Monitoring and Process Control of Vibratory Driving

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ABSTRACT: Vibrators are used increasingly in the foundation industry, primarily for installation of piles and sheet piles, but also for deep vibratory compaction. Fundamentals of vibratory driving are described that make it possible to choose vibrator performance parameters based on field monitoring and performance control. Variable frequency and amplitude vibrators have become available that make it possible to adapt the driving process to project-specific requirements. The components of modern electronic measuring systems are detailed that can be used to monitor, control, and document different aspects of vibratory driving. Two examples are presented—vibratory driving of sheet piles and resonance compaction—which show how the performance of vibrators and sheet piles can be analysed and adapted to meet specific requirements. By using the advanced monitoring and process control systems, the efficiency of vibratory driving is enhanced. From the retrieved parameters, a better understanding of the vibratory driving process is gained, which can be used to develop a valuable database.

KEYWORDS: Vibrator, Pile, Sheet pile, Compaction, Ground vibration, Monitoring.

1. INTRODUCTION

Powerful vibrators with variable amplitude and frequency have become available for use at different types of foundation works, such as driving and extracting of piles and sheet piles or compaction of granular soils. Hydraulic vibrators with variable frequency were first introduced in Europe during the 1980s. The operating frequency was varied using a special hydraulic system. The next step in this development was the introduction of vibrators with variable eccentric moment.

The advantage of the latter system is that the vibrator can be started up at zero eccentric moment (and thus zero movement amplitude). When the vibrator has reached the desired frequency, the eccentric moment (and thus the amplitude) can be gradually increased. By this process, resonance effects during the start-up and shut-down phase of the vibrator can be avoided. For a detailed description of vibrator types and their applications in foundation engineering, reference is made to the geotechnical literature, e.g. Viking (2002), Deckner (2017), DFI (2014) or Massarsch and Fellenius. (2017).

At present, in Europe and North America, hydraulic vibrators dominate, while in the Far East electrically powered vibrators are more common. Although vibrators are widely used, fundamental parameters governing the driving process are not yet fully appreciated by the foundation industry, and, in particular, by the foundation contractors, while manufacturers of vibrators do not always appreciate the geotechnical and dynamic aspects of vibratory driving that govern the practical application of their equipment. Moreover, an unfortunate communications gap appears to exist between manufacturers of vibrators and their users, the foundation contractors.

Although electronic equipment can measure a variety of performance parameters, the significance of these parameters for the application of vibrators is rarely appreciated. Thus, many of the advances made by equipment developers have not yet been applied in practice.

The paper illustrates by two examples how measuring different parameters during vibratory driving help to better understand the often complex process of dynamic pile-soil interaction. Better understanding of the vibratory driving process can result in improved driving performance, but it can also minimize environmental impact, such as excessive ground vibrations, (Massarsch et al. 2017a). At the same time, when changing vibrator characteristics, loose granular soils can be effectively improved using the resonance compaction concept, (Massarsch and Fellenius 2017).

2. FUNDAMENTALS OF VIBRATORY DRIVING

Two important parameters to be considered by contractors when selecting a vibrator for pile and sheet pile installation are the eccentric moment and the centrifugal force. From the eccentric moment, M_e (kgm), and the vibration frequency, f (Hz), the centrifugal force, F_v (kN) can be determined

$$F_v = M_e(2\,\pi\,f)^2 \tag{1}$$

Thus, the centrifugal force depends on the eccentric moment and the square of the operating frequency. In order to install piles or sheet piles in granular soils, the centrifugal force must be sufficient to overcome the shaft and toe resistances.

Another important parameter affecting the driving performance is the displacement amplitude, s (mm), which can be determined from the eccentric moment, M_e (kgm), and the vibrating mass, m_t (kg).

$$s = \frac{M_e}{m_t} \tag{2}$$

Note that vibrator manufacturers usually state the peak-to-peak amplitude (S = 2s).

The vibrating mass comprises all components of the driving system which need to be accelerated by the vibrator: vibrator mass, clamp, and sheet pile. Note that the static mass suspended on top of the vibrator by vibration dampers (elastomers) is not included as it serves primarily to tune the driving system. From Eq. 2, it can be seen that the displacement amplitude is independent of the operating frequency. Thus, in order to increase the amplitude, it is necessary to either increase the eccentric moment and/or to decrease the dynamic mass. A large displacement amplitude is generally required when driving piles or sheet piles into stiff cohesive soils. Also, the compaction effect increases with high displacement amplitude.

An important, but often neglected parameter for enhancing driving performance is the operating frequency of the vibrator. The dynamic force increases with increasing frequency, cf. Eq. 1. However, when the vibrator frequency is lowered gradually and approaches the resonance frequency of the vibrator-pile-soil system, penetration slows down and ground vibrations increase (Massarsch et al. 2017a).

At resonance, the pile or sheet pile oscillates in optimum phase with the surrounding soil, achieving an efficient emission of vibrating energy, an effect which is used in the resonance compaction concept

(Massarsch and Fellenius, 2017). However, the resonance mode should be avoided during vibratory driving in order to minimize negative environmental effects. This can be achieved by using vibrators with variable eccentric moment.

The significance of vibratory driving is illustrated in a video presentation, initially presented at the DFI International Conference on Piling and Deep Foundations (DFI/EFFC 2014).

3. MONITORING AND PROCESS CONTROL CONCEPT

The electronic control of vibrators has experienced a rapid development. Different types of sensors and field measuring systems have become available which can measure with high accuracy even complex dynamic processes under demanding field conditions. The measured parameters can be displayed in real time to the machine operator, providing the possibility to adjust and optimize the driving process. Thanks to the availability of modern computers and access to the Internet, large quantities of data can be compiled, stored, analysed, and transmitted from the project site to manufacturers, designers, or clients. In the present paper, the practical application of an advanced Monitoring and Process Control System (MPCS) is described and illustrated by examples. Key aspects of the MPCS concept include, not only real-time display of various parameters (monitoring), but also parameter adjustments to optimize the process (process control). In addition, the MPCS provides detailed documentation of the entire driving process for each pile or sheet pile, meeting even the most demanding quality control requirements.

An important long-term benefit of using the MPCS is that data collected from different projects can be fed into, and evaluated in a database. This aspect is of benefit for all participants in the foundation industry, i.e., equipment manufacturers, contractors, designers, and, last but not least, project owners.

3.1 Early Developments

The MPCS concept for vibratory driving was developed in the early 1980s with two objectives in mind: a) monitoring the vibratory driving process by displaying information in real time to the machine operator and b) controlling different vibrator parameters in order to actively optimize the driving process (driving, extraction, compaction). More than 30 years ago, a relatively simple electronic monitoring system was assembled and applied to resonance compaction, e.g., Massarsch and Vannest (1988). Figure 1 shows a digital volt-meter that served as oscilloscope to determine the optimal vibration frequency during compaction and probe extraction, as described in detail by Massarsch et al. (2017a).

