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Monitoring and Process Control of Deep Vertical Vibratory Compaction Using Resonance Amplification

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ABSTRACT: *Compaction trials using deep vertical vibratory compaction in a hydraulic fill are reported. The compaction system consisted of a vibrator with variable frequency and a flexible, double Y-shaped probe. Openings in the probe reduced the dynamic weight and enhanced the probe-ground interaction. The compaction process was documented by a monitoring and process control system. The dynamic ground response was measured during different phases of the compaction process by sensors on the compaction machine and in the ground. Ground vibrations were amplified by adjusting the vibrator to the resonance frequency of the vibrator-probe-soil system. Cone penetration tests with pore water pressure measurements were performed before and after treatment, and showed a significant increase in both cone and sleeve resistance. Geophones were installed on and below the ground surface to record vertical and horizontal ground vibrations. The magnitude of horizontal ground vibrations was measured at two distances from the compaction probe, making it possible to determine vibration attenuation. The vertically oscillating compaction probe generated vibrations in both vertical and horizontal directions. Strong horizontal vibrations were emitted during resonance, which can explain the permanent increase in horizontal stress. The increase in horizontal stresses is about twice that of static horizontal stresses. As a result of vibratory compaction, a stress gradient of horizontal stresses is created, which is likely to equalize with time.*

KEYWORDS: Compaction, CPTU, horizontal stress, pre-stressing, resonance, sand, vibration, vibrator, shear wave speed

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INTRODUCTION

Different deep vibratory compaction methods can be used to improve the geotechnical properties of granular soils (Mitchell, 1981; Massarsch and Fellenius, 2005; Chu et al., 2009). A European Standard exists that prescribes its planning, execution, and quality control (EN 14731 2005). A special method is deep vertical vibratory compaction (DVVC), which uses a vibrator clamped to the top of a compaction probe (Anderson, 1974; Wallays, 1982; Massarsch, 1991a). The compaction probe is excited by the vertical oscillations of the vibrator. For the efficient execution of DVVC projects, it is essential that suitable equipment be used, i.e., a vibrator with variable operating frequencies and a flexible compaction probe. Also, the site personnel must be familiar with using modern vibrators on soil compaction projects. Due to its simplicity, DVVC is frequently chosen by general contractors using standard vibrators and simple compaction probes (beams or tubes). They often have limited experience in the application of vibrators for ground improvement. This has limited the successful application of DVVC on larger projects. Vibratory compaction has two effects on granular soils: a) densification (compression of voids),

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and b) pre-stressing (increase in horizontal stresses). Densification is caused by cyclic shear strain (strain amplitude and number of vibration cycles). Shear strain amplitude, γ, can be estimated from the following relationship

$$\gamma = \frac{v}{C_s} \quad (1)$$

where v = particle velocity and C_s = shear wave speed. Densification also increases with the number of vibration cycles (Massarsch, 2000; Green and Terri, 2005; Dobry and Abdoun, 2015). Thus, vibration intensity (magnitude and duration) is a key parameter for efficient vibratory compaction as shear strain increases with particle velocity (Youd, 1972; Seed, 1976). Vibratory compaction also results in a permanent increase in horizontal effective stress (pre-stressing) caused by horizontally oscillating vibrations (Massarsch et al., 2020). Deep vibratory compaction has been shown to significantly increase horizontal stress (Massarsch and Fellenius, 2020; Gasser et al., 2022). This effect is of practical significance for settlement estimates and liquefaction analyses. However, only the densification effect is usually considered in the compaction design, while the pre-stressing of the ground is generally neglected.

Case histories reporting vibratory compaction projects usually describe the compaction effect in terms of penetration resistance. Rarely is the dynamic interaction with the surrounding soil described. In the present paper, carefully instrumented field tests investigated the dynamic ground response resulting from DVVC and the change in vibration frequency. Vertical and horizontal ground vibrations were measured on and below the ground surface. The compaction effect was measured by cone and sleeve resistance changes after compaction.

RESONANCE COMPACTION CONCEPT

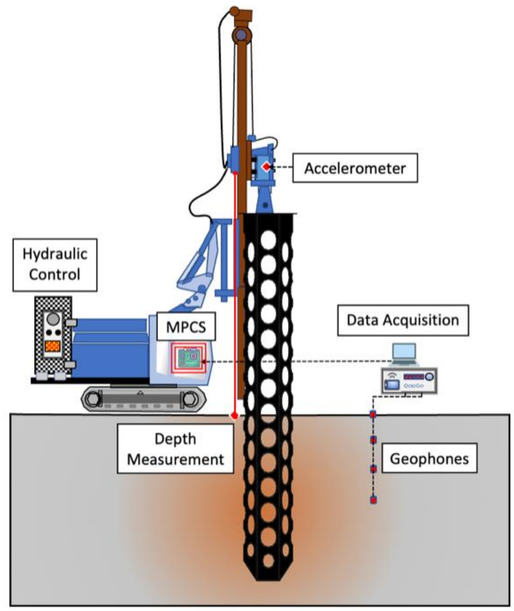
Deep vertical vibratory compaction by resonance amplification (DVVCr) is based on the increase in ground vibrations that occurs when the vibrator is excited at the resonance frequency of the vibrator-probe-ground system, subsequently called "system resonance" (Massarsch, 1991b; Massarsch and Fellenius, 2005). At system resonance, ground vibrations and, consequently, the soil compaction effect are enhanced. The shaft resistance is low when the compaction probe is vibrated at a high frequency. However, when the vibration frequency is gradually reduced, approaching system resonance, the probe and the ground vibrate "in phase," and the relative displacement between the probe and the soil becomes small. This is an essential aspect of resonance compaction. At resonance, almost static friction exists at the probe-soil interface, and ground vibrations are amplified (Massarsch et al., 2021a). Also, probe penetration slows down. The soil layer, which is penetrated by the compaction probe, oscillates strongly (Massarsch, 2002). In water-saturated, loose granular soils, spontaneous liquefaction can occur (Massarsch et al., 2021b).

DVVCr has been used successfully in different countries (Massarsch, 1991b; Choa et al., 2001; Massarsch and Fellenius, 2005; Liu and Cheng, 2012; Cheng and Liu, 2013; Massarsch and Fellenius, 2017; Guangyin et al., 2021; Massarsch et al., 2021b). In connection with the Changi airport project, extensive investigations were performed by Krogh and Lindgren (1997). These tests have been re-analyzed and are reported in this paper. The tests were carried out in a trial area at Changi Airport 1B. The objectives were to document the dynamic probe-soil interaction and, in particular, the emission of ground vibrations from the vibrator to the probe and into the surrounding soil. For this purpose, machine operating parameters were recorded during the entire compaction process. Vibration sensors (geophones) were installed on and below the ground surface

INTERNATIONAL JOURNAL OF GEOENGINEERING CASE HISTORIES
DOI: 10.4417/IJGCH-08-01-02

by which the shear wave speed before and after compaction could be measured. The geotechnical properties of the soil deposit were determined by cone penetration tests with pore water pressure measurements (CPTU). The equipment used for the DVVCr tests is shown in Figure 1.

a) Vibrator clamped to flexible compaction probe.



b) Monitoring and process control system (MPCS).

