

*Settlement in the compacted zone.
Average: 0.30 to 0.45 m.*



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LIQUEFACTION ASSESSMENT BY FULL-SCALE VIBRATORY TESTING

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ABSTRACT. Vibratory compaction of granular soils using the resonance compaction method is described. A compaction probe is oscillated in vertical direction and the operating frequency of the probe is varied to achieve amplifications of ground vibrations. A case history is described where the resonance compaction method was applied. The effect of a clayey silt layer on compaction is described. During vibratory compaction, the soil adjacent to the compaction probe liquefied, which was observed by water propagating to the ground surface. Vibration measurements demonstrated the loss in shear strength due to liquefaction. Cone penetration tests were performed prior to and several weeks after compaction and showed a significant increase in cone stress as well as in sleeve resistance. Resonance compaction has the potential of serving as a full-scale test for assessing liquefaction susceptibility of soil deposits, a method which can be useful especially in layered soils.

RESUME. Le compactage vibratoire des sols granulaires est décrit en utilisant la méthode de compactage par résonance. Une sonde de compactage est oscillée dans la direction verticale et la fréquence de fonctionnement de la sonde est varié pour obtenir l'amplification des vibrations du sol. Un historique de cas est décrit où la méthode de compactage par résonance a été appliquée. L'effet d'une couche de limon argileux sur le compactage est discuté. Pendant le compactage vibratoire, le sol à côté de la sonde de compactage est liquéfié, qui a été observé par l'eau se propageant à la surface du sol. Les mesures de vibrations ont démontré la perte de résistance au cisaillement due à la liquéfaction. Les tests de pénétration du cône ont été effectués avant et plusieurs semaines après la compaction et ont montré une augmentation significative de la résistance du cône ainsi que de la résistance du manchon. Le compactage par résonance a le potentiel de servir de test à grande échelle pour évaluer la susceptibilité à la liquéfaction des dépôts de sols, une méthode qui peut être utile surtout dans les sols stratifiés.

1 INTRODUCTION

Liquefaction can occur in loose, water-saturated granular soils due to cyclic loading. The most well-known source of liquefaction can be earthquake excitation. It is widely assumed that soil density condition (very loose, loose) is the most important factor governing liquefaction. However, liquefaction can also occur due to slow, cyclic loading or even at static loading conditions. An important aspect of liquefaction, which is not generally recognized, is the impact of soil layers with low permeability on the liquefaction potential. Low permeability can have an important influence on liquefaction but the influence is difficult to assess theoretically.

The most widely used methods of assessing liquefaction potential are based on penetration testing, such as the Standard Penetration Test (SPT) (Idriss and Boulanger 2006) or the cone penetration test (CPT), (Roberson and Wride 1998). The CPT is generally more reliable than the SPT, as it provides a continuous profile of penetration resistance. Corrections are applied to the records of both the SPT and CPT to address the effect of grain characteristics, such as fines content and plasticity. In practice, it is difficult to include the effect of layers on the development of pore water pressure increase during cyclic loading. Therefore, it is usually assumed that soil layers are homogeneous. In this paper, however, a new concept is presented based upon which it is possible to investigate the liquefaction potential by large-scale vibratory testing.

2 VIBRATORY COMPACTION

Vibratory compaction is used in practice to improve the strength and stiffness of granular soils, and to mitigate their liquefaction potential. In the investigation reported in this paper, top-driven, purpose-built vibratory compaction probes are used, combined with a vibrator with variable frequency is attached to the compaction probe inserted in the ground (Massarsch, 1991). An early development of deep vibratory compaction, called TriStar compaction (also known as Y-probe), was described by Wallays (1982). The probe consists of three steel blades, typically 0.5 m wide and 20 mm thick, which are welded together at 120 degree angles. Each blade is fitted with horizontal steel ribs at 1 to 2 m vertical spacing, to increase the interaction between the vibrating probe and the soil. The three blades increase the surface area of the vibrating probe. The process is a simple, fast, and effective for compacting loose, water-saturated granular soils.