Figure 1 Vibration monitoring of resonance compaction in 1988, at Annacis Island, Canada, (Massarsch and Fellenius 2017)

During the late 1980s, elements of an advanced vibratory compaction system were assembled, including an interactive display, instructing the machine operator with the aid of illuminated arrows to control the compaction probe movement and to adapt the vibrator operating frequency, Figure 2. The system was used on various large compaction projects in Europe, North America, and the Far East. A detailed description of the electronic monitoring system and its application to vibratory compaction was presented by Massarsch and Fellenius (2005).

At an early stage of system development, it was recognized that electronic monitoring could be applied to the optimization of the entire vibratory driving process for penetration and extraction of piles and sheet piles. In the case of pile and sheet pile driving, the objective is to avoid resonance effects, i.e., to minimize the emission of ground vibrations to the environment as well as providing good driving conditions.

Figure 2 Interactive display that guides the machine operator during the resonance compaction process showing compaction instruction display, Massarsch and Westerberg (1995)

In the case of pile and sheet pile installation, the desired efficient penetration and reduced ground vibration emission can be achieved when the pile or sheet pile is installed or extracted at a frequency significantly (about 1.5 times) higher than the system resonance frequency.

It is difficult to theoretically estimate the resonance frequency of the vibrator-pile-soil system. However, with the aid of the MPCS, vibration sensors (geophones), mounted on a building to be protected, and/or on the ground surface, can determine the system resonance frequency by field trials. The practical application of the MCPS concept will be described in the following sections. The MPCS was developed based on the DAVIS system developed by the company Gamperl & Hatlapa (GuH), Germany.

3.2 Elements of the MPCS

The most recent MPCS development can be used for a variety of different vibrator applications, such as driving or extracting piles and sheet piles, deep resonance or surface compaction using a vibratory plate. The following parameters are measured directly:

- Position of pile/sheet pile (GPS coordinates)
- Date and time (hh:mm:ss)
- Depth of sheet pile (m)
- Vibrator frequency (Hz)
- Acceleration of vibrator (cm/s^2)
- Hydraulic pressure of power supply (MPa)

- Ground vibration velocity (mm/s)
- Eccentric moment (kgm - optional)
- Static force (kN - optional).

The positions of sensors on the driving system are illustrated in principle in Figure 3. From measurements listed above, the following parameters can be derived:

- Frequency of vibrator (rpm)
- Movement amplitude at pile head (mm)
- Pile penetration speed (cm/min)
- Centrifugal force (kN)
- Penetration depth (m)
- Vibration cycles per depth interval (cycles/cm).

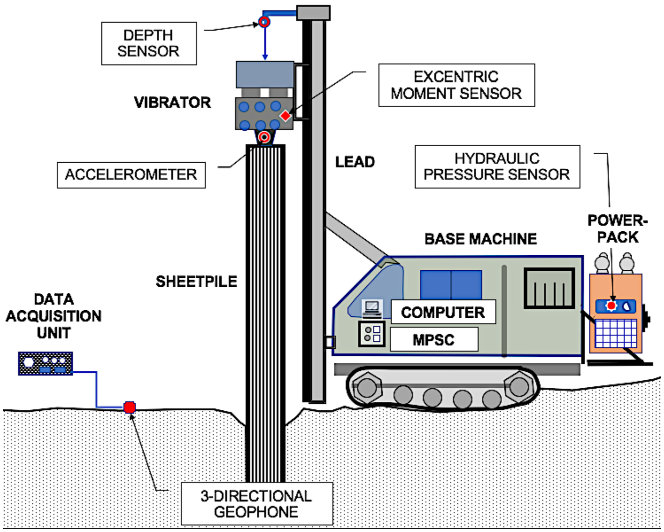


Figure 3 Principle of Monitoring and Process Control System (MPCS), showing sensors mounted on the rig and ground surface

All relevant information (measured and derived parameters) can be displayed on a screen to the machine operator. In addition, limiting values can be indicated as well as visual guidance (arrows, bar diagrams or dials) assisting the machine operator to optimize the respective process. An example of a screen display in the operator's cabin is shown in Figure 4.

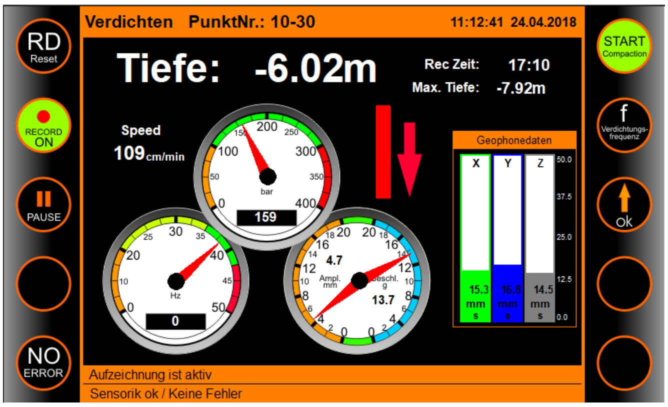
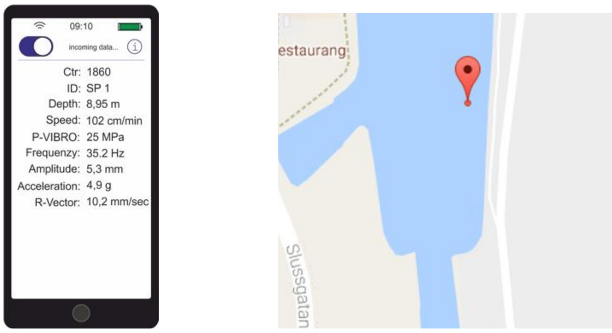


Figure 4 Display of measured and derived parameters by MPCS, developed by GuH

A powerful feature of the MPCS developed by GuH is the display of measured data in real time via the Internet. Data can be viewed on smart phone or tablets, located anywhere in the world. Figure 5 shows display of data via Internet using smart phone functions



a) Data display on iPhone b) Location of MPCS

Figure 5 Display of data via Internet using smart phone functions

3.3 Analysis of Measurements

In addition to the direct display in real time of measured and derived parameters to the machine operator (and/or site office personnel via wireless data transmission), all data are stored and available for post-treatment. An example of measured and derived parameters is shown in Figure 6. Details of the measured and interpreted parameters will be described in the following case histories.

4. EXAMPLE - SHEET PILE DRIVING

4.1 Site Conditions

In the following example, the application of the MPCS concept is demonstrated by a sheet pile installation project, located south of Stockholm. The soil at the project site was mainly sand, stone, and gravel. This paper describes some results of initial driving tests, performed in an area with relatively homogeneous soil conditions. The geological conditions are characterized by an esker, composed of sand and gravel down to 12 m depth. Cone penetration resistance (CPT) varied between q_c = 2 and 15 MPa. Similarly, the penetration resistance measured by heavy dynamic probing (DPH) varied generally between 5 and 20 bl/0.2 m.

