# FREQUENCY-VARIABLE VIBRATORS AND THEIR APPLICATION TO FOUNDATION ENGINEERING

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## 1 Introduction

In some parts of the world, vibrators are used extensively for different types of foundation engineering projects. If used correctly and in suitable soils then vibratory pile driving for example is very efficient. However, soil conditions and the installation procedure have great significance for the driving resistance and affect the bearing capacity of vibrated piles. Also the intensity of ground vibrations which are transmitted to the surrounding soil is affected by the vibration process. In spite of the increasing use of vibrators and the rapid development of vibrator technology, many aspects of pile-soil interaction are not yet understood. In order to asses the importance of factors, which govern pile installation (and extraction), it is necessary to consider the entire chain of vibration energy transmission from the vibration source to the pile, the interaction between the vibrating pile and the soil and the wave propagation in the subsoil, Fig. 1.

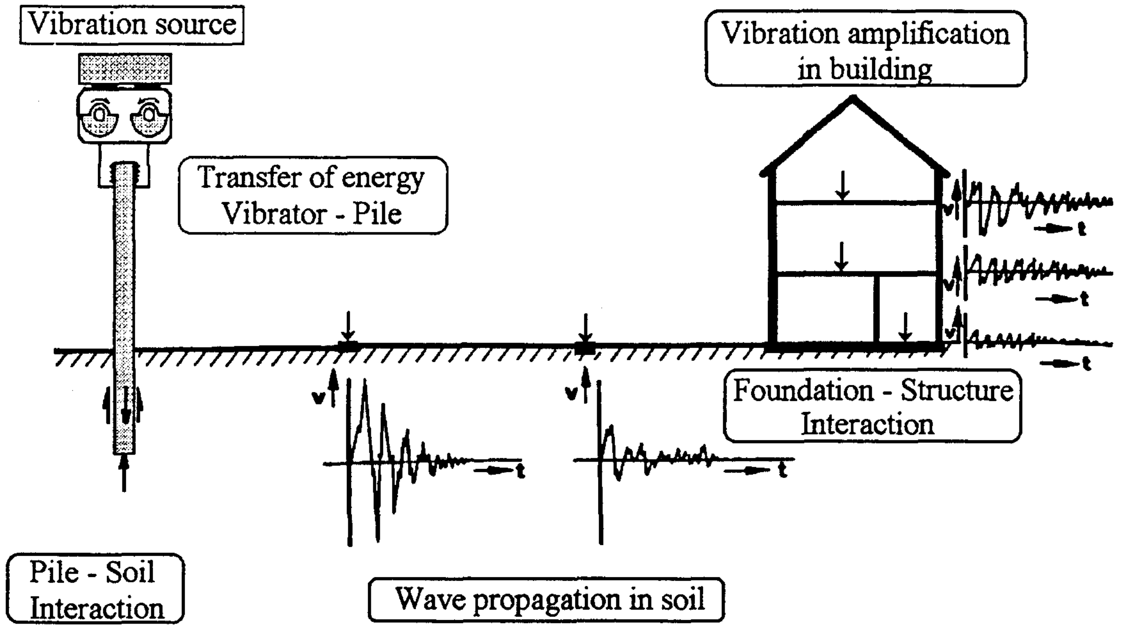

Fig.1. Transfer of vibration energy from the vibrator through the pile into the ground

In the present paper, some important aspects of vibratory driving and their significance for pile installation and soil compaction will be discussed.

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## 2. Vibrator Performance

The first vibrators used for pile driving were developed some 60 years ago in Russia and have since been used extensively on foundation projects worldwide. Modern vibrators are hydraulically driven, which allows continuous variation of the vibrator frequency during operation. The vertical oscillation of the vibrator is generated by counter-rotating eccentric masses. The static moment M, which is an important parameter for vibrator applications, is the product of the mass of the eccentric weights G and the distance r of their center of gravity to the rotation axis,

$$M = G \times r \qquad (1)$$

The static moment is thus not affected by the vibration frequency f. The peak centrifugal force $F_V$ acting in the vertical direction, depends on the static moment M and on the circular frequency $\omega$ ($2 \pi f$) of the eccentric masses,

$$F_V = M \times \omega^2 \qquad (2)$$

Another factor that influences driving performance is the displacement amplitude S (double amplitude), which together with the centrifugal force is a measure of the driving capacity of the vibrator. For a free-hanging vibrator (including pile clamp and pile) the vertical displacement amplitude $S_O$ (double amplitude) can be determined from

$$S_O = 2\,s = 2\,M / G_D \qquad (3)$$

The "total dynamic mass" $G_D$ ($G_{VIBRATOR} + G_{CLAMP} + G_{PILE}$) is the sum of all masses which need to be excited by vibratory action. It should be noted that both the static moment M and the displacement amplitude $S_O$ are independent of vibration frequency.

In order to obtain maximum displacement amplitude, the dynamic mass $G_D$ should be kept as small as possible. The displacement amplitude is reduced when the pile encounters resistance during penetration in the soil. The displacement amplitude $S_O$ is defined as the difference between the ground vibration amplitude $S_G$ and the pile vibration amplitude $S_P$. The dynamic soil resistance $R_{DYN}$ acts along the pile shaft and at the pile base. When the displacement amplitude $S_O$ is measured during vibratory driving, the dynamic soil resistance can be estimated from to the following relationship:

$$R_{DYN} = (\,G\,) \times [\,2\,M / (\,2\,M - G \times S_O) \; - 1\,] \times (S_O \times \omega^2\,) / 2 \qquad (4)$$

The dynamic soil resistance $R_{DYN}$ is a site-specific quantity which depends on the dynamic characteristics of the driving equipment (the static moment) as well as on the dynamic soil resistance (displacement amplitude). In the case of "soil resonance" during vibratory driving, the pile and the soil are oscillating "in phase". Thus, the relative displacement amplitude between the pile and the soil is small in spite of large pile and ground vibration amplitudes.

