to Eq. (1) is shown in Fig. 17. The sheet pile penetration speed during Driving Test 3 with a reduced eccentric moment (15 kgm) was significantly lower than during the previous tests (35 kgm). The number of vibration cycles, c_e, ranged between 80 and 20 cycles/0.2 m down to 7-m depth. Below this level, the resistance increased to between 200 and 300 cycles/0.2 m.

Comparison of the Results of the Driving Tests

The objective of the three driving tests was to investigate the influence of the vibration frequency and the eccentric moment on the sheet pile penetration and ground response. During Driving Test 1, the vibrator was operated at its maximum frequency and maximum eccentric moment. All parameters were kept constant during the test. It can be concluded that the vibrator with an eccentric moment of 35 kgm and operating at a frequency of 38 Hz could easily install the sheet pile into the medium-dense to dense sand. The driving resistance was primarily generated by the toe resistance, while the shaft resistance was negligible. This observation is confirmed by the fact that the sheet pile displacement amplitude did not increase with depth. Ground vibrations were generally low and occurred when the toe of the sheet pile entered into a harder layer or encountered stones or boulders. The sheet pile driving resistance was generally below 90 cycles/0.2 m, but increased in the denser layer between 3 and 5 m.

During Driving Test 2, the sheet pile was installed with the same eccentric moment (35 kgm) as during Driving Test 1, but the vibration frequency was reduced between 5 and 9 m to determine the resonance frequency of the vibrator–sheet pile–ground system. During excitation at the resonance frequency, two important observations can be made. At first, at resonance, the sheet pile displacement amplitude increased, indicating that the sheet pile was vibrating in phase with the surrounding soil. As a consequence, ground vibrations were amplified and emitted to the surrounding soil. The sheet pile penetration speed was initially high, but decreased gradually due to the lowering of the vibrator frequency. The sheet pile driving resistance was almost constant with depth, at around 50–90 cycles/0.2 m.

The third driving test was performed at a reduced eccentric moment (15 kgm) to simulate a less powerful vibrator. Between 5- and 8-m depth, the vibration frequency was reduced to below 10 Hz to perform the two resonance tests, after which the operating frequency was returned to 38 Hz. Due to the lower eccentric moment, the displacement amplitude of the sheet pile was comparatively lower. However, in spite of the less powerful vibrator, ground vibrations were significantly higher than in the case of a more powerful vibrator (maximum eccentric moment). It is no surprise that the sheet pile penetration speed was markedly lower and the sheet pile driving resistance higher.

The result contrasts with the common opinion among practitioners that a more powerful vibrator (higher eccentric moment

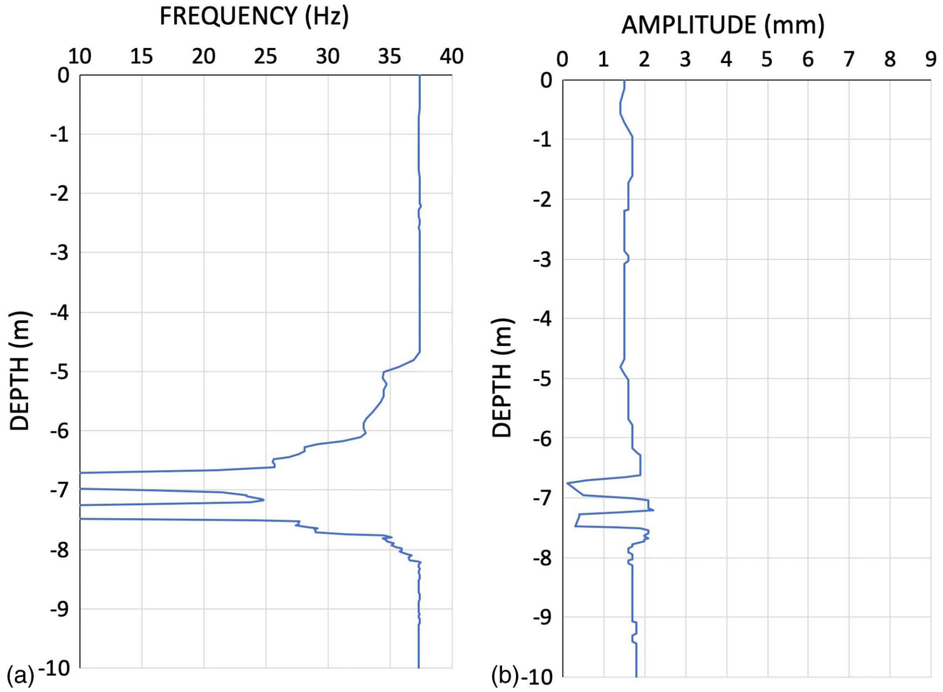

Fig. 15. Driving Test 3: (a) vibration frequency; and (b) sheet pile displacement amplitude as function of depth; see Fig. 14.