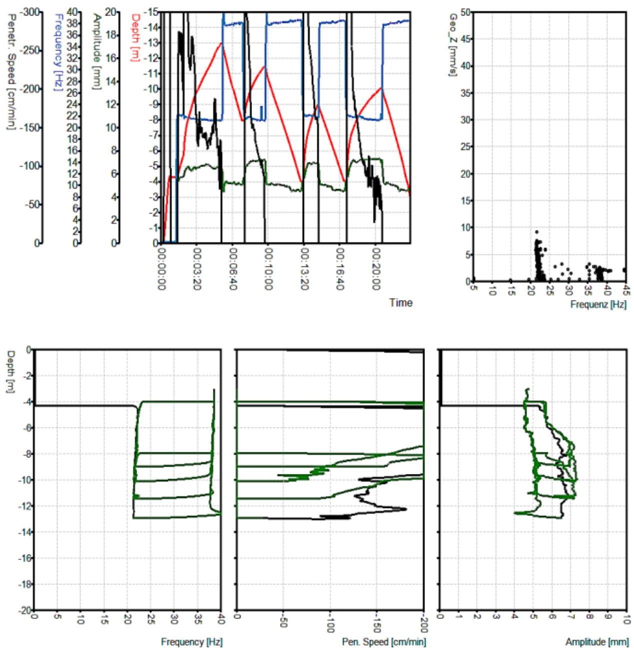


Figure 6 Illustration of MPCS data obtained during resonance compaction, Massarsch et al. (2017)

4.2 Vibrator

A vibrator with variable frequency and eccentric moment (amplitude) of type Dieseko PVE 40VM was used, having the nominal parameters specified by the manufacturer (Table 1). The vibrator was mounted on a crawler crane, type Liebherr HS853 HD Litronic with a lead. The operating weight of the rig was approximately 800 kN. The Power Pack PVE 800, piggy-back mounted on the rig, had a maximum power of 565 kW (768 hp) with an oil flow of 800 L/min. The vibrator was operated by remote control from which the vibrator frequency and the eccentric moment (vibration amplitude) could be varied.

A new development of the MPCS developed for the project was the incorporation of the eccentric moment sensor. The positions of the accelerometer and the moment sensor is indicated in Figure 3. Figure 7 shows the position of the accelerometer and eccentric moment sensor, which were mounted on the front of the vibrator.

Table 1 Vibrator characteristics according to manufacturer, type Dieseko PVE 40VM

Parameter	**Value**	**Unit**
Dynamic weight excluding clamp	4300	kg
Dynamic weight including clamp	6900	kg
Eccentric moment:	0 – 40	kgm
Max. centrifugal force:	0 – 1775	kN
Max. frequency:	2000 (33)	rpm (Hz)
Max. amplitude excluding clamp[1)]	19	mm
Max. amplitude including clamp[1)]	11,6	mm
Max. operating pressure	350 (35)	bar (MPa)

[1)] peak-to-peak amplitude

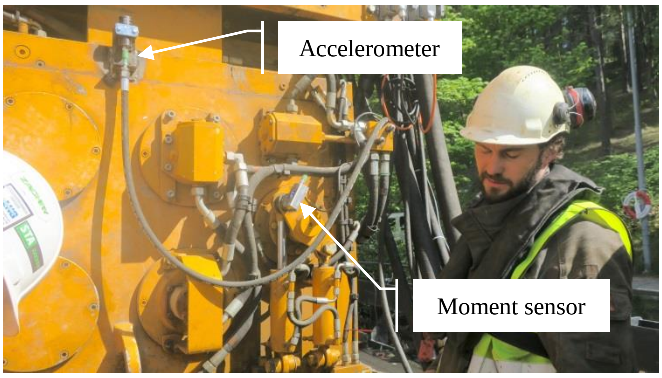


Figure 7 Accelerometer and eccentric moment sensor mounted on vibrator

4.3 Sheet Piles

Double sheet piles of type AZ 38-700N were used in the driving test, Figure 8. The mass of the 13.8 m long sheet pile was 3500 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. Thus, the total area of the sheet pile installed to 12 m (penetration depth) in contact with the soil, was 49.2 m^2.

The nominal vibration amplitude *s* of the vibrating system (vibrator-clamp-sheet pile) prior to installation can be determined from Eq.3

$$s = \frac{M_e}{m_t + m_s} \tag{3}$$

where M_e is the eccentric moment, m_t is the vibrating mass (vibrator, clamp, and sheet pile) and m_s is the mass of the sheet pile. Note that the peak-to-peak amplitude, $S = 2s$. In the case of a 13.8 m long, suspended sheet pile with a mass of 3,490 kg, the nominal double amplitude, *S*, of the suspended sheet pile was 7.7 mm at maximum eccentric moment.

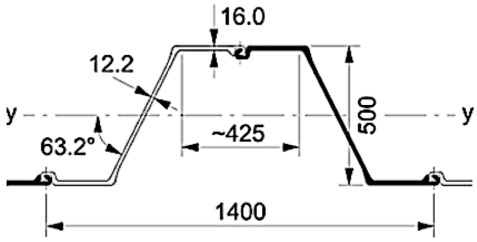


Figure 8 Dimensions of double sheet pile, type AZ 38-700N

4.4 Test Run of Vibrator

Before the start of the driving test, the freely suspended vibrator (without sheet pile) was test-run in order to verify the nominal vibrator performance parameters as given in Table. The results of a vibrator calibration run is shown in Figure 9, where the double displacement amplitude, *S*, frequency, *f*, and hydraulic pressure, p_h, are shown for different steps of the eccentric moment. The eccentric moment was increased from approximately 10 % to 30, 60, 75, and 85 %, respectively. At each step, the frequency was varied, starting from 15 Hz and achieving a maximum frequency of 39 Hz, and going back to 15 Hz.

It is interesting to note that at each level of the eccentric moment, in spite of the variation in frequency from 15 to 39 Hz, the displacement amplitude is almost constant, in conformity with Eq. 2. However, there is a slight increase in displacement amplitude. The vibrator hydraulic pressure varied with the operating frequency (between 70 and 180 bar—7 and 18 MPa). The nominal maximum pressure of 350 bar (35 MPa) was not reached, indicating that the full power of the hydraulic system was not reached.

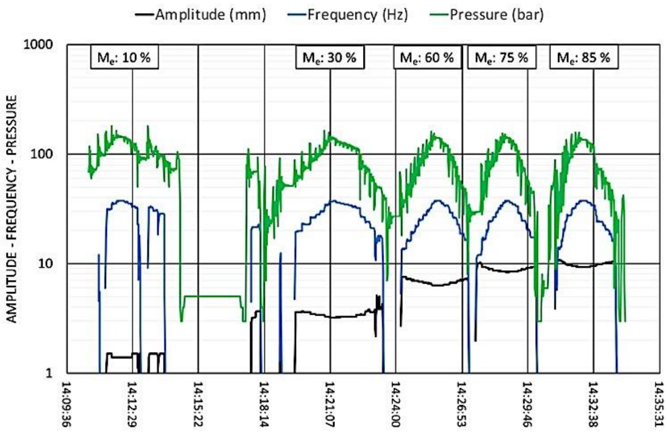


Figure 9 Vibrator calibration test of free-hanging vibrator (with clamp), showing step-wise increase of eccentric moment (%) and resulting readings of pressure, frequency and displacement amplitude, cf. Table 1

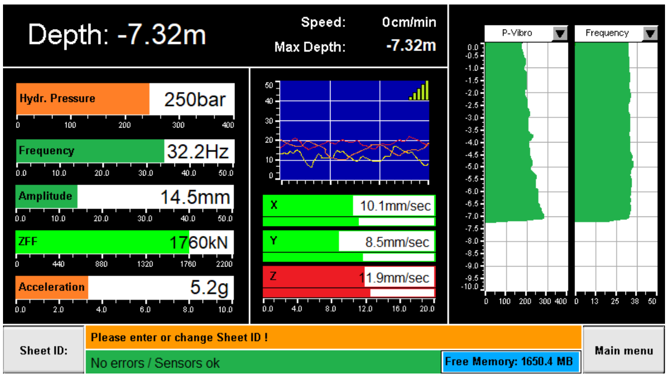
The nominal vibration amplitude (free-hanging vibrator) depends directly on the eccentric moment, but is independent of the operating frequency (this is not true during pile installation due to resonance effects). The maximum displacement amplitude was 10 mm (vibrator with clamp), which is slightly lower than the amplitude (11,6 mm) specified by the vibrator manufacturer, cf. Table 1.