Vibratory pile driving tests performed by the authors (which are discussed in section 5) suggest that there exists a soil-specific relationship between the dynamic soil resistance $R_{DYN}$ and the static cone penetration (CPT) resistance (tip resistance $q_c$ and sleeve friction $f_s$). The static resistance from CPT sounding can be empirically related to a vibratory resistance, using soil-specific parameters. Based on these empirically determined parameters it is possible to predict the soil resistance during vibratory driving, based on CPT sounding.

During the past ten years the performance of vibrators has been improved significantly. Modern vibrators can generate a centrifugal force of up to 4 000 kN (400 tons). The maximum displacement amplitude can exceed 30 mm. These enhancements in vibrator performance, combined with the use of driving aids (such as water and air jetting, pre-drilling and pre-blasting) have opened new applications to the vibratory driving technique. Recently, vibrators with variable frequency and variable static moment (displacement amplitude) have been introduced. Fig. 2 shows a vibrator with eccentric masses, arranged at separate rotation levels. During any stage of vibrator operation the position of the lower row of masses can be changed relative to that of the upper row, thereby affecting the static moment and the displacement amplitude.

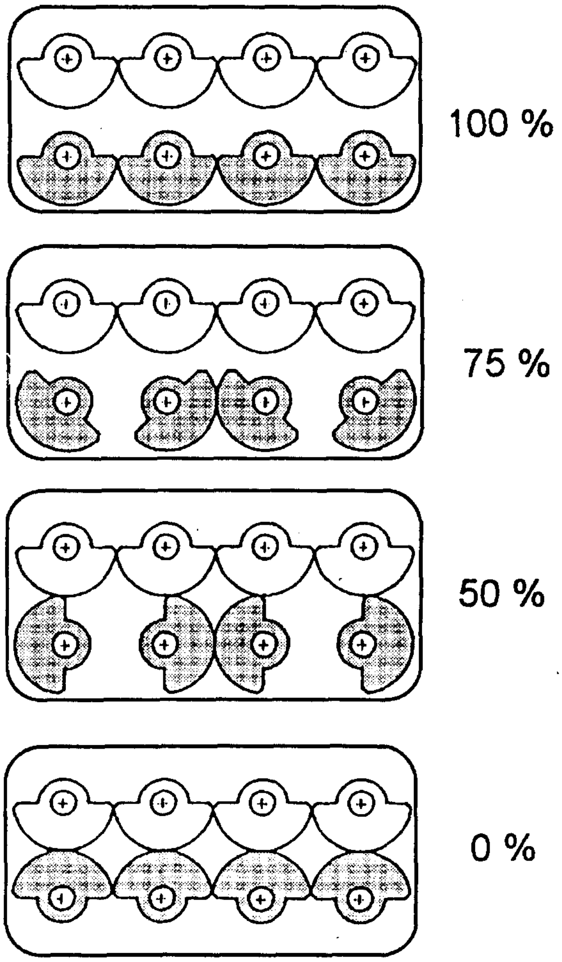


Fig. 2. Operating principle of vibrator with dual rows of eccentric masses, allowing variation of the static moment (displacement amplitude)

The vibrator can be operated at zero displacement amplitude (0%) until the desired frequency has been reached. Fig. 3 shows a comparison between conventional and resonance-free pile driving. The vibrator is started at zero static moment (displacement amplitude), thus avoiding ground vibration amplification. Once the desired operating frequency has been reached, the static moment and thus the vibration amplitude can be increased. Similarly, the static moment can be reduced to zero during the switch-off phase of pile driving.

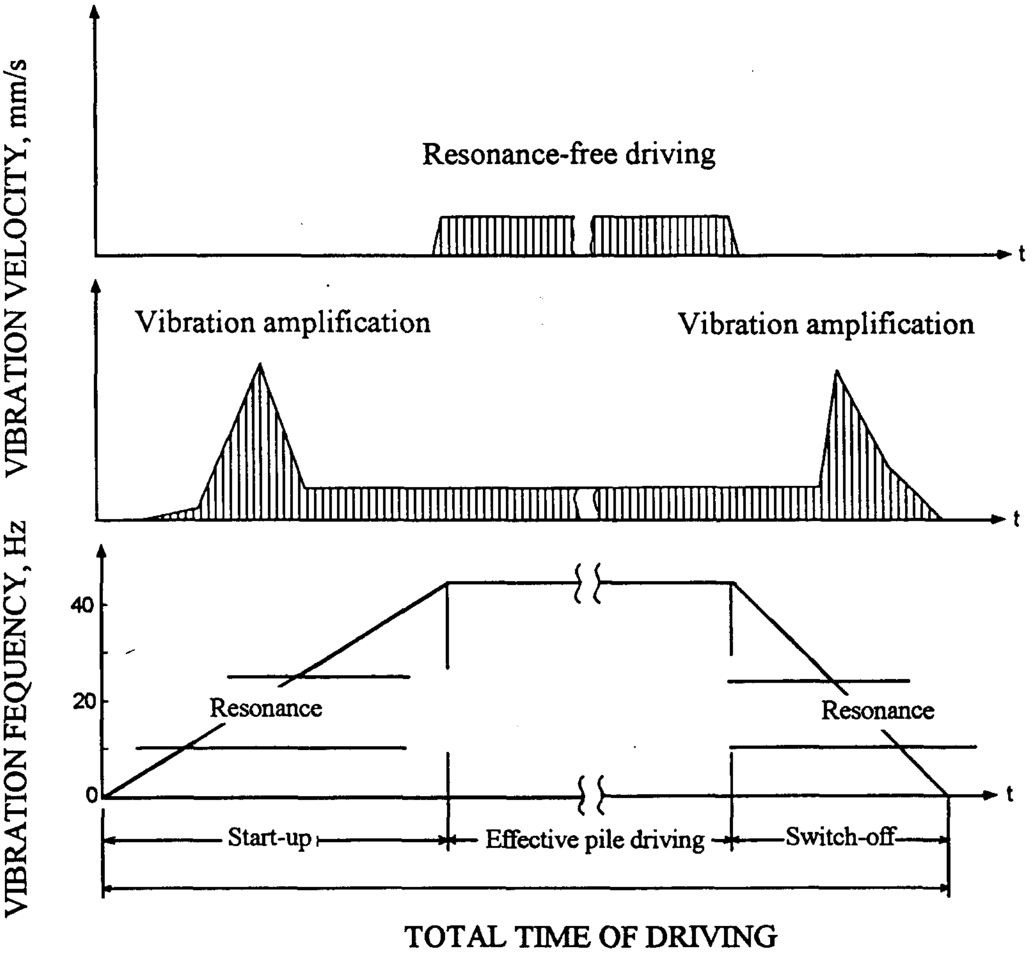


Fig. 3. Comparison of vibratory pile driving process using vibrator with constant and variable static moment

## 3. Vibratory Pile Driving Process

The following chapter describes factors which are considered most important for the pile driving process, Massarsch (1993).