Figure 1. *DVVCr equipment used for resonance compaction at Changi Airport 1B site.*

The compaction machine consisted of a variable frequency vibrator clamped to the top of a flexible probe. Compaction was performed using a monitoring and process control system (MPSC). An MS-200 vibrator was used, which at that time (1996) was one of the most powerful construction vibrators available. The characteristics of the vibrator are provided in Table 1. The vibrator had a large eccentric moment (1,900 Nm), generating a maximum centrifugal force of 4,000 kN. The vibration frequency could be varied between 10 and 28 Hz. The peak-to-peak displacement amplitude, *S*, of the vibrator (without clamp and probe) was 32 mm.

Table 1. *Characteristics of vibrator type MS-200.*

Item	Quantity	Units
Maximum centrifugal force	4,000	kN
Maximum eccentric moment	1,900	Nm
Maximum oscillation frequency	1,700/28	RPM/Hz
Total mass without clamp	18,500	kg
Dynamic mass without clamp	11,750	kg
Displacement amplitude (without clamp) $S = 2s$	32	mm
Maximum pulling force	1,200	kN
Oil pressure	380	MPa

DOI: 10.4417/IJGCH-08-01-02

A purpose-built, flexible compaction probe with a length of 12 m and a circumference of 2 m was used. The probe dimensions are given in Table 2. The mass of the probe could be reduced by more than 70% by providing the probe shaft with circular openings, thereby increasing the displacement amplitude. Also, the openings created more efficient contact between the vibrating probe and the surrounding soil, which resulted in an enhanced transfer of vibration energy.

Table 2. *Size of compaction probe.*

Item	Value	Unit
Length	12	m
Central plate width	550	mm
Wing plate length	800	mm
Vertical distance of openings	360	mm
Diameter of openings	300	mm
Openings/total surface	70	%
Total mass	8,000	kg

The vibratory driving process was controlled and monitored by the MPCS unit. It had three main functions: a) measurement and recording of all relevant driving and compaction parameters, b) display of important parameters to assist the machine operator in the execution of the driving or compaction process, and c) storage of all data for future evaluation (database). A custom-built MPCS (Loster Famos) was used at the Changi project. The evolution of the MPCS concept was described in detail by Massarsch and Wersäll (2019) and is now an integral part of DVVCr. The components and software used on the Changi project were described in detail by Krogh and Lindgren (1997). The MPCS made it possible to record the dynamic performance of the vibratory driving system as well as the ground vibrations during the entire compaction process.

CASE HISTORY

DVVCr was used to improve hydraulic fill at the Changi Airport in Singapore (Krogh and Lindgren, 1997; Choa et al., 2001). The soil deposit consisted of a hydraulic fill placed by pumping and mechanical equipment. The compaction specifications required achieving different cone resistance values (10, 12, and 15 MPa, respectively) based on the requirements of the respective project zones (Choa et al., 2001). Before the start of compaction, two CPTUs (16/17) were performed, as shown in Figure 2. After that, compaction was carried out in two passes, followed by two CPTUs (28/29) located between the compaction points. The MPCS monitored the performance of the vibrator, probe, and ground vibrations.

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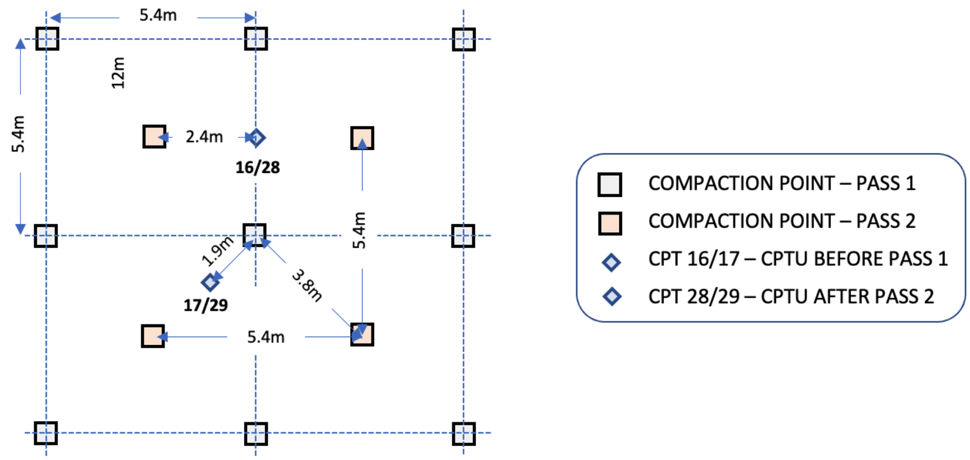


Figure 2. *Location of compaction points and CPTU investigations in the trial area, Changi Airport 1B.*

Geotechnical Conditions

The results of the CPTUs (16 and 17) before compaction are shown in Figure 3, comprising cone resistance, sleeve resistance, pore water pressure measurements, and soil classification. The top layer consisted of very dense sand reaching a cone resistance, q_c, of 15 MPa at 1 m depth. From 2 to 2.5 m depth, q_c varied between 1 and 5 MPa. In the following sand layer down to 9 m depth, the cone resistance ranged between 5 to 10 MPa, except for occasional denser and looser zones. Below 9 m, q_c increased to values exceeding 20 MPa.

The sleeve resistance, f_s, gave a similar picture of soil stratification. Below the dense surface layer at 1 m depth ($f_s \sim 40$ kPa), the sleeve resistance ranged from 10 to 60 kPa.

The pore water pressure measurements showed that the groundwater table was at 2.5 m depth. In the surface layer, positive pore pressure was observed, indicating that the material there is likely saturated (and probably of low hydraulic conductivity). The excess pore water pressure, u, fluctuated around the hydrostatic pressure, with values exceeding the hydrostatic pressure, indicating fine-grained soil. However, denser layers were also encountered with negative pore water pressures, suggesting the existence of dilating soils.

The soil type was classified according to the Robertson SBT Index, I_c (Robertson, 2010). The soil behavior type index, I_c, indicated that the soil deposit consisted down to 10 m depth mainly of sand and silty sand, with some fine-grained layers (sandy silt and clayey silt) between 4.5 and 5 m depth.

Ground Vibration Measurement

To investigate the propagation of vibrations from the compaction probe to the surrounding soil, one triaxial geophone was installed on the ground surface at 6 m distance from the center of the compaction probe (shown in Figure 4a). In addition, horizontal geophones were installed at four levels at two distances from the probe. A section with the location of the geophones is shown in Figure 5. The following installation procedure for the geophones was used (Krogh and Lindgren, 1997). A tube was equipped with a loose end plate. The geophone was placed inside the tube and pushed down to the bottom

DOI: 10.4417/IJGCH-08-01-02

by a steel rod. The tube was filled with water to prevent the inflow of water and sand into the tube. Then, the tube was slowly extracted, while simultaneously the steel rod was held against the geophone to ensure that the geophone and the end plate were released from the bottom of the tube. When the geophone was safely anchored in the ground, the tube was fully extracted, and the remaining hole was filled with sand.