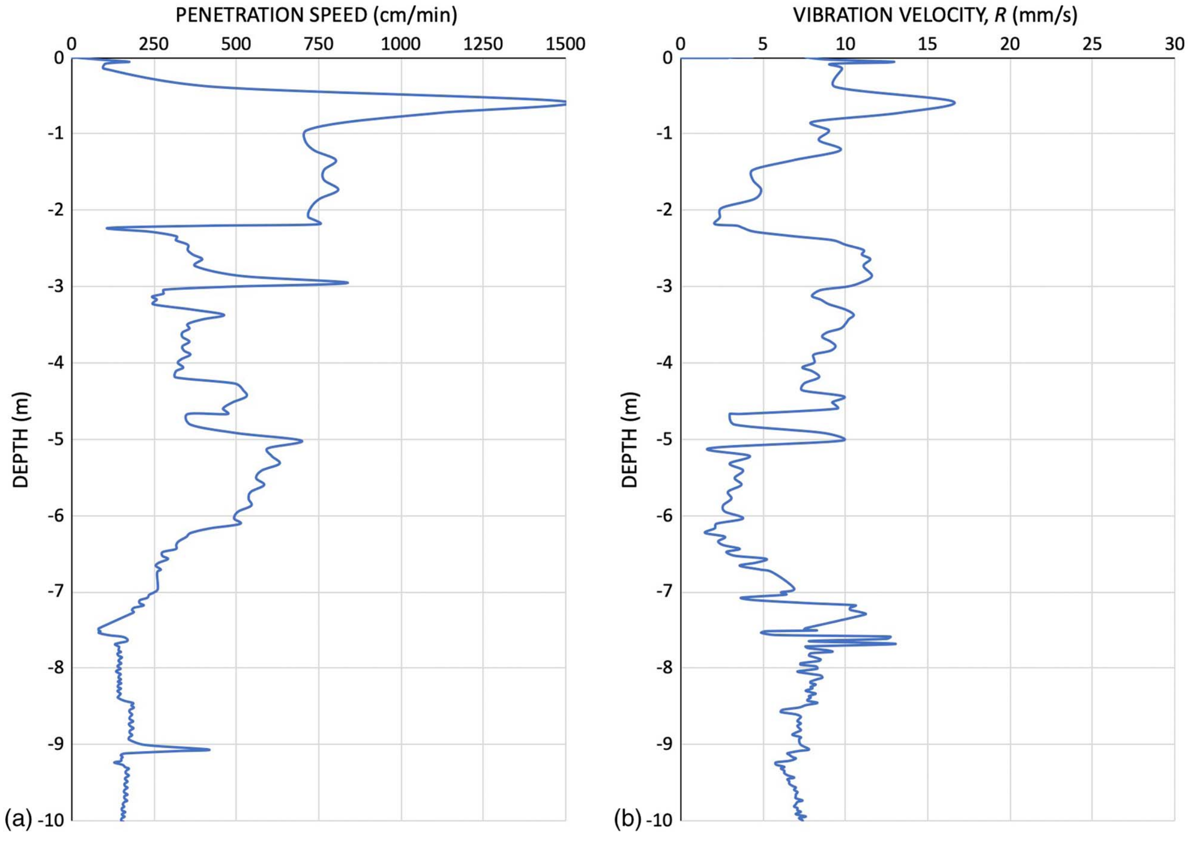

Fig. 16. Driving Test 3: sheet pile penetration speed and ground vibrations (*R* vector); see Fig. 14: (a) penetration speed; and (b) ground vibration velocity.

and higher centrifugal force) causes stronger ground vibrations. The vibration measurements of the three tests are compared in Fig. 18. They show that at the same frequency, stronger ground vibrations (larger vibration velocity) actually occurred with a vibrator operating at a lower eccentric moment.

