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Horizontal stress increase induced by deep vibratory compaction

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Compaction by vertically or horizontal oscillating probes increases not only the soil stiffness but also the horizontal effective stress. An important, but often neglected, consequence is that compaction also causes preloading of the soil. The change in horizontal stress following vibratory compaction can be measured independently by two in situ methods – a cone penetration test (CPT) and a flat dilatometer test (DMT). Values of sleeve resistance (CPT) and horizontal stress index (DMT) can be determined prior and after compaction. In this work, five case histories reported in the literature where different vibratory compaction methods were used (dynamic compaction, vibroflotation, VibroWing, TriStar and resonance compaction) were re-analysed. For each test site, the change in CPT cone resistance and sleeve resistance was determined and compared with the increase in horizontal stress index from DMTs. The preloading effect due to vibratory compaction was estimated using empirical correlations.

Notation

$E_{\rm D}$	dilatometer modulus
e_1, e_2, e_3	void ratio at stress points 1, 2, 3
$f_{\rm s}$	sleeve resistance
$f_{\rm s0}$, $f_{\rm s,bef}$	sleeve resistance before compaction
$f_{\rm s1}$, $f_{\rm s,aft}$	sleeve resistance after compaction
$I_{\rm c}$	soil behaviour index
$I_{\rm D}$	material index (flat dilatometer test (DMT))
K_0	earth stress coefficient before compaction
K_1	earth stress coefficient after compaction
$K_{\rm A}$	horizontal earth stress coefficient at active loading
$K_{\rm D}$	horizontal stress index (DMT)
$K_{\rm D0}$, $K_{\rm D,bef}$	horizontal stress index before compaction
$K_{\rm D1}$, $K_{\rm D,aft}$	horizontal stress index after compaction
$K_{\rm P}$	horizontal earth stress coefficient at passive loading
M_0	constrained modulus (normally consolidated)
M_1	constrained modulus (overconsolidated)
p_0	dilatometer pressure reading before inflation
p_1	dilatometer pressure reading after inflation
$q_{\rm c}$	cone resistance
$q_{\rm t}$	cone resistance adjusted for excess pore water pressure
$R_{\rm f}$	friction ratio ($f_{\rm s}/q_{\rm c} \times 100$)
$R_{\rm h}$	empirical factor of cone resistance increase
u	pore water pressure
u_0	hydrostatic pore water pressure
β	empirical exponent
$\Delta\sigma'_{\rm h}$	horizontal effective stress change
$\Delta\sigma'_{\rm p}$	preloading margin ($\sigma'_{\rm p} - \sigma'_{\rm v0}$)
$\Delta\sigma'_{\rm v}$	vertical effective stress change
$\sigma'_{\rm h}$	horizontal effective stress
$\sigma'_{\rm m}$	mean effective stress
$\sigma'_{\rm p}$	preloading stress; pre-insertion overburden stress (DMT)
$\sigma'_{\rm v}$	vertical effective stress
$\sigma'_{\rm v0}$	vertical effective stress before compaction
$\sigma'_{\rm v}$	horizontal effective stress before compaction
ϕ'_0	friction angle before compaction
ϕ'_1	friction angle after compaction
ϕ'	effective friction angle

1. Introduction

Vibratory compaction is widely used in loose granular soils to reduce settlement or to mitigate the risk of liquefaction. During the compaction process, cyclic stresses are generated in the ground, resulting in a denser particle arrangement and changes in effective stresses. A variety of different compaction methods have been developed, each having advantages and limitations. During the recent past, powerful and sophisticated vibratory compaction methods have been developed and described in the geotechnical literature. While compaction equipment and processes have evolved significantly, design concepts are still overly simplistic. This fact is unfortunate as the full technical and economic potential of modern soil compaction methods is not realised, thus resulting frequently in over-conservative compaction requirements.

Sophisticated analytical methods have become available to analyse settlement problems. Their limitation is the selection of realistic input parameters, such as that of the deformation properties of soils and stress conditions in the ground prior to and after compaction. In the case of compaction of granular soils, undisturbed samples can usually not be obtained and the designer must rely on field investigations. A variety of in situ tests can measure parameters that reflect soil strength and stiffness. The most widely used methods in connection with deep vibratory compaction are the cone penetration test (CPT), CPT with pore water pressure measurement (CPTU), the seismic cone penetration test, the Marchetti flat dilatometer test (DMT) or the seismic dilatometer test (Mayne *et al.*, 2009). The CPT and the DMT provide the means for detecting changes in horizontal stress. Both methods were used in parallel at the five sites described in this paper, which allows for an interesting comparison. Although the Menard pressuremeter offers similar capabilities, there is a lack of case histories reporting results from where also either CPTs or DMTs were used.