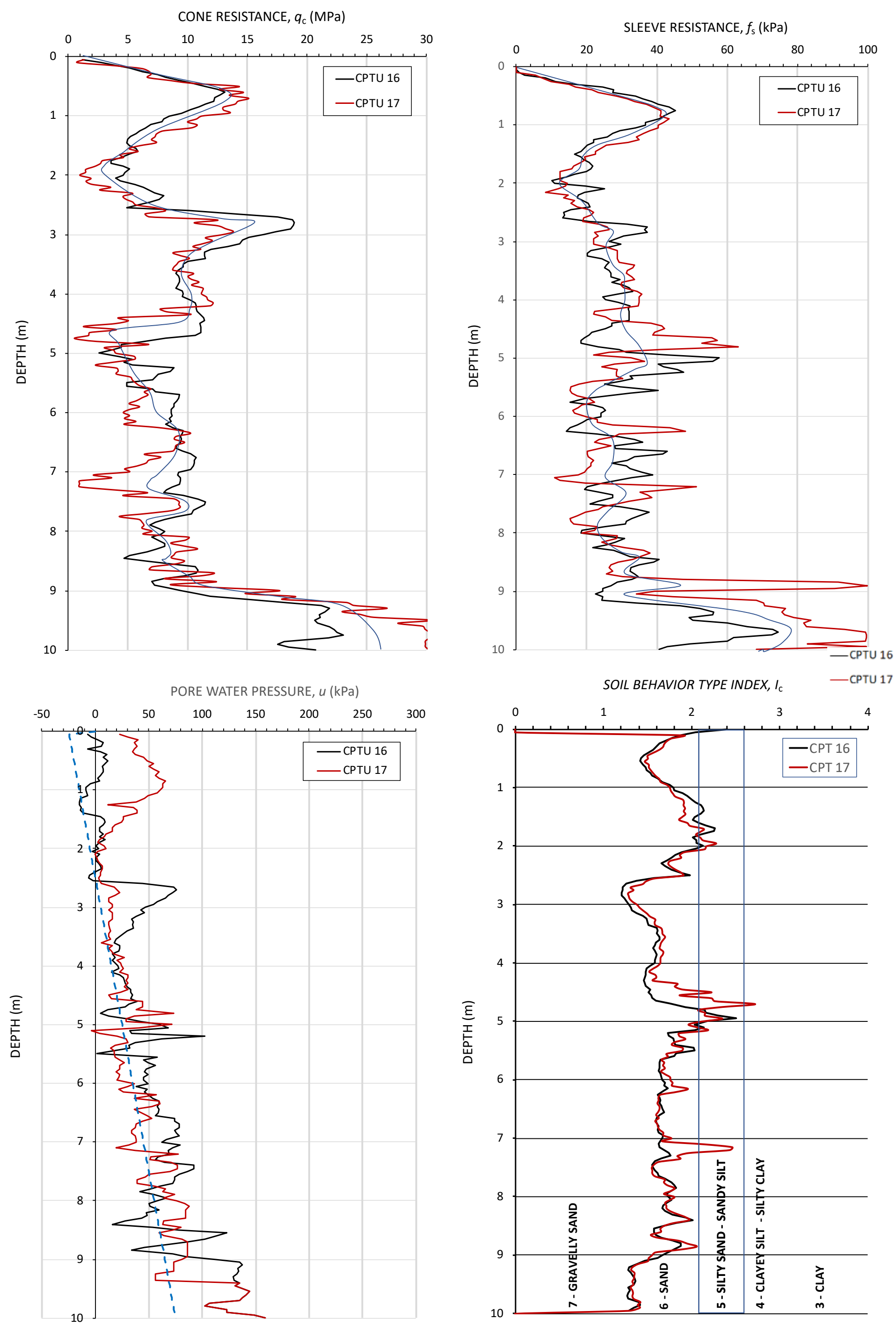
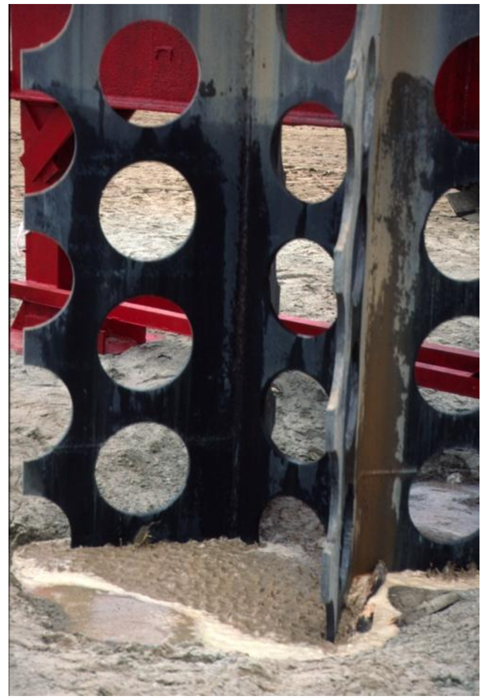


Figure 3. *CPTU results prior to compaction (CPTU 16 and 17).*

INTERNATIONAL JOURNAL OF GEOENGINEERING CASE HISTORIES

DOI: 10.4417/IJGCH-08-01-02

a) Triaxial geophone located at 6 m distance from the compaction probe



b) Liquefaction during DVVCr

Figure 4. *Resonance compaction at Changi test site 1B.*

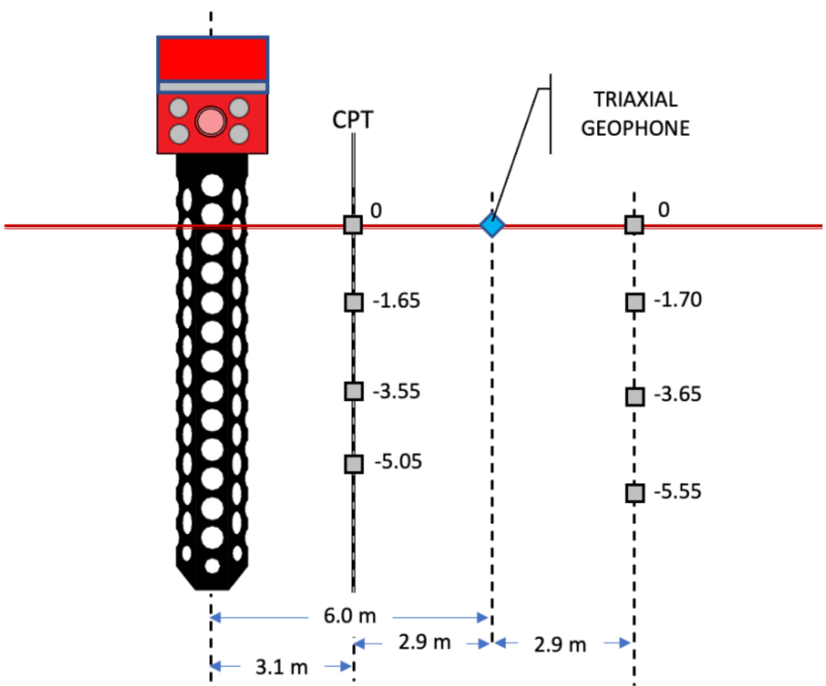


Figure 5. *Section showing the location of triaxial and horizontal geophones.*

DOI: 10.4417/IJGCH-08-01-02

DEEP VIBRATORY COMPACTION

The relatively dense top layer was heterogeneous, including fine-grained layers. Therefore, before starting trial compaction, it was decided to replace the dense surface material with loose sand down to the groundwater table (2.5 m depth). DVVCr was carried out in two passes, as shown in Figure 2. During the first pass, the spacing between the compaction points was 5.4 m (rectangular grid). During the second pass, compaction in the diagonal points resulted in a final compaction point distance of 3.8 m. The duration of compaction at each point was approximately 15 minutes, including the resonance trials. During production work, the duration of compaction at each point was less than 10 minutes.