### 3.1 Vibration Propagation in Pile

Vibratory excitation affects the pile in a different way than impact driving. The hammer is not rigidly connected to the pile head. Thus the applied energy is reduced when it passes through the pile cap and the pile cushion. Each blow must be sufficiently strong to overcome the inertia of the pile and the static soil resistance. The vibrator, on the other hand, is rigidly connected to the pile head, which eliminates energy losses. During the entire driving process, the pile is kept in an oscillating motion and the shaft friction is thereby reduced. The degree of reduction of shaft friction depends on soil type and on operating frequency, as will be discussed later.

One of the most important factors influencing the energy transfer through the pile and from the pile into the ground is the impedance I of the pile, which depends on the pile geometry and the pile material,

$$I = \rho \times C \times A \qquad (5)$$

where $\rho$ is the mass density, A is the cross-sectional area and C is the longitudinal wave propagation velocity in the pile. The maximum force P which is transmitted across a section of the pile is determined by the product of the impedance I and the particle velocity v of the pile,

$$P = I \times v \qquad (6)$$

Heckman & Hagerty (1978) have demonstrated that vibration energy transmission from the pile to the surrounding soil layers is controlled by pile impedance, Fig. 4. It is surprising that the effect of the pile impedance is not taken into account more widely in practice. The increase of energy transmission at low pile impedance can be used for soil compaction, as will be discussed in a later chapter.

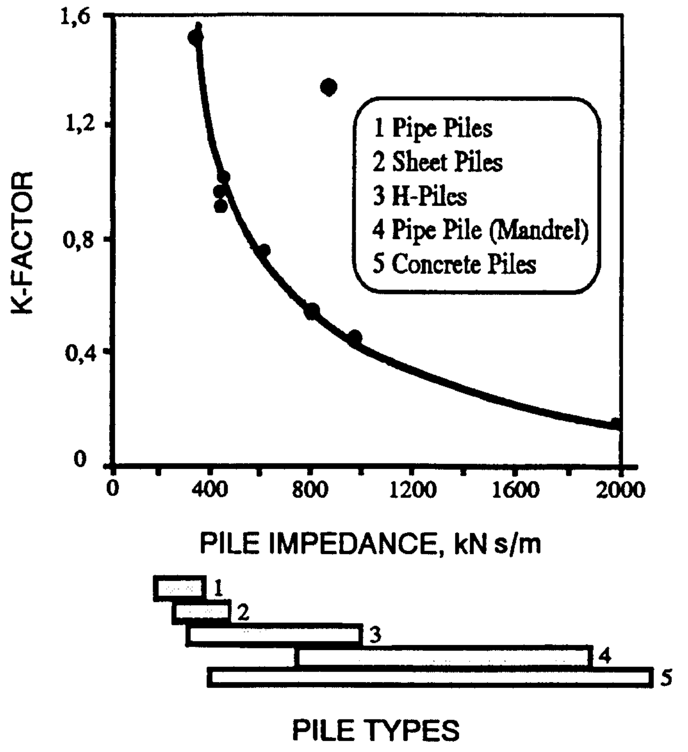


Fig. 4. Influence of pile impedance on the transmission of vibration energy from pile to soil, (after Heckman & Hagerty (1978)

### 3.2 Pile-Soil Interaction and Resonance Effects

The origin of energy transmission from the vibrating pile to the soil depends to a large extent on the soil layers through which the pile is driven. In a dense, homogenous sand deposit, a large part of the driving energy will be transferred along the pile shaft, generating friction-induced conical waves. In the case of a stiff layer, two types of wave fields may be created, one originating from the toe of the pile and another one induced by the bending of the pile, Massarsch (1993). The shaft resistance and the base resistance can change during driving when different soil layers are encountered. In addition, the soil properties can be changed as a result of ground vibrations. Therefore it is difficult to theoretically predict soil resistance during vibratory driving.

The mechanism which governs vibratory driving can be understood from observations during a simple test in sand, using a vibrator with variable frequency. The vibrator is attached to a pile with low impedance. At first, the vibration frequency is increased to the resonance frequency of the pile. As a result of pile resonance, the vertical motion of the pile is amplified and the pile penetrates rapidly into the soil. At this high frequency the vibration energy is mainly transformed into heat along the pile shaft but also at the pile toe. Only a small amount of the vibration energy is transmitted from the pile to the soil. This can be verified by vibration measurements with geophones on the ground surface.

When the vibrator frequency is lowered, the penetration speed of the pile decreases in a certain frequency range and soil vibrations increase. At this frequency, which corresponds to the resonance frequency (or an overtone) of the vibrator-pile-soil system, the penetration speed is slow and the transfer of vibration energy from the pile to the soil reaches a maximum. The pile moves “in phase with the soil” and the relative displacement between the pile and the soil is small, cf. chapter 2. The “dynamic shaft friction” increases at resonance to a maximum value, and corresponds to the “static shaft resistance”. The frequency at which resonance between the pile and the surrounding soil layers occurs, is much lower than the resonance frequency of vibrator-pile system. When lowering the vibrator frequency further, the relative displacement between the pile and the soil increases again and thus the pile continues to penetrate.

## 4. Electronic Monitoring of Vibratory Driving

Hydraulic vibrators with variable frequency and amplitude control are particularly suited for electronic process control. This has opened new possibilities for the use of vibrators on foundation projects, such as more efficient and environmental-friendly pile driving or extraction as well as efficient soil compaction.