Drivability Prediction

It is generally difficult to theoretically predict the drivability of sheet piles because the efficiency of driving is affected by a variety of parameters, such as the geotechnical conditions (penetration

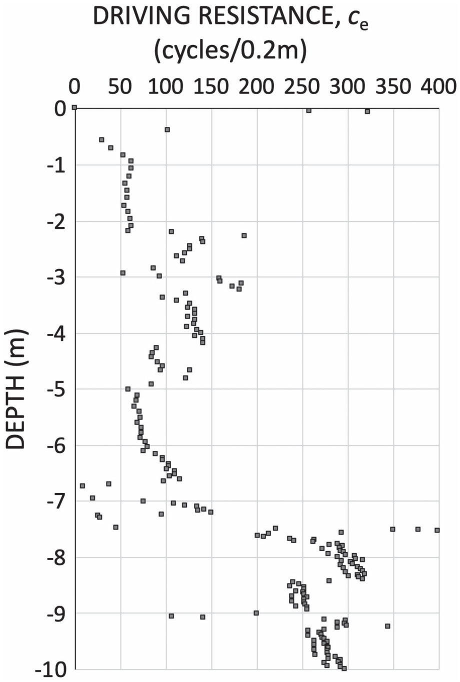

Fig. 17. Driving Test 3: equivalent number of vibration cycles at constant displacement amplitude and penetration resistance (frequency varied between 38 and 10 Hz, eccentric moment = 15 kgm).

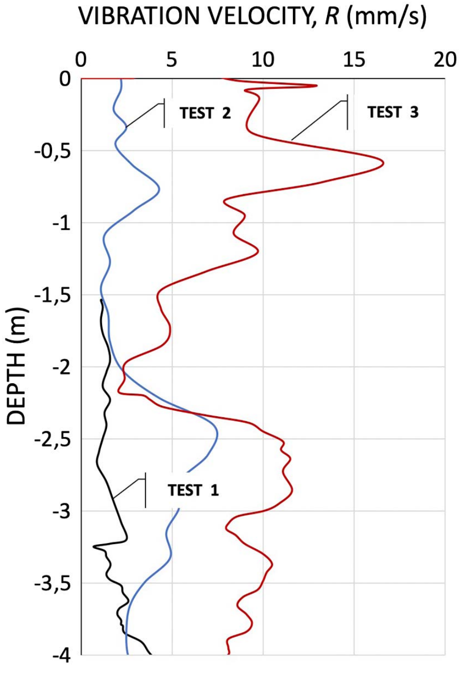

Fig. 18. Comparison of ground vibration velocity for three test runs down to 4-m depth, during which the vibrator was operated at 38 Hz. Test 3 results in higher ground vibrations despite the reduced eccentric moment.

resistance) and the dynamic characteristics of the vibrator as well as the size and shape of the sheet piles. An additional factor that can affect drivability is the effect of lock friction when driving interconnected sheet piles (wall). Empirical correlations have been developed by vibrator manufacturers to estimate the required eccentric moment for different sheet pile sizes and driving conditions (Massarsch et al. 2017). However, drivability can be determined more reliably by field trials, as described previously. Such tests can establish project-specific correlations between the penetration resistance (e.g., N_{20}) and the number of equivalent vibration cycles (c_e) for different vibrators and sheet pile sizes.

For the subject project, assuming that the vibrator was operated with an eccentric moment of 35 kgm at a frequency of 38 Hz, an average value of the driving resistance, expressed by $c_e \approx 100\ \mathrm{cycles/0.2\ m}$ could be assumed. Such a value could be correlated to results of penetration tests, assuming in the present case an average (upper limit) $N_{20} \approx 15$. Assuming that a 15-m-long sheet pile would be driven under the assumed conditions, the corresponding sheet pile penetration speed could be determined according to Eq. (1), $v \approx 450\ \mathrm{cm/min}$. Thus, the penetration time required to reach 15-m depth would be about 3.3 min. According to this concept, the drivability could be evaluated for different sizes of sheet piles and vibrator capacities.

The practical benefits of sheet pile monitoring using the MPCS concept are significant. For instance, a database could be developed for different geotechnical conditions, in which measured penetration resistance would be correlated to the driving resistance of different sheet pile sizes and vibrator parameters. This concept is already used by the authors in connection with DVVC projects, in which the compaction probe size, driving frequency, and penetration resistance are correlated to required penetration resistance. The probe penetration speed is then estimated. Thereafter, trial compaction is carried out at compaction points placed at a certain grid configuration and the probe driving resistance is recorded at each compaction point as well as, afterward, in the diagonal point of the grid. Thereafter, penetration tests are again performed. These simple tests make it possible to establish a relationship between the compaction requirements, usually expressed in terms of penetration resistance, and the probe penetration resistance. This information is incorporated in the MPCS and enables the vibrator operator to see when the compaction criteria have been achieved.