Although the groundwater table was located approximately 2.5 m below the ground surface, at resonance, the groundwater rose to the ground surface, showing clear signs of soil liquefaction. However, liquefaction could not be observed during the second compaction pass. It is apparent that DVVCr can be used to investigate the risk of soil liquefaction in loose granular soils, as described by Massarsch et al. (2021b).

CPTU After Compaction

CPTUs (28 and 29) investigated the compaction effect after two passes, as shown in Figure 2. The CPTU results are presented in Figure 6. For ease of comparison, the average cone and sleeve resistance before compaction is also shown, cf. Figure 3. After vibratory treatment, the cone and the sleeve resistance increased by about 100%. The compaction requirements expressed in terms of cone resistance were thus achieved (Choa et al., 2001).

Shear Wave Speed Measurements

Extensive down-hole and surface wave measurements were performed prior to and after compaction. The seismic measurements have been described in detail by Krogh and Lindgren (1997). In the DVVCr trial area, down-hole measurements were performed one day before and five days after DVVCr treatment. The down-hole tests after compaction were carried out in the replaced, loosened sand fill.

Shear waves were generated with a pneumatic impulse hammer. To ensure the effective transfer of the energy from the hammer to the ground, the anchor plate was equipped with long spikes. It was firmly placed on the ground surface and loaded with a static weight. The impulse direction and the orientation of the horizontal geophones were along the alignment between the two columns of sensors. A horizontal accelerometer was used as a trigger sensor. The measured shear wave speeds are summarized in Table 3.

Table 3. *Measurement of shear wave speed before and after compaction.*

Depth interval	Before compaction	After compaction
	Shear wave speed, C_s	
m	m/s	
1.7 to 3.65	153	194
3.65 to 5.65	212	231
Average	182	212

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DOI: 10.4417/IJGCH-08-01-02

The average shear wave speed increased in the replaced sand (between 1.7 and 3.65 m) from 153 to 194 m/s, and in the compacted sand fill from 212 to 231 m/s. The average shear wave speed due to vibratory treatment increased from 182 to 212 m/s (16%), which was significantly lower than the increase of the cone and sleeve resistance, cf. Figure 6. Hardin (1978) has shown that the shear modulus at small strain, G_0, is less sensitive to the increase in mean effective stress, which can explain the modest increase in shear wave speed.

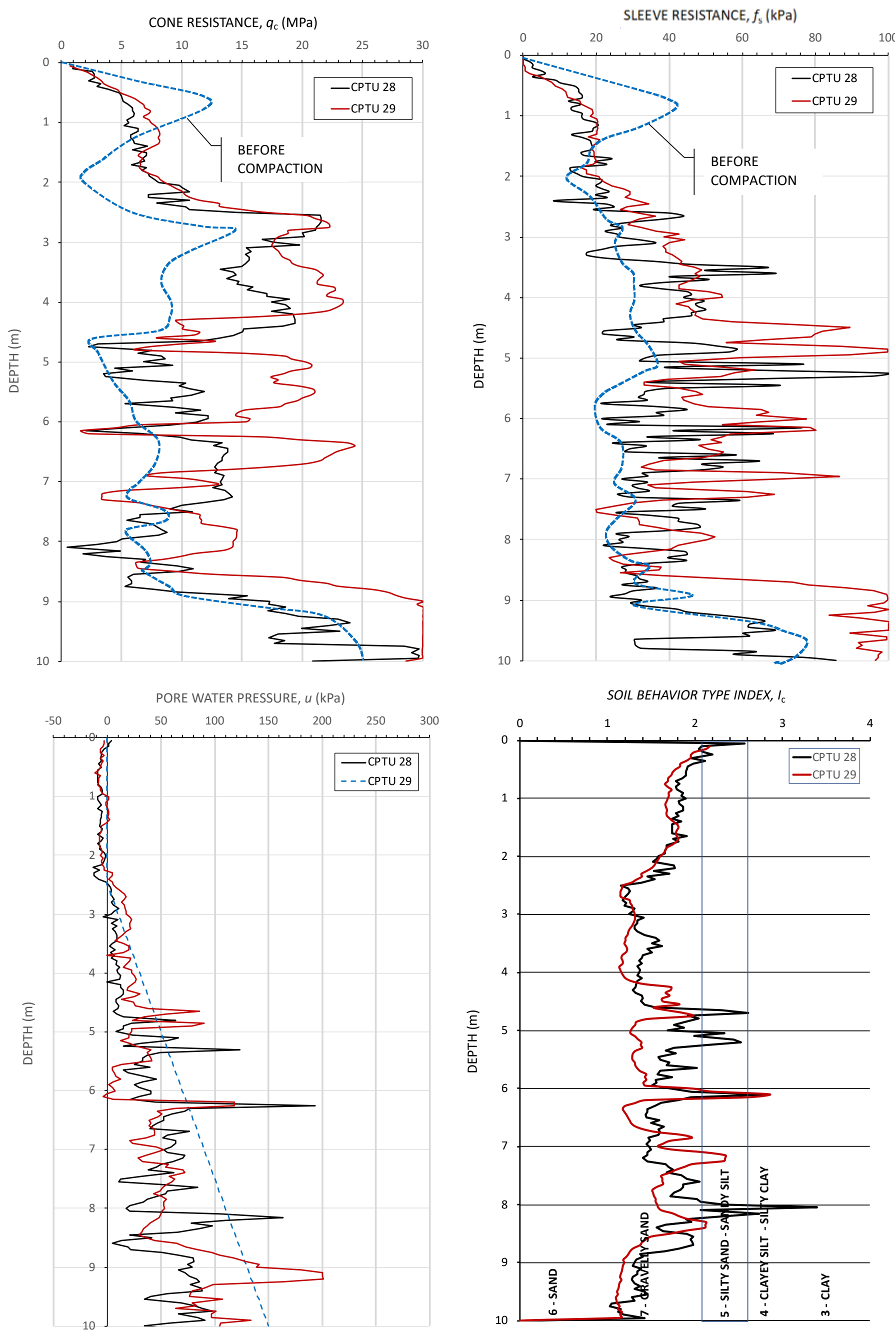


Figure 6. *CPTU results after resonance compaction (CPTU 28 and 29) and comparison with average q_c and f_s prior to compaction, cf. Figure 3.*

DOI: 10.4417/IJGCH-08-01-02

MONITORING OF RESONANCE COMPACTION

Machine Performance

The MPCS monitored the machine performance and the dynamic ground response during DVVCr (Massarsch et al., 2021c). Sensors were mounted on the compaction rig and in the ground, as shown in Figure 1b. The machine performance parameters in Figure 7 are the depth of the compaction probe, the vibrator frequency, the hydraulic pressure, the acceleration of the vibrator, and the vertical displacement amplitude.