### 4.1 Electronic Process Control

An important factor during pile driving is the influence of soil resonance (vibration amplification at resonance frequency) on the penetration resistance. It is often difficult to theoretically predict the resonance characteristics of the soil deposit without field tests. Therefore, it is preferable to determine the optimal vibratory driving procedure in the field. This can be accomplished using an electronic process control system which can record all important parameters during pile installation, Fig. 5. The purpose of electronic process control is to record the energy provided by the vibrator to the pile and to determine vibration energy transferred from the pile to the surrounding soil.

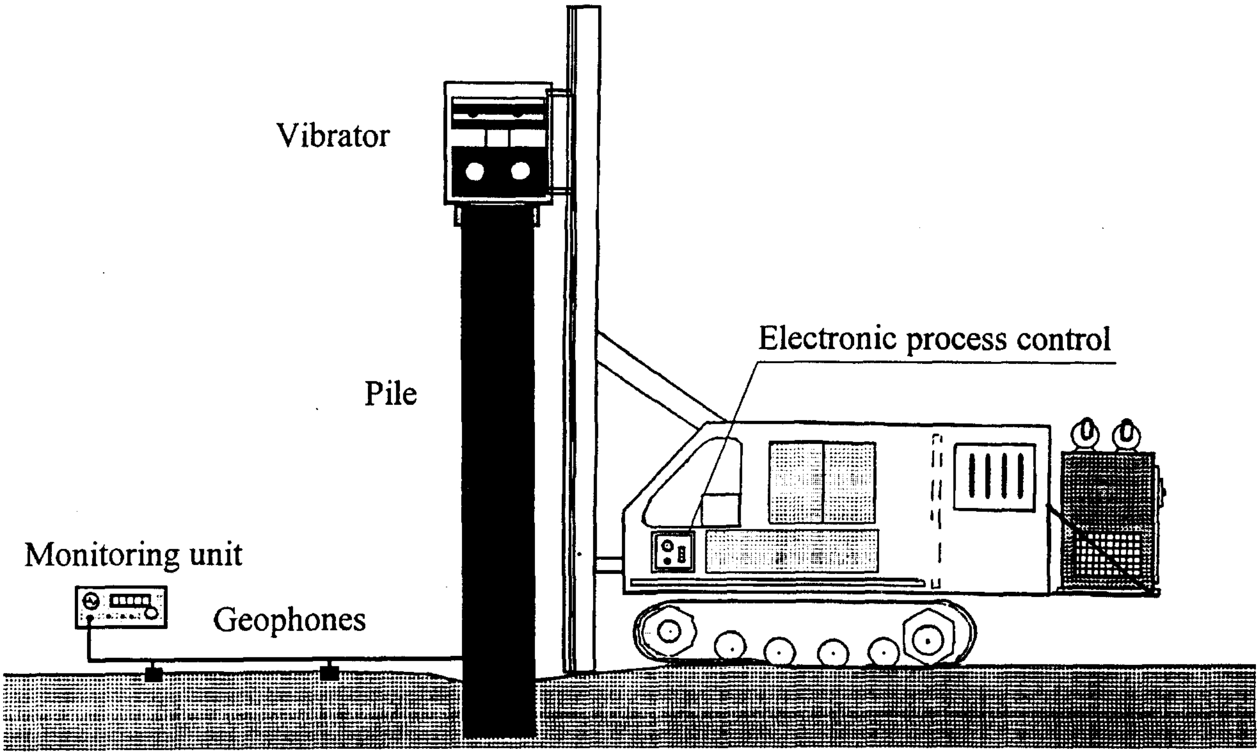
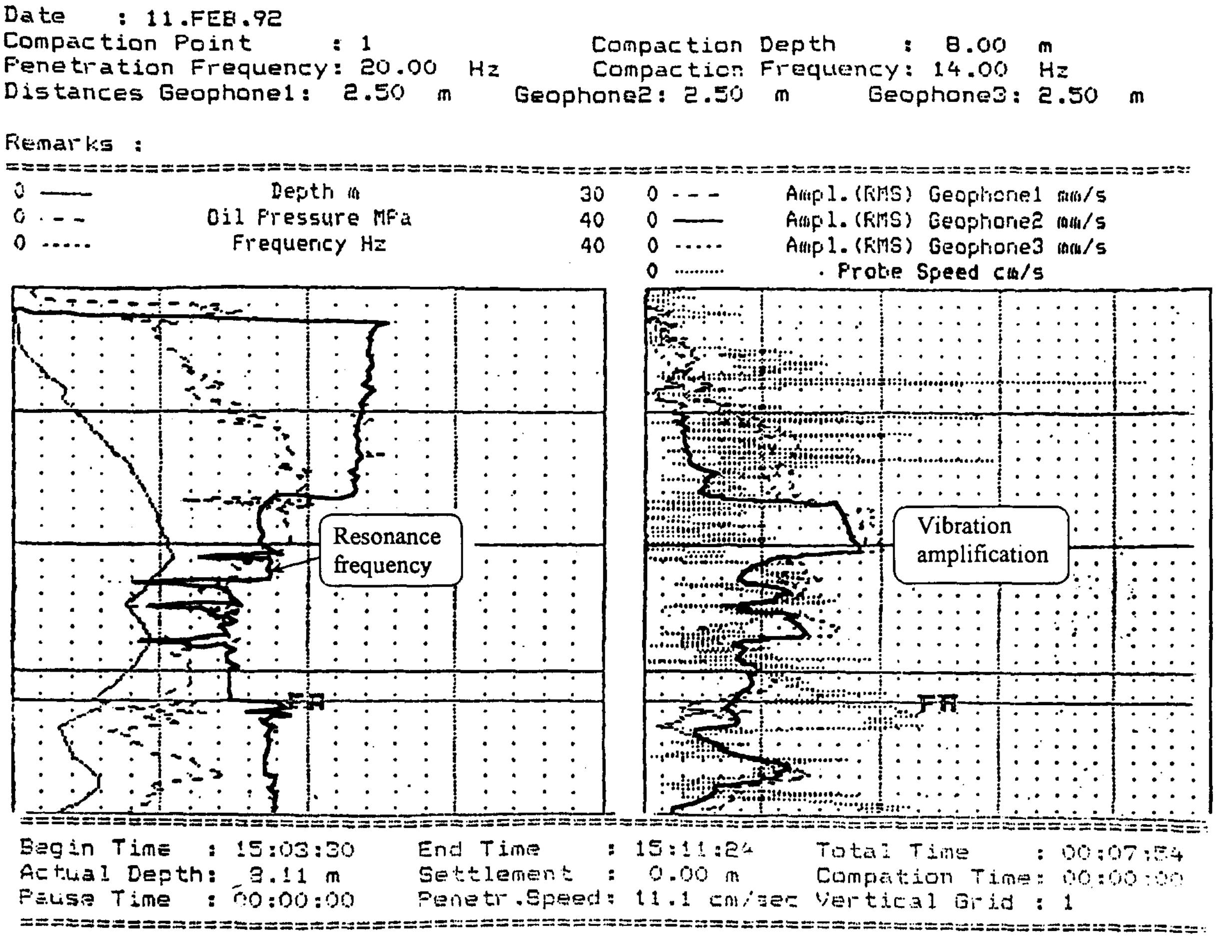