The thesis of this paper is that vibratory compaction increases horizontal stresses, resulting in a preloading effect, which is of practical significance for settlement and liquefaction problems. Although the increase in horizontal stress due to surface or deep vibratory compaction has been known for some time, its practical significance has not yet been fully appreciated and accepted by the foundation industry, thereby not taking advantage of the potential technical and economic benefits offered by vibratory compaction. Empirical correlations can be used to estimate the preloading effect based on measured horizontal stress changes.

In this work, five case histories of different vibratory compaction methods (vibroflotation, dynamic compaction, VibroWing compaction, TriStar compaction and Resonance compaction) reported in the literature were reviewed. On all these case histories, both CPT and DMT investigations were performed before and after compaction. The accompanying effect of horizontal stress change on preloading is discussed. Methods for the measurement of horizontal stresses are described. Finally, the increases in horizontal stress measured by CPTs and DMTs are compared.

2. Horizontal stress changes due to compaction

The stress history of geological formations is of great significance for all types of geotechnical problems. While it is possible to estimate the stress conditions of soil deposits from undisturbed soil samples in the laboratory, this is more difficult in the case of granular soils. Early studies of the change in stress conditions due to soil compaction were performed in connection with the use of surface vibratory rollers. Broms (1971) stated that when granular soils are compacted adjacent to a rigid wall (e.g. a basement wall), high permanent horizontal stresses are induced against the wall. Duncan and Seed (1986) and Symons and Clayton (1992) developed semi-empirical concepts for the prediction of horizontal stresses due to vibratory compaction. Duncan and Seed (1986) discussed in detail the effect of surface compaction of granular soils. In an important paper on this subject, Schmertmann (1985) listed over 60 references to demonstrate the significance of horizontal stress for geotechnical design. He pointed out that horizontal stress represents key site conditions that engineers should consider in investigations and analyses and that failure to measure and use in situ horizontal stress in design can result in uneconomical and excessively conservative foundation solutions.

The change in horizontal stresses caused by deep vibratory compaction has been addressed in the literature by, for example, Brown (1989), Massarsch (1994), Van Impe *et al.* (1994), Howie *et al.* (2000), Massarsch and Fellenius (2002), Asalemi (2006) and Massarsch and Fellenius (2017a). Case histories reporting vibratory compaction are usually based on the results of one in situ test method (standard penetration test (SPT), CPT or DMT). In the case histories presented in this paper, soil conditions were determined by both CPT and DMT measurements before and after compaction. Thus, a comparison can be made from the same sites, allowing more reliable conclusions regarding the change in horizontal stress.

In Figures 1–3, the change in effective stress in free-draining soils is illustrated for different ground improvement methods. The stress path in σ'_v–σ'_h space (vertical effective stress–horizontal effective stress space) is discussed for three different ground improvement methods (static preloading, vertical vibrocompaction and horizontal vibrocompaction).

2.1 Static preloading

Figure 1 describes the stress path for static preloading. The stress state is shown before compaction (K_0) and after preloading, (K_1), as well as for active (K_A) and passive (K_P) stress conditions. The stress conditions prior to compaction (assuming normally consolidated soil) are represented by stress level A. After application of a vertical stress (preload) $\Delta\sigma'_v$, stresses increase to B, resulting in an increase in horizontal stress along the K_0 line (earth stress for at rest conditions). After removal of the vertical effective stress from B to C, horizontal stresses also decrease, but by less than the vertical stress. Thus, preloading causes an increase in horizontal stress ($\Delta\sigma'_h$). As a result of preloading, the soil has become 'overconsolidated', although in free-draining granular soils, a consolidation process does not occur. Nevertheless, the term overconsolidation ratio (OCR) is used in this paper to express the ratio of vertical effective stress between stress levels B and A.

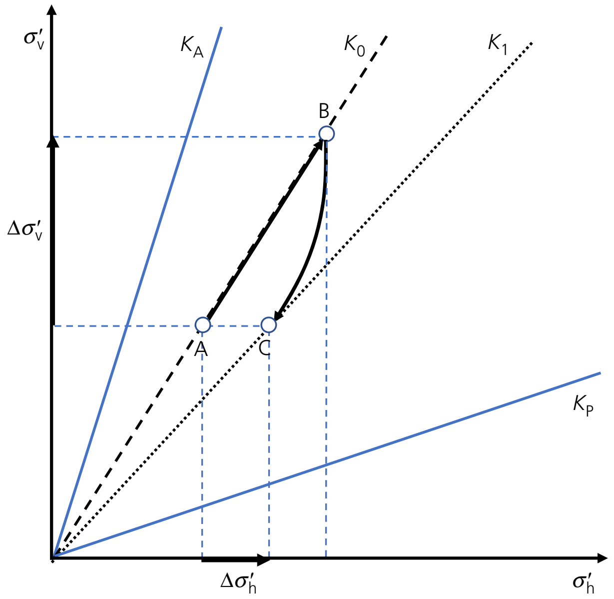

Figure 1. Stress path for static preloading at drained conditions, illustrating the increase in horizontal stress due to preloading: stress prior to loading (A), at peak load (B) and after unloading (C), resulting in a horizontal stress increase