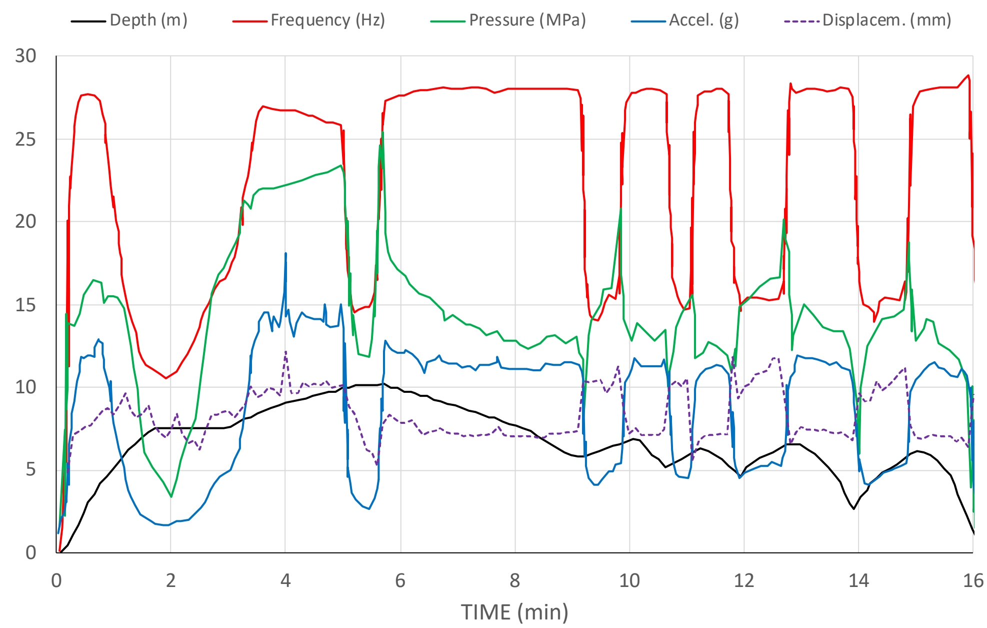


Figure 7. *Performance data of the compaction machine.*

The compaction probe was inserted at a high frequency (27 Hz). Two resonance tests were carried out after 1.5 min (7 m depth) and again after 5.5 min (10 m depth). The hydraulic pressure and the vibrator acceleration decreased when the vibration frequency was lowered. During the resonance tests, the vibration frequency was gradually reduced to 11 Hz and then increased again to the maximum frequency. After that, probe penetration continued to maximum depth (10 m) at 28 Hz. The probe was extracted in steps at a high frequency (28 Hz) to avoid decompaction (loosening) of the ground. After each extraction step, the probe was pushed downward again at the resonance frequency (15 Hz), during which soil compaction was achieved. The compaction process was completed after four re-penetration cycles. It is relatively simple to determine the system resonance frequency by field measurements. On the other hand, theoretical analyses of the probe-ground interaction can be very complicated, as these require that the nonlinear probe-soil interaction is correctly modelled.

An important observation is that during the resonance phase, when the vibrator was operating at a low frequency (15 Hz), vertical ground vibrations were amplified. However, the hydraulic pressure decreased, resulting in reduced energy consumption. This aspect is important considering the effect of ground treatment on fuel consumption and, thus the project economy.

DOI: 10.4417/IJGCH-08-01-02

Vibration Response of Ground Surface

The vibration response of the ground surface was recorded by one triaxial geophone located at 6 m from the center of the compaction probe (see Figure 4). The measured vibration amplitudes (RMS) are shown in Figure 8. System resonance occurred at approximately 15 Hz, at which the ground vibrations were strongly amplified. The radial vibration amplitude was slightly higher than the vertical component, which can be attributed to the beneficial effect of the double-Y shape of the probe, which enhances the transfer of compaction energy. The tangential vibration amplitude was generally lower and did not show a significant amplification effect at resonance.

The vertical ground vibrations result from the cylindrical shear waves emitted from the oscillating compaction probe (Massarsch, 2002). Cylindrical shear waves are not affected by amplitude amplification at the ground surface. The increase in vertical vibration amplitude is thus primarily the result of the enhanced contact of the compaction probe and the surrounding soil during system resonance.

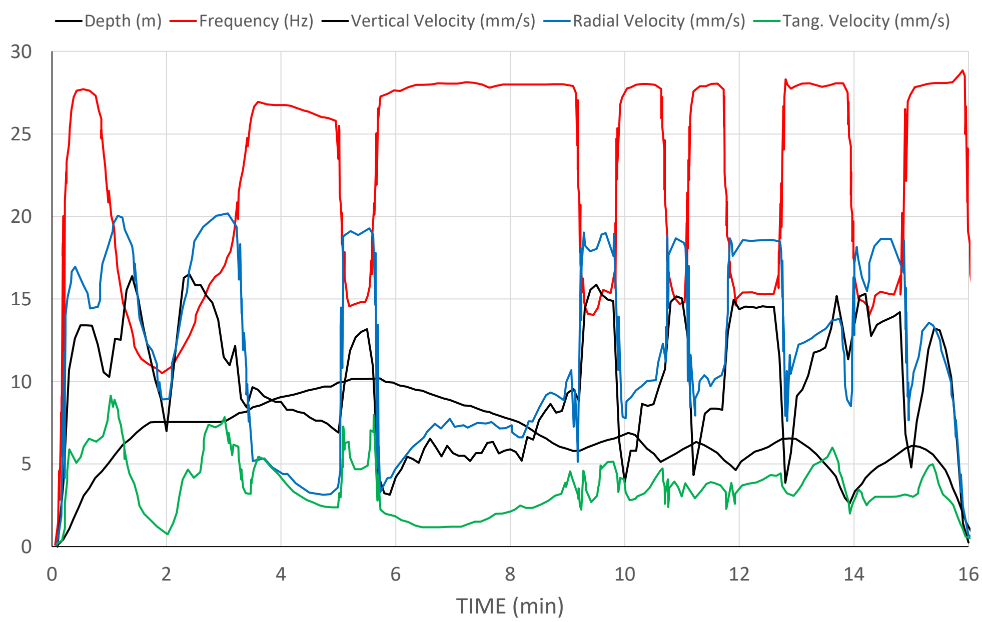


Figure 8. *Ground vibrations (RMS value) recorded by triaxial geophone at the ground surface, at 6 m distance from the probe.*

Figure 9 shows the vertical and radial ground vibration velocity (RMS) as a function of vibration frequency. The vertical and radial ground vibrations are amplified between 12 to 18 Hz. At system resonance, vibration velocity amplitudes are in the range of 12 to 20 mm/s but much lower (5 to 8 mm/s) during penetration and extraction (28 Hz). It should be noted that the resonance frequency gradually increases during compaction as the shear wave speed of the soil increases.