Fig. 5. Electronic process control system for vibratory driving of piles

A typical record of vibratory pile driving in partially saturated sand is presented as an example in Fig. 6. The measured parameters are shown in the horizontal direction as a function of time along the vertical axis (each thick line indicates one minute). The left diagram gives the vibrator frequency, the penetration depth of the pile toe and the hydraulic oil pressure (applied energy). On the diagram to the right is shown the vibration velocity (three components of the RMS-value) on the ground surface and the penetration speed of the pile during installation.

The diagram shows the influence of vibration frequency on the penetration speed of the pile and on the intensity of ground vibrations. At the start of pile installation, a relatively high frequency (24 Hz) was used. After about 1,5 minutes, at a depth of 7,5 m the vibrator frequency was reduced to the resonance frequency, in this case at around 18 Hz. It is apparent that at this frequency, ground vibrations are amplified whereas pile penetration speed decreases (and thus soil resistance increases). Since the vibrating pile is in resonance with the surrounding soil layer, the vibrator consumes less energy, which can be seen from the decrease of the oil pressure. Another interesting observation is that each time the vibrating pile is withdrawn (with all other parameters unchanged), the ground vibration velocity decreases significantly. The pile penetration speed (shown on the right side of the diagram) reflects at constant frequency the variation of soil resistance during pile installation. This record can be correlated to conventional penetration tests (e.g. CPT) and provides thus valuable information regarding the soil conditions at the location of pile installation.



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Date      : 11.FEB.92
Compaction Point      : 1                 Compaction Depth      :  8.00  m
Penetration Frequency: 20.00  Hz         Compaction Frequency: 14.00  Hz
Distances Geophone1:  2.50   m     Geophone2: 2.50   m      Geophone3: 2.50   m

Remarks  :
==============================================================================
0 ——             Depth m                 30    0 - - -      Ampl.(RMS) Geophone1 mm/s
0 · - -       Oil Pressure MPa           40    0 ——         Ampl.(RMS) Geophone2 mm/s
0 -----         Frequency Hz             40    0 -----      Ampl.(RMS) Geophone3 mm/s
                                               0 ·········     · Probe Speed cm/s
==============================================================================
Begin Time    : 15:03:30     End Time       : 15:11:24     Total Time      : 00:07:54
Actual Depth:  8.11 m        Settlement     :  0.00 m      Compation Time: 00:00:00
Pause Time    : 00:00:00     Penetr.Speed: 11.1 cm/sec  Vertical Grid  : 1
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Fig. 6. Installation of a steel pile in sand with a Müller-vibrator MS-50 HF with variable frequency, monitored by the electronic process control system (Massarsch, 1993).

With the aid of modern frequency-variable vibrators (cf. Fig. 3) it is possible to install piles even in the close vicinity of vibration-sensitive structures. Geophones (vibration sensors) are placed on critical locations of the structure to be protected and monitored. The signals from the geophones are fed into the field computer and compared with the pre-set, permissible values. When a threshold value is reached, the electronic process control changes the vibration frequency and the static moment (amplitude) of the vibrator, automatically searching for the optimal driving conditions. All measured parameters are printed on site for instant inspection and objective documentation of the pile driving process, an aspect which is important in the case of legal disputes.

4.2 MRC Compaction

The electronic process control system can also be used to increase the efficiency and quality of deep vibratory compaction of granular soils. The objective of the patented MRC system is to compact soils as efficiently as possible, using frequency-variable vibrators (Massarsch, 1991, Massarsch and Heppel, 1991). Each compaction point can be documented in detail, cf. Fig. 6. This includes general project information, such as compaction point location, grid spacing and vibrator characteristics, as well as start and finish time and possible interruptions of the compaction process.

The process control system can also be used for special measurements such as determination of resonance frequency, surface wave propagation velocity etc. In order to achieve optimal soil compaction, the vibrator frequency is adjusted continuously during the different phases of compaction, taking advantage of the electronically controlled MRC system. The installation process consists of three phases: insertion of the probe, soil compaction and extraction of the probe. The probe is inserted at high frequency in order to reduce the soil resistance along the shaft and at the toe. At the required depth the frequency is adjusted to the resonance frequency of the soil layer (or an overtone). The compaction duration depends on the soil properties and on the required densification effect. When the intended soil density has been achieved the probe is extracted, again varying the vibrator frequency. The main components of the MRC system are the frequency variable vibrator, the flexible probe and the electronic process control system, Fig. 5.

The MRC system uses a special, flexible steel probe (FLEXI PROBE) in order to achieve maximum soil densification, Fig 7.