The TriStar-probe was used for the first time in Borechem near Antwerp, Belgium (Wallays, 1982). The hydraulic fill consisted of fine to medium grained sand with the d_{10} -particle size ranging from 0.03 to 0.15 mm. The average grain size, d_{50} , was approximately 0.2 mm. The grain size distribution was within the lower range of grain size distribution recommended by Mitchell (1981). Compaction was carried out by a hydraulic vibrator (PTC 40 A2). The vibrator had an eccentric moment of 40 kgm and an operating frequency of 26 Hz. The maximum centrifugal force was about 1,000 kN. The thickness of the sand fill to be compacted was approximately 10 m. The groundwater surface was located approximately 2 m

below the ground surface. Below a surface layer ($q_c \approx 4 - 6$ MPa), the cone stress prior to compaction ranged between $q_c \approx 2$ and 4 MPa. Compaction was carried out during a trial phase at different points spaced in a triangular grid. The point spacing was varied from 2.5 m to 4.5 m. At a point spacing of 3.5 m, the cone stress after compaction was higher than 8 MPa. Wallays (1982) presented details of the compaction effect. It is interesting to note that during the initial phase of vibratory compaction, the hydraulic fill liquefied, as is evidenced by the sand volcano shown in Figure 1.



Figure 1. Liquefaction caused by TriStar soil compaction at Borechem (Wallays 1982).

When soil compaction is performed at the resonance frequency of the vibrator-probe-soil system (Massarsch and Fellenius, 2006), a more efficient compaction results due to the vibration amplification effect developing at the resonance frequency can be achieved. The process involves operating the vibrator at high frequency during the penetration phase, at resonance frequency during the compaction phase, and, again, at high frequency during the extraction phase after compaction.

The energy transmission process of compaction involves vibration emission from the vertically oscillating probe. As described by Massarsch (2002), adjacent to the vertically oscillating compaction probe, three zones can be identified: (1) plastic zone at the interface between the probe and the soil: the soil is subjected to large shear strain levels $>1 \times 10^{-3}$ %; (2) elasto-plastic zone: the strain level ranges between approximately 1×10^{-3} and 1×10^{-1} % shear strain, and (3) elastic zone: shear strain level is below 1×10^{-3} %, and strain will be small.

An important aspect of the energy transmission concept is that the vertically oscillating probe also generates strong horizontal vibrations. Permanent increase in horizontal effective stress after vibratory treatment has been observed on a large number of compaction projects (Massarsch and Fellenius, 2014).

3 VIBRATORY COMPACTION AT ANNACIS CHANNEL, BC

3.1 Site Conditions

An interesting vibratory compaction project was carried out for an industrial development in the Fraser River delta adjacent to the Annacis Channel, Vancouver, BC. Because of the liquefaction susceptibility at the site, the designer decided to densify loose, granular soil layers along a 230 m long, 3.0 to 4.5 m wide area. Compaction was required to a depth of 10 to 11 m. Details of the project have been described by Neely and Leroy (1991). The results of cone penetration tests with pore water pressure measurement (CPTU) are shown in Figure 2.

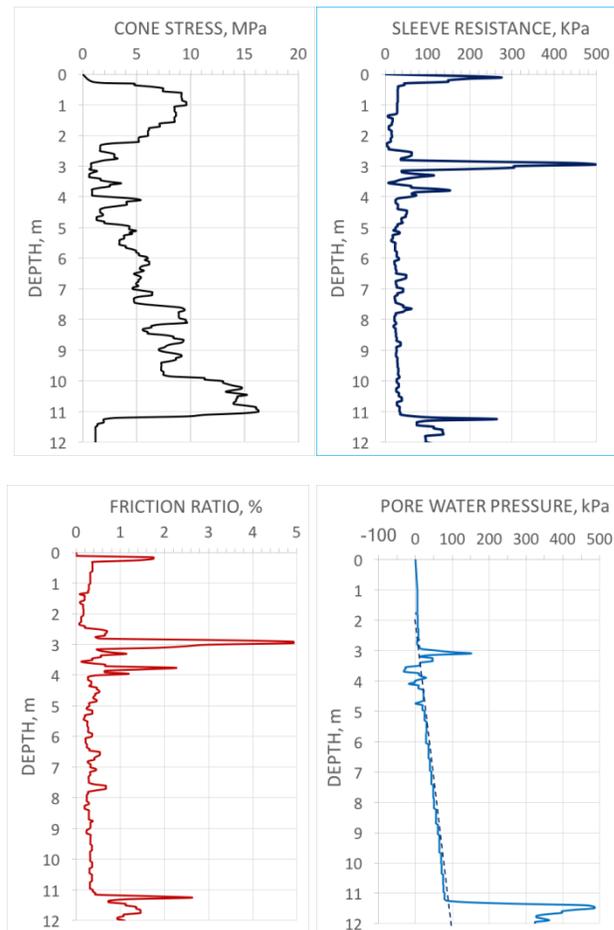


Figure 2. Results of cone penetration test with pore water pressure measurement prior to compaction.