DOI: 10.4417/IJGCH-08-01-02

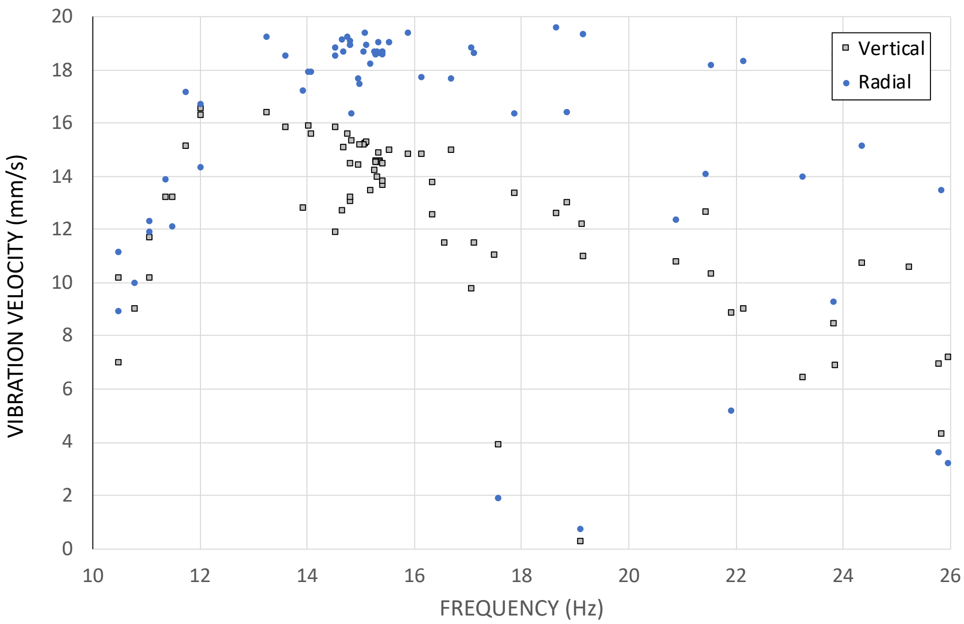
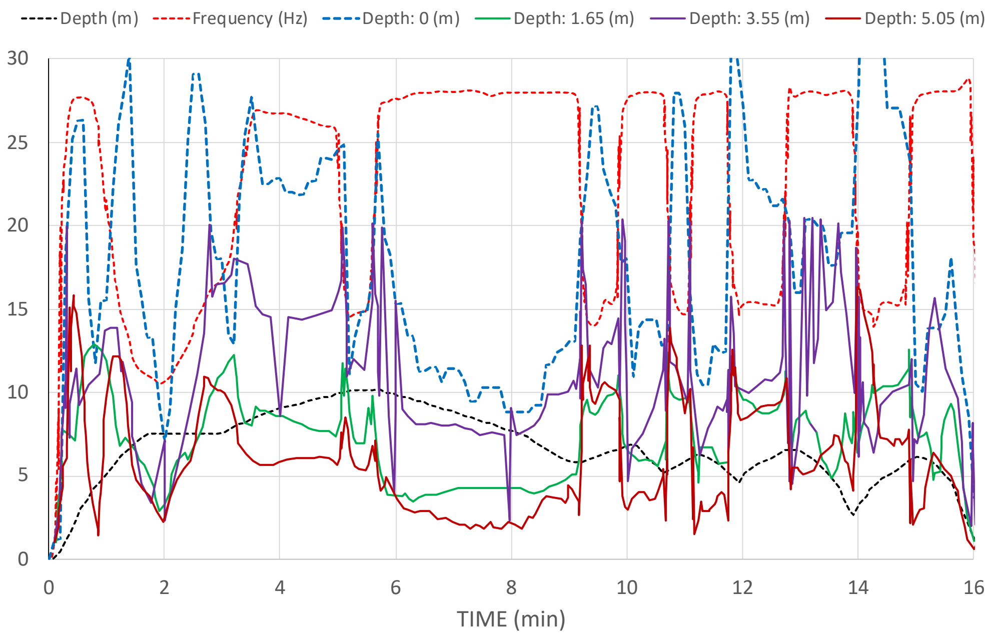


Figure 9. *Vertical vibration response (RMS) on the ground surface as a function of frequency.*

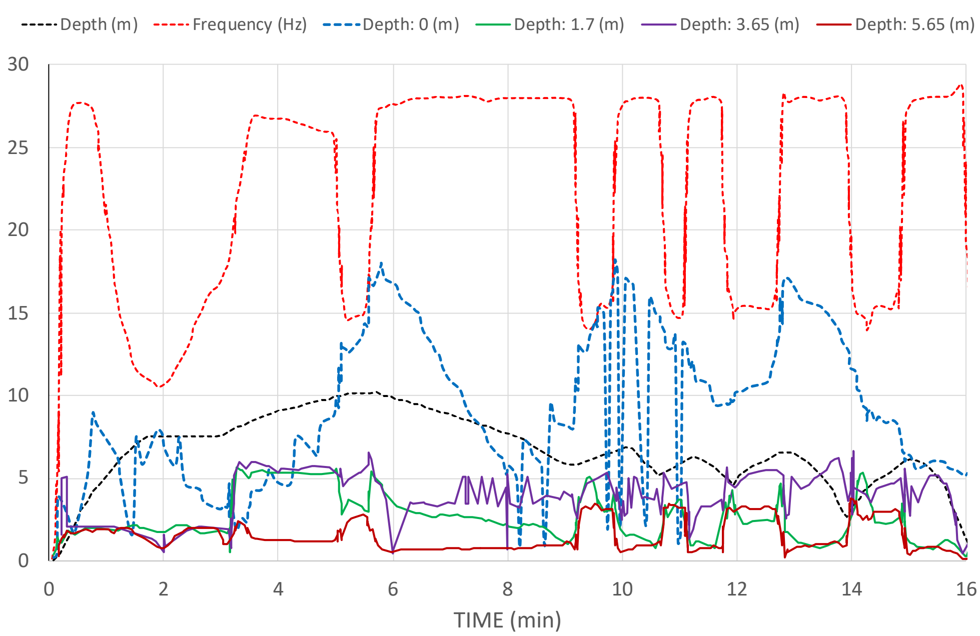
Horizontal Ground Vibrations

Horizontal ground vibrations were measured at the ground surface and three depths (1.65, 3.55, and 5.05 m). The sensors were located at 3.1 and 8.9 m distance from the compaction probe, as shown in Figure 5. The measured vibration velocities (RMS) during probe penetration, resonance compaction, and extraction at 3.1 and 8.9 m distance from the compaction probe are shown in Figure 10.

DOI: 10.4417/IJGCH-08-01-02



a) Horizontal ground vibrations measured at four levels (0, 1.65, 3.55, and 5.05) at 3.1 m lateral distance from the probe.



b) Horizontal ground vibrations measured at four levels (0, 1.75, 3.65, and 5.65) at 8.9 m lateral distance from the probe.