Recommendations for Efficient Vibratory Driving

The objective of the presented test was to identify which parameters are important for efficient driving of sheet piles. Modern vibrators allow the variation of several parameters, such as the vibrator frequency and the eccentric moment. However, in practice, vibrators are often selected without considering the project-specific requirements. Often, a smaller vibrator is chosen to minimize equipment costs and the operating frequency is selected as low as possible to reduce wear and operational costs. However, selecting a vibrator power pack system that is too small can result in low driving performance and excessive vibrations. In the opinion of the authors, it is generally more cost-effective to choose a more powerful vibrator and to optimize the driving process by field tests. From such tests, the optimal vibrator frequency can be determined, avoiding resonance effects that result in slow sheet pile penetration and excessive environmental effects.

Conclusions

Sheet pile installation tests were carried out in an esker, composed of sand with gravel and stones. The soil conditions at the test site were variable. Heavy dynamic penetration tests (DPSH-A) were available from three test points, located at a distance of about 15 m. The average penetration resistance ranged between $N_{20} = 5$ and 20, corresponding to a medium-dense to dense sand.

Driving tests were performed where the eccentric moment and vibrator frequency were varied in a consistent manner. The vibrator performance specifications provided by the equipment manufacturer can be checked by simple tests prior to the start of the project.

An important aspect of the tests was the detailed measurement and monitoring of vibratory driving and ground response using an advanced MPCS, which guides the vibrator operator during the sheet pile installation process.

For the installation of a 13-m-long double sheet pile, a vibrator with variable frequency (0–38 Hz) and variable eccentric moment (0–40 kgm) was used.

According to the presented concepts, the vibratory driving equipment can be used as a large-scale ground investigation machine, provided that the operating parameters are known and controlled. By such tests, the driving resistance and sheet pile penetration speed can be measured—parameters that are important for the planning and execution of sheet pile installation projects. With this information, it is possible to determine the sheet pile driving resistance, expressed in terms of cycles/0.2m. The results of such tests can be used to develop site-specific correlations with penetration tests, from which a knowledge base can be developed for planning future projects.

An initial test run of the vibrator with clamp was used to verify the specifications provided by the machine manufacturer. Good agreement was obtained between measurements and calculated values to machine specifications.

Test 1 was run at a constant frequency of 38 Hz and an eccentric moment of 35 kgm. It can be concluded that for the prevailing ground conditions, a double sheet pile could be easily installed without generating excessive ground vibrations.

Driving Test 2 was carried out with the same eccentric moment. However, after penetration to about 4 m, the vibrator frequency was gradually reduced from 38 to 24 Hz. The tests showed that when approaching resonance of the vibrator–sheet pile–soil system, sheet pile penetration speed decreases and ground vibrations increase, Thus, in order to achieve efficient sheet pile installation, resonance conditions should be avoided.

Driving Test 3 was carried out to simulate a less powerful vibrator, with the eccentric moment reduced to 30%. The driving resistance when operating the vibrator at maximum frequency (38 Hz) was significantly lower than in the previous tests. Also, ground vibrations increased significantly. The resonance frequency was approximately the same as that for Driving Test 2 and appears thus to be independent of the eccentric moment.

From the detailed tests the following conclusions can be drawn:

- When a sheet pile was installed at a high frequency (38 Hz) and with a sufficiently high eccentric moment (35 kgm), sheet pile installation was fast, with a penetration speed generally exceeding 500 cm/min. Ground vibrations measured at 4-m distance were lower than 10 mm/s.
- The displacement amplitude was almost constant during driving, suggesting that the driving resistance was generated at the toe of the sheet pile.
- The resonance frequency of the vibrator–sheet pile–soil system was 24 Hz. It would have been difficult to estimate the resonance frequency theoretically, but it can be readily determined on site.
- When the sheet pile was vibrated at system resonance, the sheet pile displacement amplitude, as well as ground vibrations, increased significantly.
- Ground vibrations were significantly higher when the sheet pile was installed at 38 Hz but at a reduced eccentric moment (15 kgm).

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

Acknowledgments

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Notation

The following symbols are used in this paper:

c_e = equivalent number of penetration cycles per depth interval (e.g., cycles/0.2 m);
C_u = coefficient of uniformity;
$d_{10\%}$ = particle size where 10% of the particles are smaller;
f = vibrator operating frequency;
H = horizontal direction;
$M_{e,\max}$ = maximum eccentric moment;
N_{20} = number of blows to penetrate 0.2 m;
p = hydraulic pressure;
R = vector of vibration velocity;
V = vertical direction;
v = vibration velocity; and
v_P = sheet pile penetration speed.

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