4.5 Driving Test

Three driving tests were performed with a 12 m long sheet pile, using the MPCS to monitor and optimize the driving operation (Figure 10). The machine operator could observe selected parameters as considered important for the installation of sheet piles. At Test Drive 1, the sheet pile was installed using full eccentric moment and maximum operating frequency, Table 1.

The MPCS records for Test Drive 1 are shown in Figure 11: (a) time record and (b) depth record. The MPCS documentation of Test Drive 1 provides valuable information about the performance of the equipment. In the first test, installation of the 12 m long sheet pile was intentionally interrupted at 8 m depth. The operating frequency of the vibrator was then higher (38 Hz) than the nominal frequency (33 Hz); this is attributed to the use of a more powerful powerpack than required. The hydraulic pressure (varying between 14 and 15.5 MPa) was almost constant and well below the maximum pressure stated in Table 1.

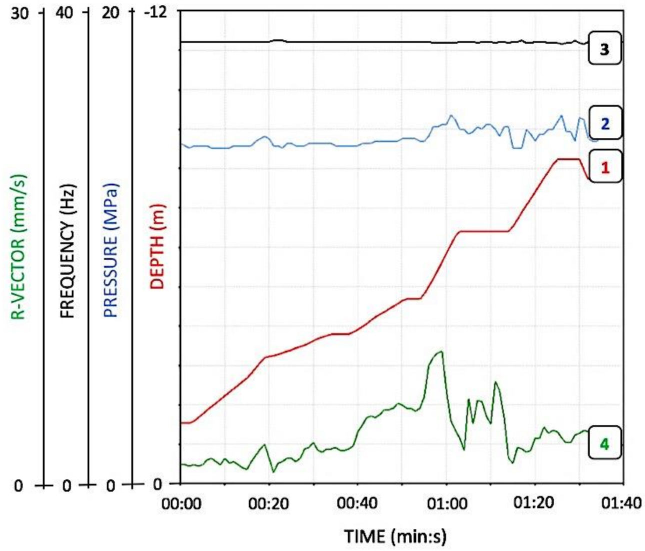
a) View of machine operator following driving instructions on MPCS screen



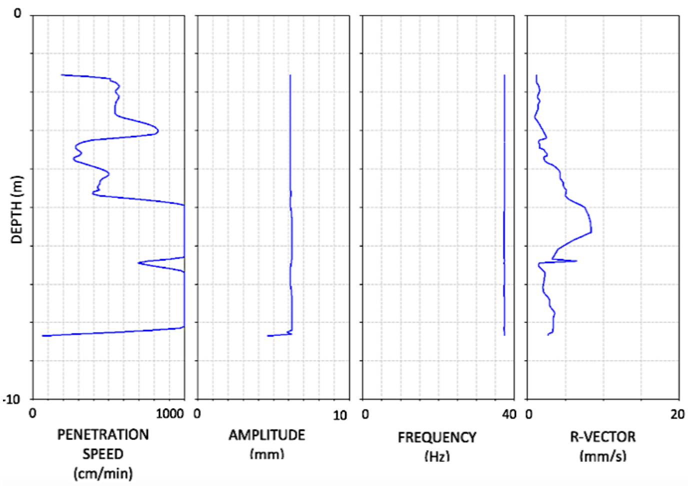
b) Display of measurement data on custom-configurated screen.

Figure 10 Test installation of sheet piles using the MPCS to control and calibrate different sensors. Display shows real-time driving parameters

Due to the higher operating frequency, also the centrifugal force, calculated according to Eq. 1, was higher (2,280 kN) than the specified value. From the three components of the ground vibration velocity, measured at 4 m distance from the sheet pile, the resultant vector (R-vector) was determined. The ground vibrations increased between 4.8 and 6.4 m depth, indicating a denser soil layer. The penetration speed was in general higher than 5 m/min, suggesting easy to very easy driving conditions. It is also interesting to note that the displacement amplitude of the sheet pile remained unchanged (7 mm) throughout the entire driving phase, indicating low shaft resistance.



a) Time record: depth (1), hydraulic pressure (2), frequency (3), and vibration vector (4), as function of time

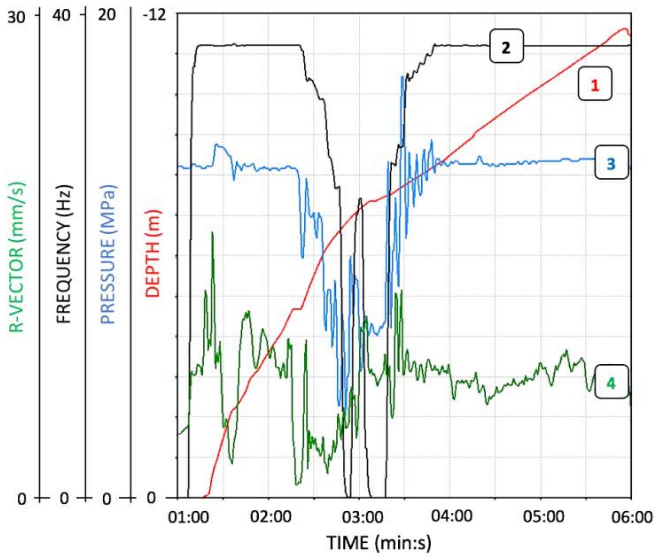


b) Depth record

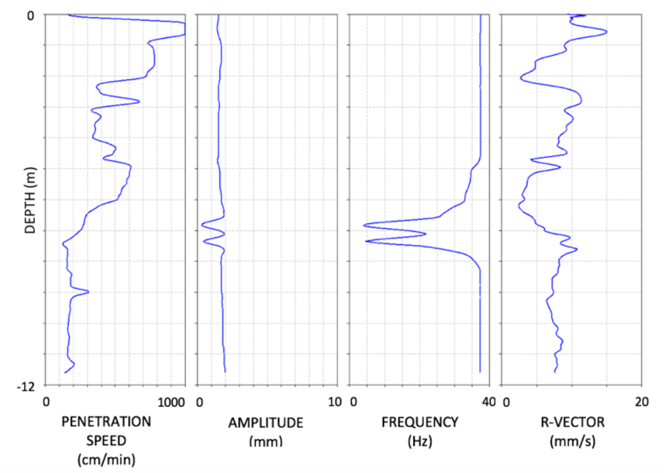
Figure 11 MPCS record, Test Drive 1 with full eccentric moment (45 kgm) and constant maximum frequency (38 Hz)

During the second driving test, Test Drive 2, the eccentric moment was intentionally lowered to about 30 % of the maximum value, while the vibrator was started at maximum frequency. The results of Test Drive 2 are shown in Figure 12.