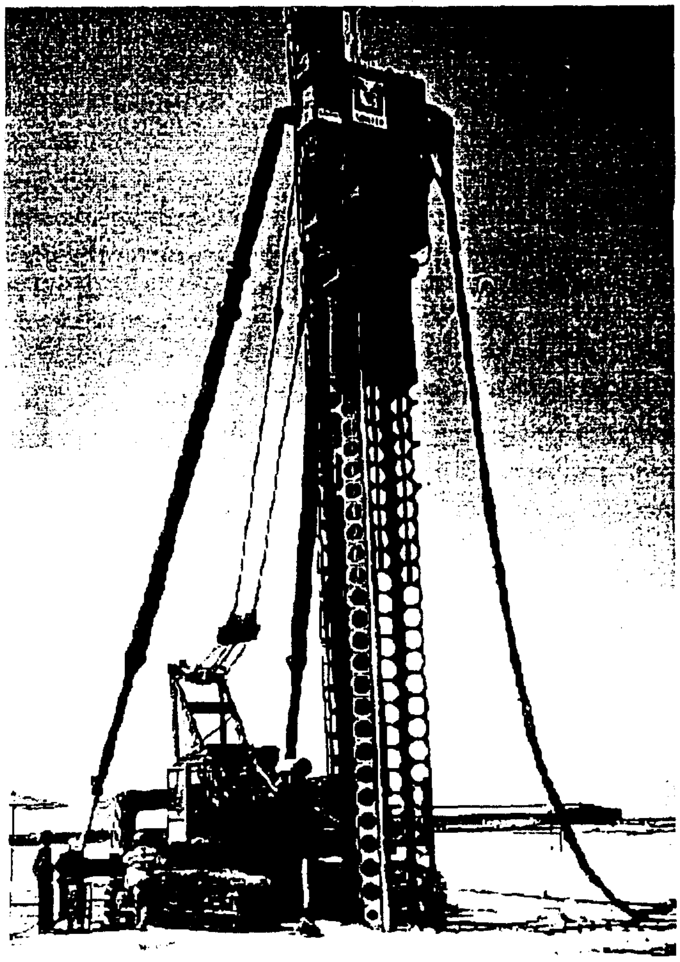


Fig. 7. MRC deep compaction with a frequency-variable Müller-vibrator (MS-100 HF) and a flexible compaction probe (FLEXI PROBE 100) at a compaction site in Map Ta Phut, Thailand

Extensive field tests and theoretical analyses support the findings by Heckman and Hagerty (1978), that a low pile impedance amplifies transmission of vibration energy to the surrounding soil. The reduction of the probe stiffness is achieved by openings in the probe. By attaching vertical or horizontal steel plates across the openings of the probe its stiffness can be adjusted to the site-specific soil conditions. The openings in the probe have further benefits for efficiency of compaction. The lighter probe generates a larger displacement amplitude than a massive probe of the same size. Moreover, the openings provide better contact between the vibrating probe and the soil, further enhancing the compaction effect.

During resonance compaction it is important to determine the optimal compaction frequency. In Fig. 8 the results of resonance measurements are shown at the Map Ta Phut project site. It is apparent that in this case soil resonance occurs at a frequency of 15 Hz which gives the best compaction effect.

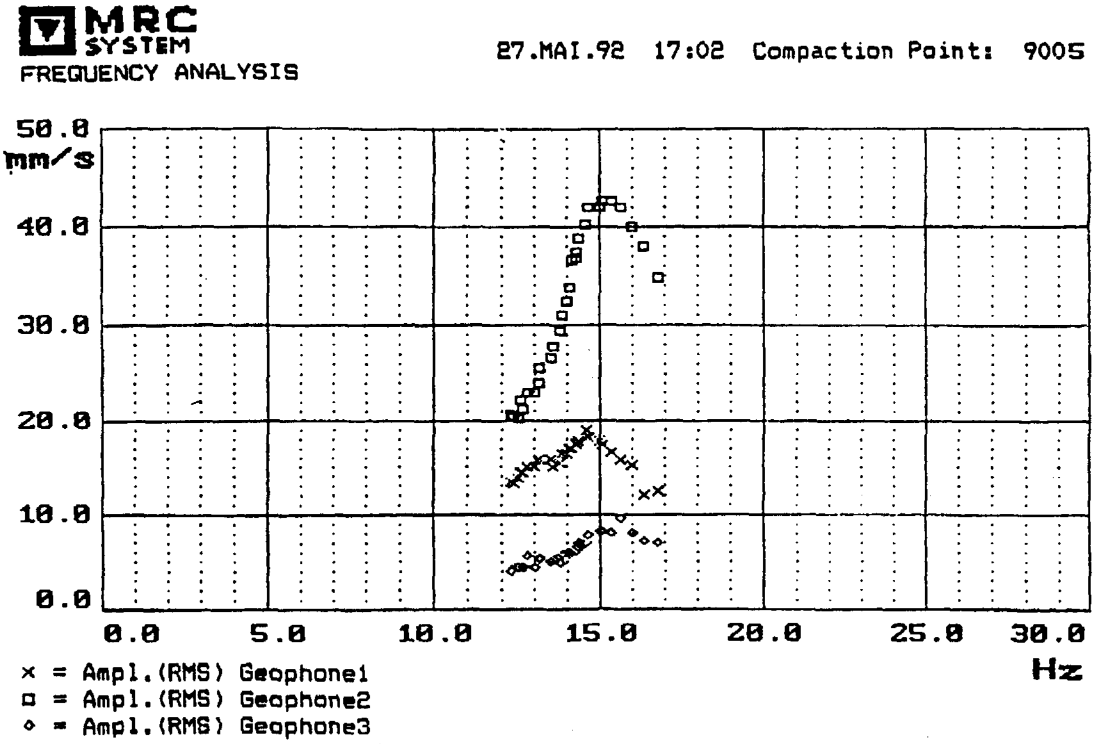


Fig. 8. Results from resonance measurements during MRC compaction

## 5. Vibrated SOILEX Pile

The vibrated SOILEX pile was developed in Sweden during the past 5 years and is characterized by its expandable base (Expander Body). The Expander Body is welded to the lower end of the pile and vibrated into the ground. When the desired depth is reached the pile base is expanded by injecting of concrete or grout (Massarsch & Wetterling, 1993). The SOILEX pile is especially suited for installation by a vibrator, as the pile toe does not have to be driven to refusal into a dense bottom layer. The pile load is carried mainly by the enlarged Expander Body, thus the length of the pile can be reduced significantly, Fig. 9. The SOILEX pile can be used both as an end bearing pile or as a soil anchor.