Figure 10. *Horizontal ground vibrations (RMS) on, and at three levels below the ground surface, at 3.1 and 8.9 m distances from the center of the compaction probe.*

As the vibrator frequency was decreased to resonance, horizontal ground vibrations were amplified significantly, similar to the vibrations measured by the triaxial geophone on the ground surface. Thus, it is apparent that compaction at system resonance also amplifies ground vibrations in the horizontal direction.

DOI: 10.4417/IJGCH-08-01-02

As expected, the horizontal signals at 8.9 m distance are significantly weaker than at 3.1 m but show the same response pattern. The horizontal ground vibrations at 3.1 m distance are higher than those measured by the triaxial geophone at 6 m distance (see Figure 8).

VIBRATION ATTENUATION DURING RESONANCE COMPACTION

An important objective of horizontal ground vibration measurements was to determine the vibration attenuation as a function of distance from the compaction probe. As the amplitude was measured at two distances (3.1 and 8.9 m), vibration attenuation could be estimated from the following relationship (Richart et al., 1970; Massarsch, 1993):

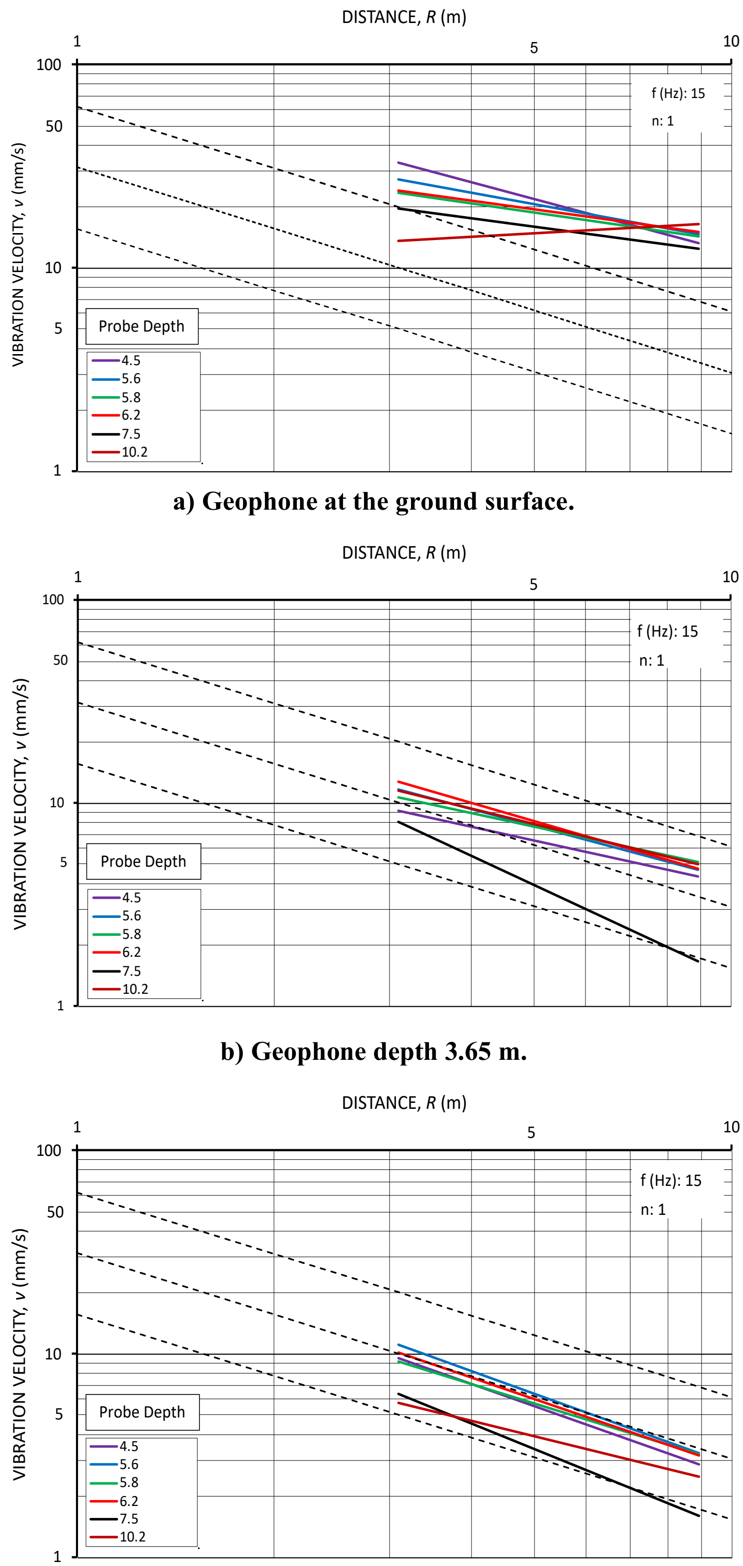
$$v_2 = v_1 \left(\frac{R_1}{R_2}\right)^n e^{-\alpha(r_2 - r_1)} \quad (1)$$

where v_1 = vibration amplitude at distance R_1, v_2 = vibration amplitude at distance R_2, e = base of the natural logarithm, n = wave attenuation exponent, and α = absorption coefficient that can be estimated from the following relationship (Haupt, 1986; Massarsch, 1993):

$$\alpha = \frac{2\,\pi\,D\,f}{C} \quad (2)$$

where α = absorption coefficient, D = damping coefficient, f = vibration frequency, and C = wave propagation speed. Horizontal vibration velocities were measured during system resonance at 3.1 and 8.9 m in the lateral direction from the compaction probe, thus representing compression waves. Vibration attenuation during the resonance phase was determined according to Equations (1) and (2), assuming a vibration frequency of 15 Hz. The compression wave speed in water-saturated sand was assumed to be C_P = 1450 m/s with a wave exponent n =1. The vibration attenuation was determined during resonant compaction at two depths (3.65 and 5.0 m), at 3.1 and 8.9 m from the center of the compaction probe. The results in Figure 11 show vibration attenuation at a) the ground surface, b) at 3.65, and c) at 5.0 m depth. The probe penetration depth (4.5 to 10.2 m) is indicated for each case.

INTERNATIONAL JOURNAL OF
GEOENGINEERING
CASE HISTORIES
DOI: 10.4417/IJGCH-08-01-02



a) Geophone at the ground surface.

b) Geophone depth 3.65 m.

c) Geophone depth 5.0 m.

Figure 11. *Attenuation of horizontal vibration velocities during resonance compaction.*

DOI: 10.4417/IJGCH-08-01-02

The vibration attenuation in the horizontal direction at the ground surface is slow, suggesting that resonance amplifies horizontal vibrations at the ground surface. From Figure 11a, it is possible to estimate the horizontal vibration velocity at 6 m distance, where horizontal ground vibrations were measured by the triaxial geophone. The measured vibration velocity at resonance, according to Figure 9 (15 to 20 mm/s), is in excellent agreement with the predictions shown in Figure 11a.

However, good agreement is obtained below the ground surface if the attenuation is calculated according to Eq. (1) and (2), assuming $f = 15$ Hz, $C_P = 1450$ m/s, and $n = 1$. The average horizontal vibration velocity at 3 m from the center of the probe varies in a relatively narrow range, between 5 and 10 mm/s. It is now possible to estimate the horizontal vibration velocity at the perimeter of the compaction probe (1 m), which is approximately 30 mm/s. At 2 m, the horizontal vibration velocity is approximately 15 mm/s.