During the initial driving phase, the penetration speed was high, but decreased with increasing penetration. Also, the movement amplitude remained almost constant. However, ground vibrations were significantly higher than during Test Drive 1. At about 6 m depth, the operating frequency was slowed down to 10 Hz, increased to 25 Hz and decreased again to investigate resonance conditions. It is apparent that in spite of using the vibrator at lower eccentric moment, ground vibrations increased at resonance to values significantly higher than at higher operating frequency. The penetration speed of the sheet pile became significantly slower than during Test Drive 1. As the movement amplitude did not decrease with increasing depth of penetration, it can be concluded that shaft resistance was low.

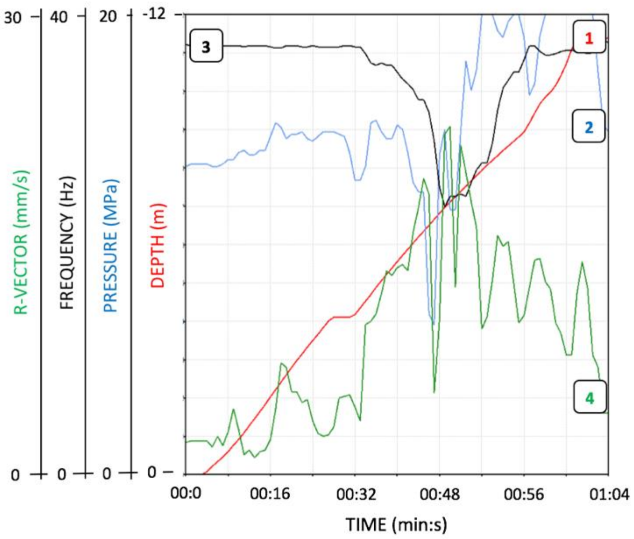


a) Time record: depth (1), hydraulic pressure (2), frequency (3), and vibration vector (4), as function of time.

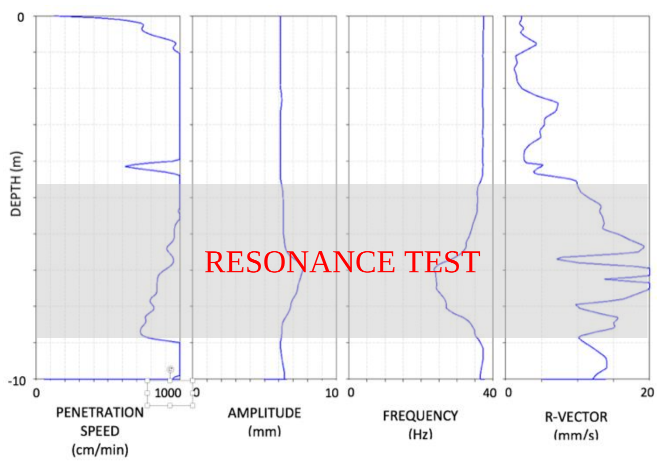


b) Depth record

Figure 12 MPCS record, Test Drive 2 with reduced eccentric moment (ca. 15 kgm)



a) Time record: depth (1), hydraulic pressure (2), frequency (3) and vibration vector (4) as function of time



b) Depth record

Figure 13 MPCS record, Test drive 3 with full eccentric moment (approx. 55 kgm) and frequency varied between 38 and 25 Hz. The zone where the resonance test was carried out is indicated

The third trial, Test Drive 3 was again carried out at maximum eccentric moment, similar to Test Drive 1, cf. Figure 13. However, at about 5 m depth, the vibrator frequency was gradually reduced to determine the system resonance frequency of the vibrator-sheet pile-ground system, as indicated in Figure 13. Figure 13 a) shows measured parameters as function of time and Figure 13 b) measured parameters as function of depth. The displacement amplitude increased slightly, confirming that the sheet pile moved in resonance with the surrounding soil. As a consequence of approaching resonance, the penetration speed slowed down and the ground vibrations increased markedly. When the vibrator frequency again was raised, the penetration speed also increased. The operation was terminated at 11 m depth.

5. EXAMPLE – RESONANCE COMPACTION

Vibratory compaction has a long tradition in Sweden. For treatment of deep soil layers, different compaction probes have been developed, such as the VibroWing in Sweden (Massarsch and Broms, 1983) and the TriStar in Belgium (Neely and Leroy 1991). Compaction probes are inserted into the soil layer to be treated and then extracted in steps. In both applications of vibratory treatment, an important—often neglected factor—is the effect of vibrator operating frequency (Massarsch 1991, Wersäll and Larsson 2013).

When the vibrator operates at the resonance frequency of the vibrator-probe-soil system, maximum densification (compaction) is achieved, which the resonance compaction method takes advantage of.

5.1 Resonance Compaction Concept

The resonance compaction concept has been described in the literature (see Massarsch and Heppel 1991, Massarsch and Westerberg 1995, van Impe et al. 1994, and Massarsch and Fellenius 2017). The fundamental concept of resonance compaction is to insert a purpose-built compaction probe into the ground to be improved, Figure 14.

The double-Y shaped (in this case) probe is provided with circular openings, which serve several purposes. First, the openings reduce the weight (and impedance, EA/c), which results in increased vibration amplitude, cf. Eq. 2. Second, the openings create an efficient interaction between the probe and the surrounding soil, enhancing the transfer of vibration energy. Third, the flexibility of the probe is increased, which is beneficial for the execution of the compaction process.

Compaction is achieved by matching the operating frequency of the vibrator to the system frequency of the vibrator-probe-soil system.

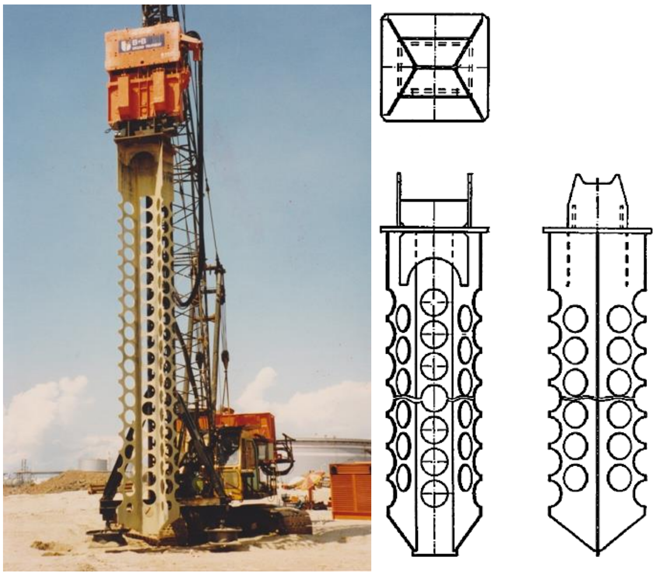


Figure 14 Double Y-shaped resonance compaction probe, developed for resonance compaction, from Massarsch and Fellenius (2005)

At resonance, the compaction probe moves in phase with the surrounding soil, thereby efficiently transmitting vibrations along the shaft of the probe. The compaction process is illustrated in Figure 15.