The soil deposit consisted of an about 2.5 m thick, compact sand fill ($q_c \approx 5 - 10$ MPa), overlying an approximately 2 m of soft clayey silt. Below, loose alluvial sand was encountered down to about 11 m depth, followed by stiff clay. The cone stress varied in the alluvial sand between 2 and 5 MPa, with occasional higher values and SPT N -indices in the alluvial sand ranged between 5 to 24 blows/0.3 m, with an average of $N = 12$. Below the

alluvial sand followed stiff clay with a cone stress $q_c \approx 1$ MPa. The sleeve resistance, friction ratio and pore water pressure show the existence of an impermeable layer above the alluvial sand.

The compaction requirements were to increase N -indices to 14 at 4.5 m depth increasing to 17 at 9 m depth. The groundwater level varied but was on average located 2 m below the ground surface. The d_{50} -mean grain size was about 0.3 mm and the fines content was around 10%. The densification requirements were converted to equivalent cone stress values, using a cone to SPT ratio of $q_c/N = 0.5$, thus, requiring compaction between 7 MPa at 4.5 m depth and 8.5 MPa at 9 m depth.

3.2 Resonance Compaction

The resonance compaction method was used to improve the alluvial fill. The three-bladed TriStar probe with a length of 12 m was attached to a vibrator with variable frequency (ICE 812). The compaction system was operated from a 60 ton crane. The total mass of the vibrator was 6,670 kg and the eccentric moment 46 kgm. At the maximum operating frequency of 26 Hz, the vibrator generated a 1,100-kN centrifugal force. The dynamic mass of the vibrator was 4,500 kg (including clamping but without TriStar probe device). The vibrator generated a 20-mm vertical vibration amplitude (peak to peak). This corresponds to a 1,634 mm/s (single amplitude) vibration velocity and a 27-g corresponding acceleration. Figure 3 shows a photo of the compaction equipment, consisting of the vibrator with variable frequency and TriStar probe, used for resonance compaction



Figure 3. Resonance compaction at Annacis Channel, Vancouver by TriStar probe with variable frequency vibrator.

Before the start of the production work, field trials were carried out to determine the optimal spacing of compaction points and the resonance frequency. The results of the investigations have been described in detail by Massarsch and Vanneste (1988).

The resonance compaction process consisted of several phases: probe penetration at high frequency (about 25 Hz), which took approximately 2 minutes, followed by the compaction phase at low frequency, which lasted typically for 5 minutes. Thereafter, the probe was withdrawn in 4 steps, where extraction was carried out at high frequency followed by and re-penetration at low frequency. Figure 4 shows the resonance compaction procedure chosen for the production phase. The average compaction depth was 10 m and the total time of compaction in each point was 12 minutes.

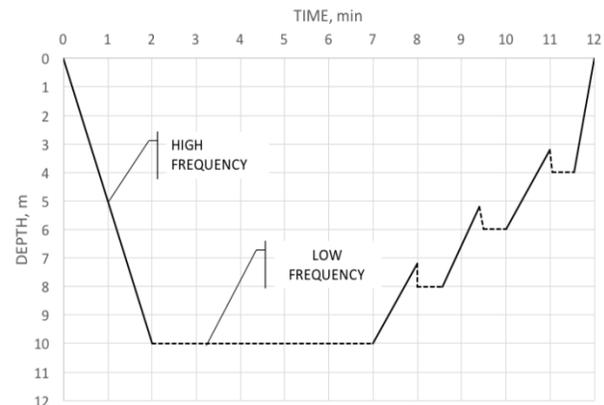


Figure 4. Typical process of variable frequency, resonance compaction (here, down to 10 m depth).

During penetration, the vibrator frequency was about 25 Hz. During the following compaction phase, the vibrator frequency was lowered to 13 Hz. In order to avoid loosening of the compacted soil, the vibrator frequency was increased during the pull-out phase to 25 Hz. For the following re-penetration, the frequency was again 13 Hz.



Figure 5. Liquefaction of a zone around the TriStar probe during resonance compaction. The geophone (in circle) installed 1 m away from the compaction probe.

The liquefaction potential depends on three important factors: the initial density of the water-saturated sand; the amplitude and number of vibration cycles, and the drainage conditions. In the present case, the low permeability clayey silt soil layer at about 3 m depth

delayed the gradual dissipation of excess pore water pressure and precipitated liquefaction as shown in Figure 5. As a result of compaction, the ground surface settled between compaction points on average between 0.30 m and 0.45 m, cf. Figure 6.