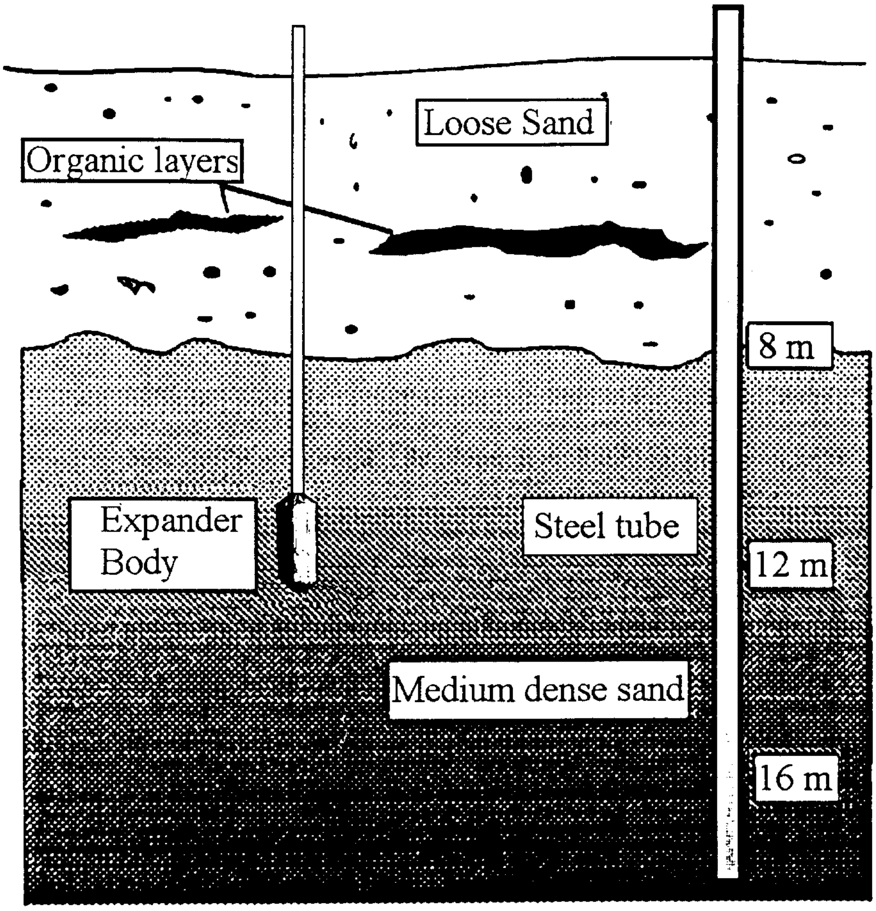
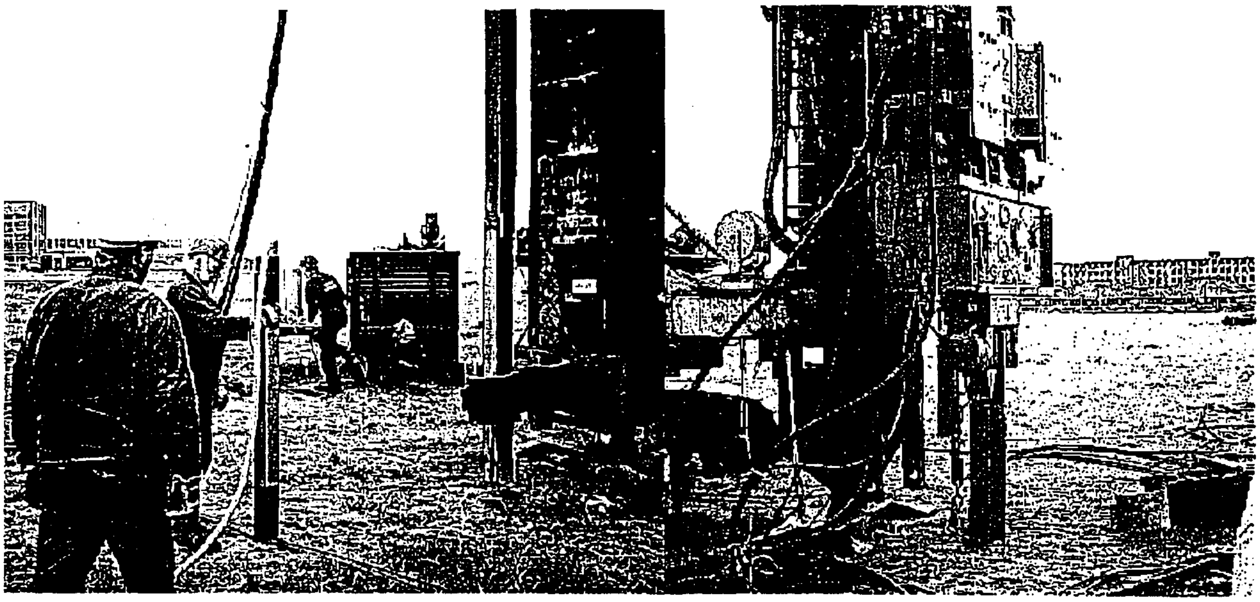


Fig. 9. Installation of SOILEX pile with Expander Body and conventional steel tube pile, Allermöhe, Germany

Extensive field tests were carried out at Allermöhe, Germany, in order to study vibratory driving of different piles types, such as open and closed steel tubes, and SOILEX piles. The test program included vibration monitoring with the MRC system as well as pile load tests. The geotechnical conditions on the site are typical for many areas of northern Europe. The top 8 m of soil consist of loose to medium dense sand with organic lenses and occasional layers of dense sand. The cone penetration resistance in these layers varies between 0,5 and 20 MPa (SPT N-values ranging between 1 - 40). These very variable soil deposits are underlain by a sequence of medium dense to dense sand layers to great depth, with CPT-values ranging between 5 and 20 MPa (corresponding to N-values of approximately 10 - 50). Based on the cone penetration tests it was possible to estimate with sufficient accuracy the driving resistance of different pile types.