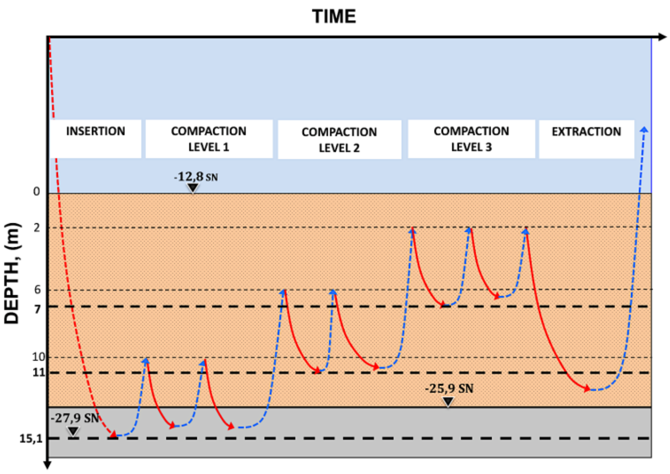


Figure 15 Procedure of under-water resonance compaction inside steel caisson. Red line: low frequency (resonance compaction); blue line: high frequency (extraction)

5.2 Under-water Compaction, Sundsvall, Sweden

In the following case history, the application of under-water resonance compaction at a complex and sensitive project is illustrated. The pier foundations of a bridge, crossing the Sundsvall estuary, were constructed using sand-filled caissons. Resonance compaction was used to densify sand inside steel caissons. Figure 16 shows the water-filled caisson in front and the barge from which compaction was carried out.

The geotechnical aspects of resonance compaction and the achieved densification effect were described by Massarsch et al. (2017b). A particular challenge of the project was the requirement to compact the sand inside a caisson consisting of interlocking steel sheet piles, which were sensitive to high horizontal stresses.

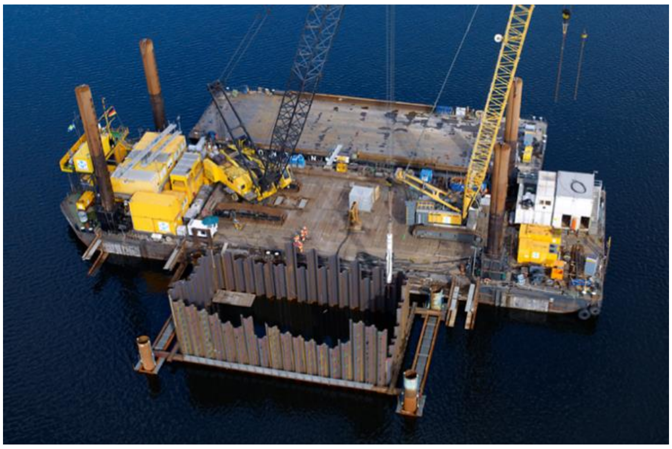


Figure 16 Water-filled caisson constructed of sheet-piles in foreground. In background, the barge is seen from which compaction was carried out, from Massarsch et al. (2017b)

A typical cross-section of one of the ten constructed piers is shown in Figure 17.

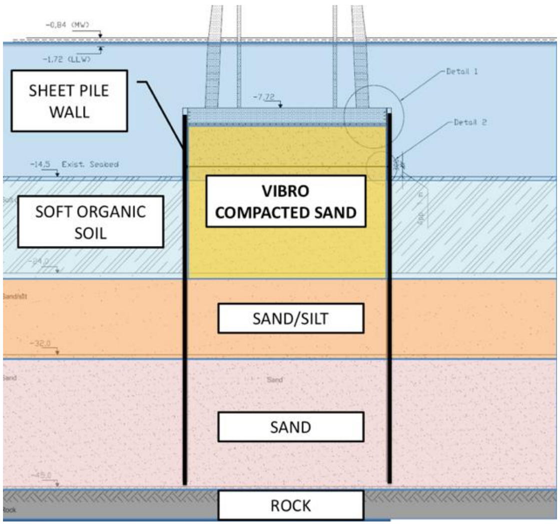


Figure 17 Foundation conditions of bridge pier with vibratory-compacted sand inside steel caisson

Resonance compaction was chosen, using the MPCS system, as described above. In addition to conventional MPCS sensors, inclinometers were also installed at critical sections of the sheet pile wall to detect unacceptable horizontal movements. Failure of the sheet pile locks during compaction would have had serious consequences. Therefore, the client required an exceptionally high degree of production documentation and quality control and extensive field tests were carried out prior to the start of production work. An important aspect was that during compaction, vertical vibration velocity could be measured in the sheet pile wall and monitored in real time. It was also possible to document in great detail all phases of sand compaction, being executed by the submerged vibrator within the water-filled caissons, cf. Figure 18.

A hydraulic vibrator of type PVE 2319VM, with a maximum centrifugal force of 1,100 kN and variable frequency (0-38 Hz) oscillated the 12 m long compaction probe. The maximum eccentric moment could be varied between 0 and 19 kgm. Vibrator specifications provided by the manufacturer are given in Table 2.

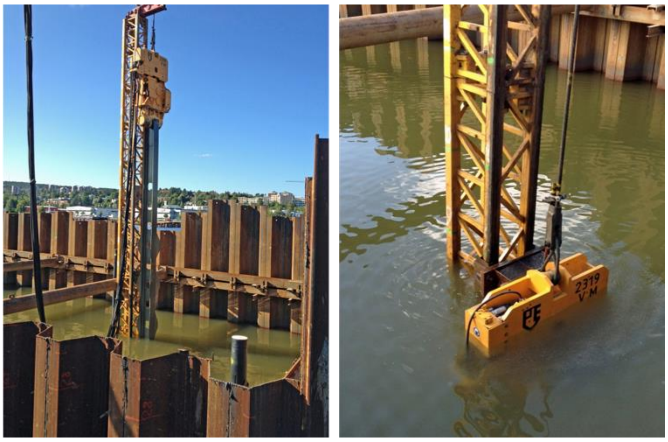


Figure 18 Under-water compaction of sand inside steel caisson using resonance compaction concept

Table 2 Vibrator performance information, Dieseko PVE 2319VM

Parameter	**Value**	**Unit**
Dynamic mass excluding clamp	2,675	kg
Dynamic mass with clamp	3,425	kg
Eccentric moment:	0 – 19	kgm
Max. centrifugal force:	0 – 1,100	kN
Max. frequency:	2,300 (38)	rpm (Hz)
Max. amplitude excluding clamp[1)]	14	mm
Max. amplitude including clamp[1)]	11,1	mm
Max. operating pressure	350 (35)	bar (MPa)

[1)] peak-to-peak amplitude.

In order to minimize adverse effects of vibratory compaction, treatment of the sand fill was carried out in several phases, starting during phase (1) at the perimeter of the caisson wall, and progressively continuing compaction towards the centre, Figure 19.