Figure 6. Settlement in the compacted zone, averaging 0.3 to 0.45 m. A zone of soil liquefaction is apparent in the right of the picture.

4 VIBRATION MEASUREMENTS

An important aspect of the compaction trials was to measure the vibration response of the ground by three-directional and vertical geophones. However, at the time of the project (1988), vibration measurements were still a complex task and could only be performed to a limited extent. The AC-voltage generated by vibrations was transformed into the root mean square (RMS) vibration velocity. The signal was displayed on site and continuously recorded by a strip recorder and/or digital volt meter, cf. Figure 7. Yet, even these simple measurements provided valuable insight into the response of the soil during resonance compaction.



Figure 7. Vibration measurements by digital volt meter and signal display on site

Based on past experience, it was expected that the vertically oscillating compaction probe would give rise to both vertical and horizontal ground vibrations. Vibrations were therefore measured in all three axis directions and the results of the measurements are presented in the following paragraphs.

4.1 Vertical Ground Vibrations

During trial compaction, a geophone for vertical direction measurements was placed at 1 m distance from the compaction point, cf. Figure 7. The vertical vibration velocity was recorded during the entire compaction phase and the result is shown in Figure 8.

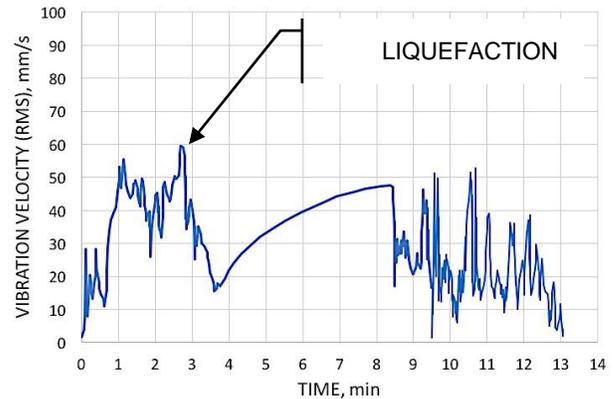


Figure 8. Vertical vibration velocity (RMS value) measured 1 m away from the compaction point. The onset of liquefaction results in drop of vibration velocity.

After an initial phase of probe penetration (first minute) at high frequency (25 Hz), the operating frequency was gradually lowered to 13 Hz. Vertical ground vibrations at 1 m distance from the probe were at first more than 50 mm/s. However, after a few minutes, ground vibrations dropped dramatically to about 20 mm/s, indicating development of liquefaction. During the following about 4-minute, steady-state compaction phase, ground vibrations increased gradually, indicating reconsolidation of the soil adjacent to the compaction probe. Next, during the following extraction phase (step-surfing), ground vibrations increased during re-penetration (low frequency) and decreased during extraction (at high frequency), cf. Figure 4. Ground vibration measurements provide important information regarding ground response during resonance compaction.

The variation of vertical ground vibrations as a function of distance from the center of the compaction probe for three tests is shown in Figure 9. It should be noted that the vertical vibration velocity varies significantly during compaction as is evident from Figure 8. Measurements were made by moving the geophone to increasing distance from the compaction point. With modern vibration monitoring equipment, it is possible to measure vibration amplitudes simultaneously at several locations (distances from the compaction point).

Vibration amplitudes decreased with distance from the compaction point. At a distance of about 3 to 5 m, the vibration velocity became lower than 10 mm/s.

4.2 Horizontal Ground Vibrations

As mentioned above, the vertically oscillating probe generates cylindrical waves with a vertical vibration amplitude as well as lateral (longitudinal) compression

waves directed away from the probe. While the vertical vibration amplitude causes shear deformations, the horizontal vibration amplitude gives rise to horizontal compression waves. Measurements reported by Massarsch (2002) demonstrated that the horizontal vibration amplitude is approximately constant along the length of the compaction probe.

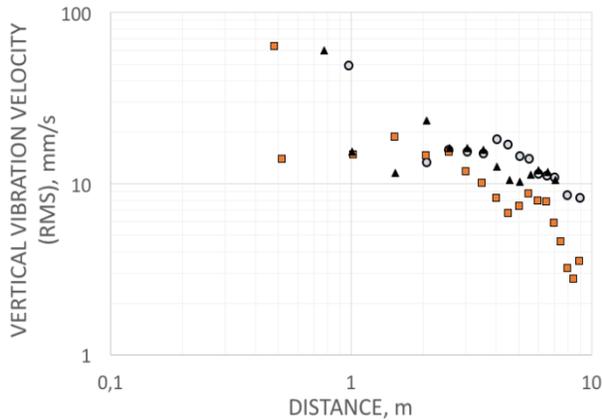


Figure 9. Variation of vertical vibration velocity during resonance compaction (at 13 Hz) as function of distance from compaction point for three tests.