HORIZONTAL STRESS INCREASE

An important objective of this study was to measure the horizontal stress changes resulting from the horizontal ground vibrations at resonance. Vibrations in the horizontal directions were measured at four levels and two distances from the compaction probe, as shown in Figure 10. The horizontal vibration velocities during the entire compaction process (penetration, compaction, and extraction) at and below the ground surface are summarized in Figure 12. Vibrations were measured at 3.1 m distance (blue), and 8.9 m distance (brown), where the average measured values during resonance have been estimated by dotted lines.

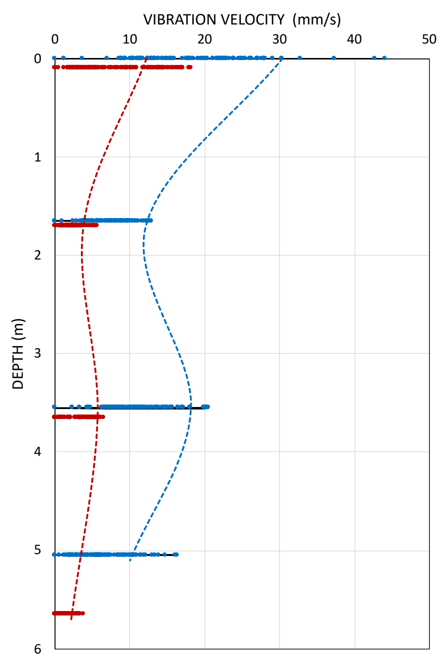


Figure 12. *Variation of horizontal ground vibration velocity (RMS) at 3.1 (blue) and 8.9 m (brown) as a function of depth during probe penetration to 10 m depth.*

The horizontal ground vibrations were strongest at the ground surface at both distances and decreased to almost constant values at depth. These horizontal vibrations at depth are caused by the friction between the vertically oscillating compaction

DOI: 10.4417/IJGCH-08-01-02

probe and the surrounding soil. The increase in horizontal stress increase, $\Delta\sigma_h$, caused by ground vibrations can be estimated from the following relationship (Massarsch, 2002):

$$\Delta\sigma_h = v_h \, C_P \, \rho \tag{3}$$

where v_h = the vibration velocity in the direction of wave propagation, C_P = compression wave speed, and ρ = bulk density of the soil. According to Eq. (3), assuming a bulk density of 1800 kg/m^3 and v_h = 15 mm/s, the horizontal stress pulse caused by horizontal ground vibrations is approximately 40 kPa. It can be assumed that between 3.5 and 5 m depth, the horizontal effective stress varies between 20 and 26 kPa (assuming K_0 = 0.4). Thus, the horizontal stress increase (40 kPa) is about twice the static horizontal stress prior to compaction. It can be concluded that horizontal stress will increase permanently due to horizontal vibrations.

Also, the number of vibration cycles affects soil compaction. During DVVCr, assuming a vibration frequency of 15 Hz and a vibration duration in each layer is approximately 5 minutes, about 4,500 vibration cycles are generated. Thus, the accumulated effect of horizontal ground vibrations on horizontal stress increase will be enhanced.

As shown by the CPTU measurements in Figure 6, the sleeve resistance increased after vibratory compaction by a factor of 2. This increase can be explained by the horizontal stress pulses caused by vibratory treatment. The pre-stressing effect during different types of vibratory treatment has been reported by Massarsch and Fellenius (2020). Gasser et al. (2022) reported similar observations in connection with deep horizontal vibratory compaction (DHVC). The horizontal pre-stressing effect can have important consequences for settlement and liquefaction analyses (Massarsch et al., 2020). As is the case on most vibratory compaction projects, neglecting this effect results in an unnecessarily conservative design and excessive costs.

The permanent increase in horizontal stresses varies in the lateral direction, which, with time, will equalize stress levels. This effect can at least partly explain the so-called "time effect" described in the literature. According to this hypothesis, stresses will decrease with time in the vicinity of the compaction point but increase with increasing distance.

CONCLUSIONS

The equipment and process used for deep vertical resonance compaction (DVVCr) are described by a case history. An objective of the field tests was to document resonance compaction. A monitoring and process control system (MPCS) was used to measure the dynamic performance of the vibratory compaction system and vibration propagation on the ground surface. Vibrations were also measured by horizontal geophones at different depths and distances from the compaction probe.

The effect of vibratory compaction in granular soils depends on shear strain, which is directly related to ground vibration. It has two effects: a) densification (compression of voids), and b) pre-stressing (increase in horizontal stresses). The measurements during resonance compaction lead to the following conclusions:

1. Ground vibrations are amplified when the vibrator-probe-soil system is excited at its resonance frequency (system resonance). At system resonance, the compaction probe oscillates in phase with the surrounding soil, enhancing the transmission of vibration energy to the ground.

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2. As a result of DVVCr, both the cone and sleeve resistance increase by at least 100%.

3. The hydraulic pressure decreases significantly at resonance, resulting in significant energy savings.

4. DVVCr emits vertically polarized shear waves primarily at the shaft of the compaction probe. These are not amplified at the ground surface.

5. As a result of friction, horizontal ground vibrations are also emitted from the vertically oscillating compaction probe. The horizontal ground vibrations are amplified at the ground surface but are almost constant at depth.

6. Recorded at two distances from the compaction probe, horizontal vibrations propagate as compression waves. Empirical predictions of vibration attenuation agree well with measurements.

7. Vibratory compaction at resonance causes pulsating horizontal vibrations, which at 3 m distance generate vibration amplitudes of at least 15 mm/s (RMS). The estimated magnitude of horizontal stresses (40 kPa) is about twice that of the horizontal effective stress (about 25 kPa).

8. Close to the compaction point, the increase in horizontal stresses is highest and decreases with distance. This stress gradient will equalize with time or due to construction activities. This effect could explain the "time effect" measured by penetration tests.

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NOTATIONS

C	=	Wave propagation speed
C_P	=	Compression wave speed
C_S	=	Shear wave speed
CPT	=	Cone penetration test
D	=	Damping coefficient
DHVC	=	Deep horizontal vibratory compaction
DMT	=	Flat dilatometer test
DVVC	=	Deep vertical vibratory compaction
e	=	Base of natural logarithm
f	=	Frequency
fs	=	Sleeve resistance
G_0	=	Shear modulus at small strain
I_C	=	Soil behavior type index
MPCS	=	Measurement and process control system
n	=	Wave attenuation exponent
N	=	Number of vibration cycles
q_c	=	Cone penetration resistance
R_f	=	Friction ratio
RPM	=	Revolutions per minute
s	=	Displacement amplitude
S	=	Peak to peak displacement amplitude (2 s)
SPT	=	Standard Penetration Test
u	=	Pore water pressure
v	=	Particle velocity
v_h	=	Horizontal vibration velocity in direction of wave propagation
v_S	=	Vibration velocity perpendicular to direction of wave propagation
a	=	absorption coefficient
g	=	Shear strain
r	=	Bulk density
σ_η	=	Horizontal stress
s	=	Shear stresses