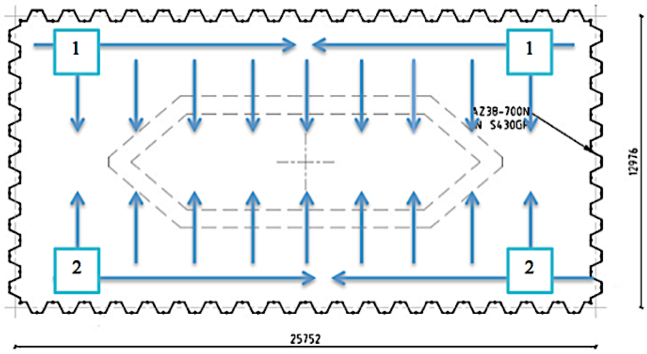


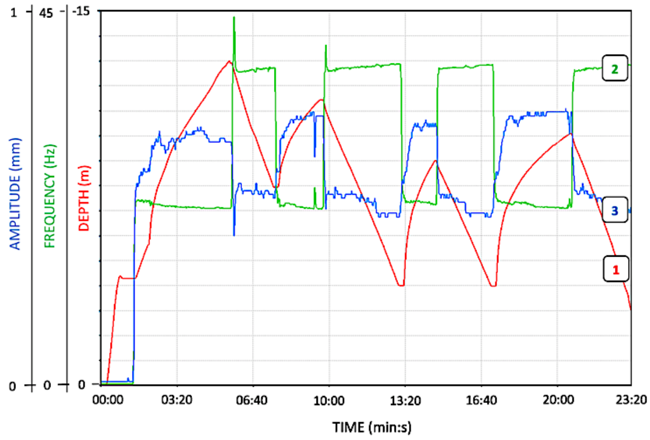
Figure 19 Execution of resonance compaction in phases, starting at the perimeter of the caisson, from Massarsch et al. (2017b)

The compaction process was carried out by a trained machine operator, who was assisted by information regarding probe movement and frequency control, displayed on the MPCS screen, cf. Figure 4.

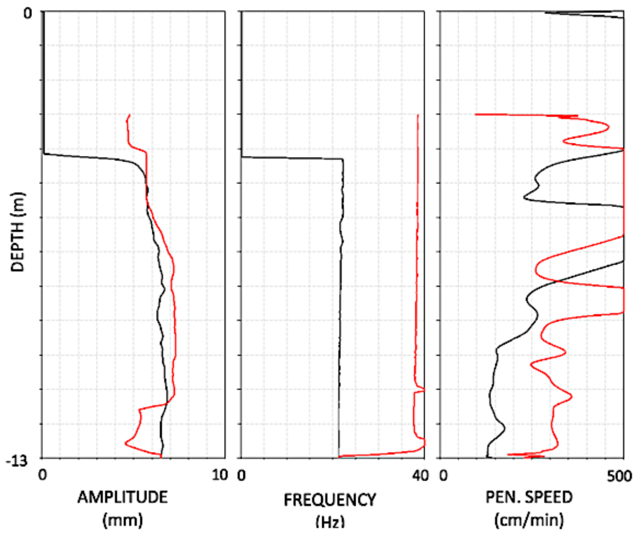
5.3 Resonance Compaction Monitoring and Process Control

As described above, compaction was carried out at a 4-m water depth, using the MPCS concept. This aspect was of particular importance as during most of the compaction phase, the vibrator remained submerged below the water surface inside the steel caisson, cf. Figure 12. An example of an MPCS record summarizing the compaction process is shown in Figure 20. Compaction was carried out inside the water-filled caisson in four depth steps; at each step, the vibrator frequency was decreased to resonance during penetration (22 Hz) and increased during extraction (38 Hz). Figure 20 a) shows a time record of the compaction process and b) a depth record of compaction parameters.

As is shown in Figure 20 a), compaction was carried out in four intervals, where the probe was inserted to the required depth at the resonance frequency (22 Hz) and extracted at the maximum frequency. The displacement amplitude of the compaction probe increased distinctively when the vibration amplitude was lowered to resonance, confirming the efficiency of the resonance compaction concept. Figure 20 b) shows the variation of displacement amplitude, vibrator frequency, and probe penetration speed as a function of depth. Red lines show maximum values during penetration and black lines equivalent values during extraction. Important information can be gained from measuring the probe penetration speed, which is a measure of the probe resistance, as discussed below.



a) Summary sheet of resonance compaction parameters as function of time: 1) depth, (2) frequency, (3) amplitude as function of time



b) Summary sheet of resonance compaction parameters as function of time: penetration in black; extraction in red

Figure 20 MPCS record of underwater compaction at 4 m water depth. Sand layer thickness 8 m

5.4 Compaction Verification

Several different methods can be used to assure that the required compaction effect is achieved. The method used during the production phase was to determine the number of probe vibration cycles per 0.1 m.

As most of the probe resistance is created by the resistance at the toe of the probe, the probe resistance can be related to the penetration resistance from dynamic or static penetration tests, Massarsch et al. (2017a). Prior to the start of production work, compaction trials were carried out. The cone penetration test (CPT) was used to compare the cone stress and sleeve resistance with different compaction parameters (duration of compaction, compaction point spacing etc.). The results have been reported by Massarsch and Fellenius (2017). Typical results of calibration tests are shown in Figure 21, where the probe penetration resistance and the variation of vertical vibration velocity area shown. Based on these calibration tests, it was possible to correlate the probe penetration resistance (cycles per 0.1-m penetration) to the cone stress from CPT. The compaction requirements were determined for each compaction point and varied depending on the phase of compaction. During the first compaction pass, the objective was to densify the sand fill to a medium dense state. During the second and third compaction pass, the probe penetration resistance increased significantly, compared to the first pass. It was found that for the conditions on the site, the required cone stress of 10 MPa was achieved when the probe penetration resistance exceeded approximately 200 cycles/0.1 m.

The resonance frequency can be measured in each compaction point, by plotting the vertical vibration velocity as a function of vibration frequency, cf. Figure 21. In the shown case, the resonance frequency was approximately 22 Hz, but increased slightly with increasing compaction, indicating that the stiffness of the ground had been improved.