Vibration measurements were carried out at increasing distance from the compaction probe in the vertical and longitudinal direction. The ratio between vibration velocities (RMS) is shown as a function of distance in Figure 10.

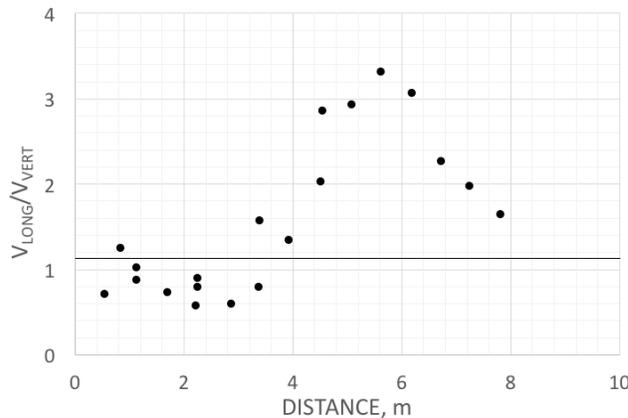


Figure 10. Ratio between horizontal vibration velocity (RMS) and vertical vibration velocity at increasing distance away from the probe.

4.3 Shear Strains due to Vertical Vibrations

The shear strain, γ , for plane wave fields can be estimated from the following relationship

$$\gamma = \frac{v_v}{c_s} \quad 1$$

where γ = shear strain
 v_v = vertical vibration amplitude
 c_s = shear wave speed

It can be assumed that a distance greater than about 2 m from the compaction probe, the shear strain amplitude can be estimated from Equation 1. If the shear wave speed of uncompacted sand is about 150 m/s, the shear strain (γ) at a vertical vibration velocity of 20 mm/s is approximately 0.01 %. If the vertical vibration amplitude is on average 50 mm/s (cf. Figure 8), the shear strain amplitude will be 0.033 %.

Moriwaki et al. (1982) and others have investigated the effect of the number of vibration cycles (N) required to cause liquefaction in a silty sand, defined as the ratio between induced pore pressure to effective stress, σ'_k , in the soil. They performed cyclic shear and cyclic triaxial tests with increasing number of vibration cycles. The results of their cyclic triaxial tests are shown in Figure 11. It should be noted that if a 5-minute effective period of vibratory compaction is assumed, the soil will be subjected to significantly more than 5,000 vibration cycles.

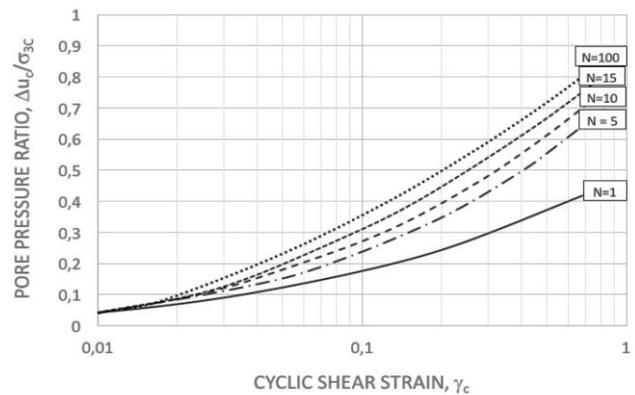


Figure 11. Results of cyclic triaxial tests on silty sand: development of pore water pressure as function of shear strain and number of vibration cycles (Moriwaki et al. 1982).

According to Figure 11, excess pore water pressure will be generated due to vibratory compaction of the soil adjacent to the compaction probe. However, the risk of liquefaction was enhanced by the existence of the low permeability silty clay layer at about 3 m depth, which impeded drainage and increased the excess pore water pressure in the underlying sand layer. This aspect is difficult to take into consideration by conventional liquefaction assessment procedures, where it is normally assumed that soil layers are homogeneous.

5 COMPACTION EFFECT

The compaction effect achieved by resonance compaction at the Annacis Channel was verified by SPT and CPT investigations, before start of the project, and 67 and 82 days after completion of compaction. The increase in cone stress and sleeve resistance is shown in Figure 12.