A vibrator of type Müller MS 25 with variable frequency (0- 35 Hz) and a maximum centrifugal force of 750 kN was used, Fig. 10. In order to improve driving performance, a static weight of 16 kN was added to the vibrator. Prior to installation of a SOILEX pile, a steel tube with diameter 139 mm (with closed bottom) was used to pre-form a hole. Thereafter, the SOILEX pile was installed. Vibratory driving proved to be very efficient in spite of the variable soil conditions. An interesting result of the vibration tests was that during driving of the open end steel pipe, no plug was formed inside the tube, which would have been typical for impact-driven piles. Instead, soil penetrated inside the tube to a level of 4,5 m below the ground surface. The penetration speed for driving open tube piles was about 5 times higher compared to piles with a closed toe. It was also found that penetration efficiency in dense soil layers with a small vibrator could be increased by pre-driving with a closed tube of smaller diameter.



Mounting of Expander Body

Pile installation with frequency-variable vibrator MS 25

Fig. 10. Installation of SOILEX pile with Expander Body at Allermöhe, Germany

Two steel tube piles (diameter 356 mm) and two types of SOILEX piles (Expander Body's with diameter 500 and 800 mm) were tested. The Expander Body's were welded to steel tubes with diameter 273 mm.

Typical results from the pile load tests are shown in Fig. 10. The SOILEX piles with expanded base (EB 500 and EB 800, respectively) of 12 m length can be compared with open tube piles of 12 and 17 m length, respectively. The test results show that a 12 m long SOILEX pile with Expander Body 500 has about the same bearing capacity as a 17 m long open tube with a diameter of 356 mm. The SOILEX pile with Expander Body 800 has a bearing capacity which is about twice as high as that of the open 356 mm tube pile of the same length.

## 6. Summary and Conclusions

The paper discusses factors influencing the installation of vibrated piles. The entire chain of energy transmission, from the vibrator, through the pile and into the soil must be considered. The penetration resistance during vibratory driving differs significantly from impact driving. The transmission of ground vibrations is influenced by the operation of the vibrator and its characteristics, the pile impedance and the dynamic properties of the soil.

The relative displacement amplitude between the pile and the soil is an important parameter which affects pile penetration speed and influences the degree of energy transmission from the pile to the surrounding soil.

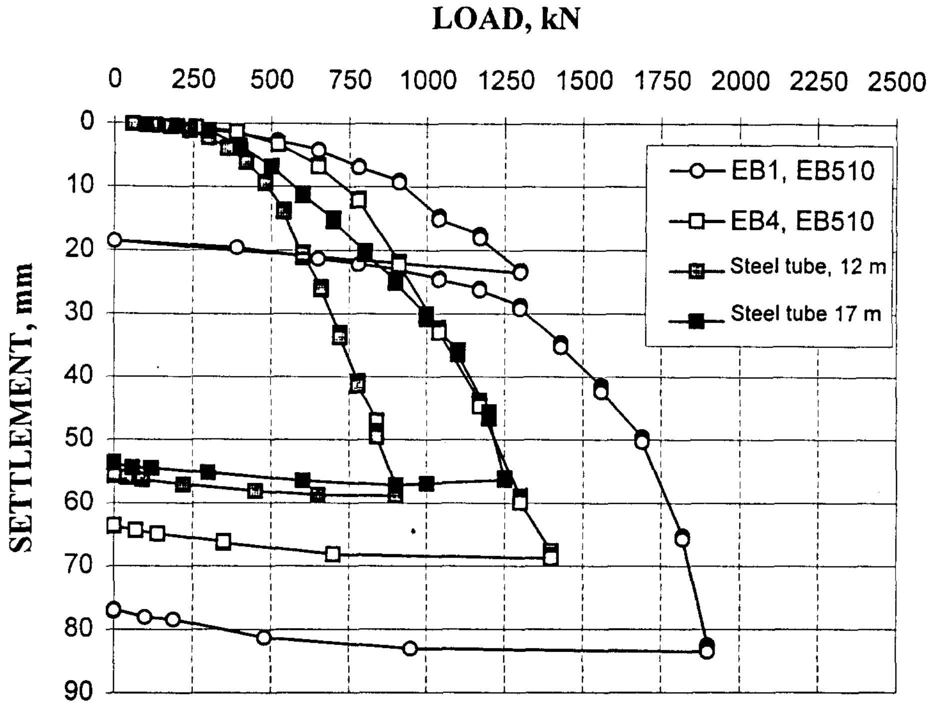


Fig. 10. Pile load test for steel tube piles with and without an Expander Body, Allermöhe, Germany

Whereas soil behavior during vibratory pile driving is difficult to predict theoretically, it is possible to monitor driving performance on the construction site with an electronic process control system. This information is important for the optimal use of vibrators for pile installation and soil compaction.

Modern vibrators can accomplish the continuous variation of frequency and static moment (displacement amplitude) during all phases of pile installation or soil compaction. This makes it possible to adjust vibrator operation in order to minimize vibration problems and to maximize driving efficiency. Thus it has become possible to install piles with vibrators even in the close vicinity of vibration-sensitive structures.

Vibratory compaction can be carried out efficiently with a frequency-variable vibrator, a flexible compaction probe and an electronic process control system, which adjusts vibrator operation during the different phases of soil compaction.

SOILEX piles with expanded base (Expander Body) are particularly suitable for vibratory driving since they do not require driving to refusal. The bearing capacity of SOILEX piles is high in granular soils.

## 7. Acknowledgments

The research work presented in this paper has been carried out with the help of many people during a ten-year period in Sweden, Belgium and Germany. The most important development steps were carried out the Royal Institute of Technology (KTH) in Stockholm, Sweden. The research was financed partly by the Swedish Council for Building Research (BFR) and the Swedish Development Fund of the Construction Industry (SBUF). SOILEX AB has sponsored the test program in Allermöhe, Germany. The assistance by Katarina Eriksson during the tests in Allermöhe is especially acknowledged. The extensive field tests at several sites outside Sweden were made possible by support from Krupp GfT Tiefbautechnik (Müller vibrators) and from Franki Grundbau.

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