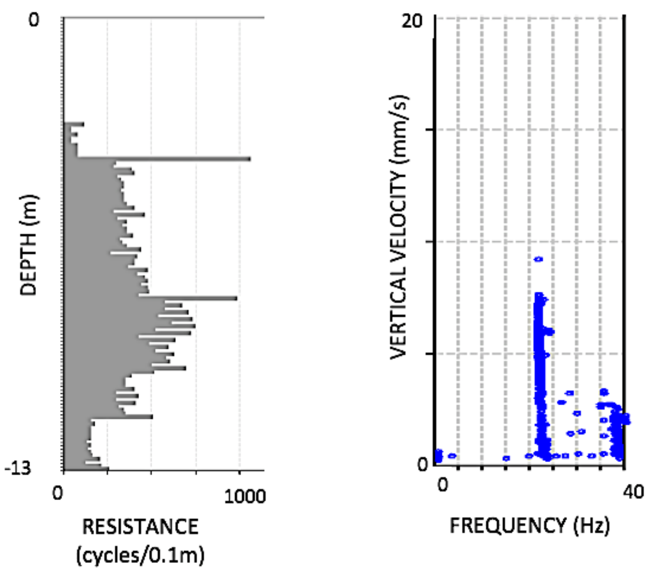


Figure 21 Results of compaction calibration test showing probe penetration resistance as function of depth and vertical vibration velocity as function of frequency

The probe penetration speed is also a valuable parameter which can be used to optimize the compaction process. For instance, during the initial phase of compaction, the probe penetration speed in the loose, uncompacted sand was very high, in excess of 800 cm/min. However, when the intermediate points were compacted during the second pass, the probe penetration speed decreased, which was also reflected by the number of vibration cycles per depth interval (0.1 m). For instance, when the probe penetration speed during the second pass was similar to that observed during the first pass, compaction intensity had to be increased (reduced point spacing, increased duration of compaction etc.). However, when the penetration speed during the second pass was significantly slower than during the first pass (for instance, on some occasions, it was not possible to insert the probe into the compacted soil), it was concluded that too much during the first pass. Thus, the information gained from using the MPCS to monitor the compaction process was very important to assure that a homogeneous densification effect had been achieved. In the present case, over-compaction not only would have increased cost and delayed the project. Too high compaction would have resulted in an increase in horizontal stress, which could have jeopardized the safety of the steel caissons.

6. CONCLUSIONS

The incorporation of electronic monitoring offers new insight into the field performance of sheet pile driving and soil compaction. The development of advanced monitoring and process control of vibratory driving and compaction is a useful addition to the practical use of vibrators. The machine operator is informed in real time about different driving parameters and can adjust and optimize the driving process depending on the objective of the project. Two examples are presented which demonstrate how vibratory driving parameters can be evaluated and used to select the optimal driving conditions.

The first example presents the results of test driving of sheet piles in an esker. The effect of variation of eccentric moment and vibrator frequency on ground vibrations (resonance) and penetration speed are shown. An important new addition to the MPCS was the incorporation of a sensor which can measure the eccentric moment and thus the centrifugal force applied to the sheet pile.

The second example describes under-water compaction of loose sand inside of vibration-sensitive steel caissons. Compacting sand below the water surface, with the compaction equipment submerged would have not been possible without the information provided by the MCPS.

The electronic components operated without problems in spite of the rugged site conditions. Compiling data from different projects will enable the foundation contractor to create a valuable knowledge base, which can be used on future projects to predict drivability and selection of appropriate vibrator size and capacity.

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An early monitoring system for resonance compaction was developed during the 1980s by Mr. P. Loster, Germany. The MPCS described in this paper was produced by Gamperl & Hatlapa, Germany. The assistance of Mr. J. Hatlapa in developing the electronic system and the eccentric moment sensor is acknowledged.

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8. REFERENCES

DFI/EFFC (2014) Video Session, International Conference on Piling and Deep Foundations, Stockholm, May 21 – 23, 2014 http://www.georisk.se/web/page.aspx?refid=63.

DFI (2015) "Comparison of impact versus vibratory driven piles", DFI Committee on Marine Foundations, Report Nr. 14007-01, 76 p.

Deckner, F. (2017) "Vibration transfer process during vibratory sheet pile driving - from source to soil", Doctoral Thesis, Royal Institute of Technology (KTH). Department of Civil and Architectural Engineering. Division of Soil and Rock Mechanics. TRITA-JOB PHD 1026, 145 p.

Massarsch, K.R. (1991) "Deep Soil Compaction Using Vibratory Probes", ASTM Symposium on Design, Construction and Testing of Deep Foundation Improvement: Stone Columns and Related Techniques, Robert C. Bachus, Ed. ASTM Special Technical Publication STP 1089, Philadelphia, 1990, pp. 297-319.

Massarsch, K.R. (2017) "Recent developments in vibratory driving and soil compaction". 3rd Bolivian International Conference on Deep Foundations, Santa Cruz de la Sierra, Bolivia, April 27-29, Vol. 1, 123-139.

Massarsch, K.R. and Broms, B.B. (1983) "Soil Compaction by VibroWing Method". 8th European Conference on Soil Mechanics and Foundation Engineering, Helsinki, 23 - 26 May, 1983, Proceedings, Volume 1, pp. 275 - 278.

Massarsch, K.R. and Heppel, G. (1991) "Resonance Compaction for Granular Soils", Southeast Asia Building Journal, December 1991, pp. 36 - 40.

Massarsch, K. R., Westerberg, E. (1995) "The active design concept applied to soil compaction", Bengt B. Broms Symposium in Geotechnical Engineering, Singapore, 13 - 15 December 1995, Proceedings, pp. 262 - 276.

Massarsch, K.R. and Vanneste, G. (1988). "TriStar vibrocompaction Annacis Island", FIT Report, Franki International, Liege, Belgium, 109 p.

Massarsch, K.R. and Fellenius, B.H. (2005) "Deep vibratory compaction of granular soils", Chapter 19, in Ground Improvement-Case Histories, Geo-Engineering Series Volume 3, Elsevier (UK), B. Indraratna and Chu J. (Editors), pp. 633 - 658.

Massarsch, K.R. and Fellenius, B.H, (2017), "Evaluation of resonance compaction of sand fills based on cone penetration tests", Ground Improvement. Proceedings of the Institution of Civil Engineers. Paper 1700004, August, 2017, 170(3) 149-158.

Massarsch, K.R., Fellenius, B.H. and Bodare, A. (2017a) "Fundamentals of the vibratory driving of piles and sheet piles". Geotechnik. Ernst & Sohn Verlag für Architektur und Technische Wissenschaften GmbH & Co. KG, Berlin · Geotechnik (2017), pp. 1-16.

Massarsch, K.R., Zackrisson, P. and Fellenius, B.H. (2017b). "Underwater resonance compaction of sand fill" 19th International conference on soil mechanics and geotechnical engineering, Seoul, Korea, 17-22 September, 2017. Proceedings 2017, pp. 2587 - 2590.

Neely, W.J. and Leroy, D.A. (1991) "Densification of sand using a variable frequency vibratory probe", ASTM Symposium on Design, Construction and Testing of Deep Foundation Improvement: Stone Columns and Related Techniques, Robert C. Bachus, Ed. ASTM Special Technical Publication STP 1089, Philadelphia, 1990, pp. 320-332.

Van Impe, V.F., De Cock, F., Massarsch, K.R., and Mengé, P. (1994), "Recent experiences and developments of the resonant vibrocompaction technique". International Conference on Soil Mechanics and Foundation Engineering, ICSMFE XIII, New Delhi, Jan. 1994. Proceedings, Vol. 3, pp. 1151-1156.

Viking, K. (2002) "Vibro-drivability - a field study of vibratory driven sheet piles in non-cohesive soils". Doctoral thesis, Royal Institute of Technology. Division of Soil and Rock Mechanics (KTH), TRITA-JOB PHD 1002, 281 p.

Wersäll, C., Larsson, S. (2013) "Small-scale testing of frequency-dependent compaction of sand using a vertically vibrating plate", ASTM. Geotechnical Testing Journal. 36(3), pp. 394-403.