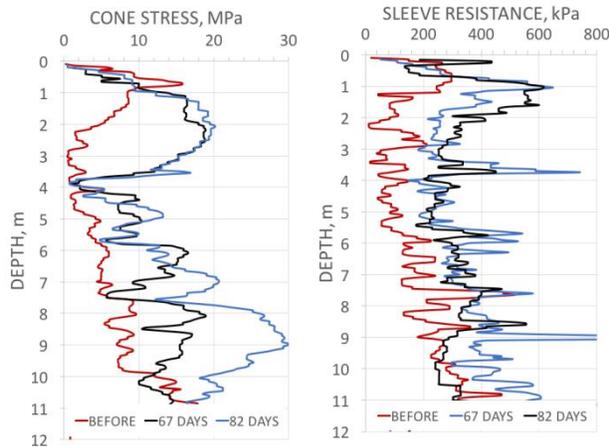


Figure 12. Cone stress and sleeve resistance before, 67 and 82 days after compaction, measured between compaction points

The cone stress and the sleeve friction increased throughout the soil deposit, with the exception of the clayey silt layer between 3 and 4 m, cf. Figure 2. It is interesting to note that the increase in cone stress and sleeve resistance continued even up to 82 days after compaction. The time effect, probably due to reconsolidation after dissipation of excess pore water pressure, is most pronounced in the soil layer between 6 and 10 m.

On most compaction projects reported in the geotechnical literature, only the increase in cone stress is reported. However, the sleeve friction is of equally high interest as it reflects the change in lateral effective stress caused by vibratory compaction, cf. Massarsch and Fellenius (2002). This effect is not surprising, considering the high vibration velocities recorded in the longitudinal direction from the compaction probe. The increase in cone stress and sleeve resistance is shown in Figure 13.

For comparison of the tests, the geometric average of cone stress and sleeve resistance was used. The average increase in cone stress is significant, by a factor of 2 to 4 and higher. What is generally not appreciated is that also the sleeve resistance increased by approximately the same degree, at least to a depth of 8 m.

6 CONCLUSIONS

The resonance compaction method has been applied to improve a deposit consisting of a layer of granular surface fill, overlying a 3 m thick layer of clayey silt on top of natural sand. The groundwater level was located about 2 m below the ground surface. Resonance compaction was carried out using a 12 m long TriStar probe. The compaction frequency was about 13 Hz. During resonance compaction, a soil cylinder adjacent to the compaction probe liquefied, which was evidenced by ground water propagating to the ground surface. Vibration measurements confirmed the liquefaction process and gradual reconsolidation.

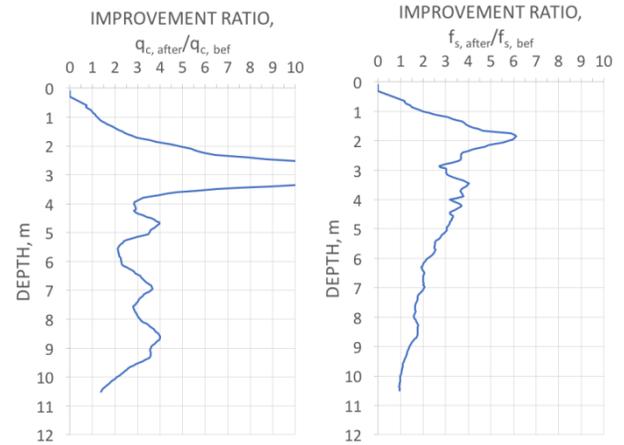


Figure 13. Increase in cone stress and sleeve friction 82 days after compaction compared to values prior to compaction

The compaction effect was investigated by SPT and CPTU measurements prior to, 67 and 82 days after compaction. The cone stress increased by a factor of 2 to 5. However, more interesting, also the sleeve resistance, which reflects changes in horizontal effective stress, increased by the same degree.

The effect of layers with low permeability on liquefaction is difficult to assess by conventional design procedures, which generally assume homogeneous soil layers. However, low permeability soil layers can govern the development of excess pore water in loose and medium dense sand layers, sandwiched between layer of low permeability.

The resonance compaction system has the potential of being used as a full-scale testing method to investigate the liquefaction hazard of layered soils, where liquefaction is controlled to a high degree by the drainage conditions of loose sand layers, sandwiched between layers of lower permeability. This can be accomplished by performing a resonance tests in the uncompacted soil and to compare the vibration response of the soil to that after vibratory treatment. Such an approach would add valuable information to the empirical liquefaction analyses based solely on SPT and CPT data.

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