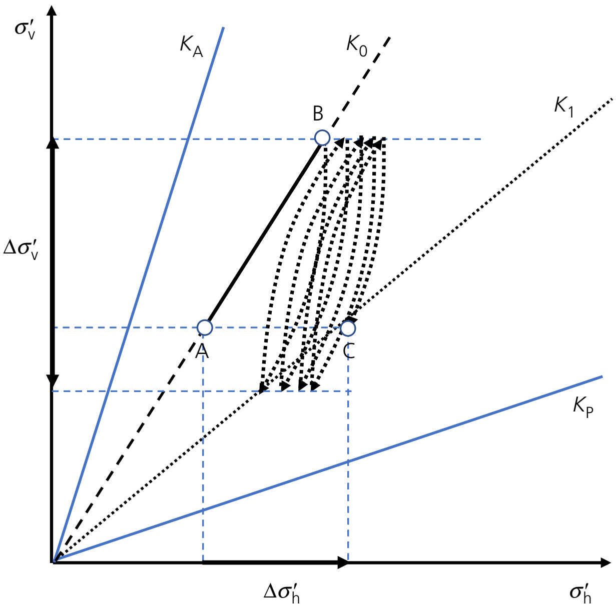

Figure 2. Stress path for vibratory compaction by vertically oscillating probe: stress prior to loading (A), at peak of first loading (B) and after repeated loading cycles (C), resulting in horizontal stress increase from A to C and preloading

2.2 Vertical vibratory compaction

During compaction, vertical and horizontal vibrations are transmitted from a vertically oscillating probe to the surrounding soil. CPTs performed by Massarsch and Fellenius (2002)

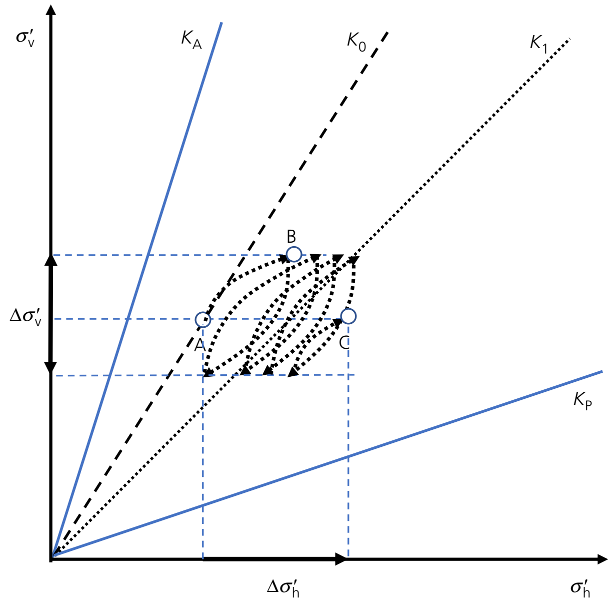

Figure 3. Stress path for vibratory compaction by horizontally oscillating probe: stress prior to loading (A), at peak of first loading (B) and after repeated loading cycles (C), resulting in horizontal stress increase from A to C and preloading

before and after compaction showed a distinct increase in sleeve resistance as a result of compaction. The stress path for vibratory compaction using a vertically oscillating probe is illustrated by Figure 2. Due to the vertically vibrating probe, the soil surrounding the probe is subjected to a large number of unloading and reloading cycles, varying between B and C. Vibration measurements in the horizontal direction reported by Massarsch (2002) showed that a vertically oscillating probe generates strong horizontal ground vibrations on and below the ground surface. At the end of compaction, horizontal stresses have increased from A to C. This increase in horizontal stress $\Delta\sigma'_h$ due to vertical cyclic loading $\Delta\sigma'_v$ is similar to the effect of static preloading (see Figure 1). Thus, vertical vibratory compaction results in a preloading effect similar to surcharging. However, due to the large number of reloading cycles, the horizontal stress increase is significantly higher than during equivalent static loading (one loading–unloading cycle).

2.3 Horizontal vibratory compaction

Compaction using a horizontally oscillating probe does result in a permanent increase in horizontal stress, as shown in Figure 3. A comprehensive research project on the interaction between a horizontally oscillating compaction probe (vibroflotation) and the surrounding soil was described by Nagy *et al.* (2018). Field tests and numerical simulations were performed to study the interaction between the probe and the surrounding soil. The test results and simulations showed that horizontal stresses increased as a result of horizontal vibrator movement. However, the vertical stress increase (A/B) is lower than in the case of a vertically oscillating probe (see Figure 2).

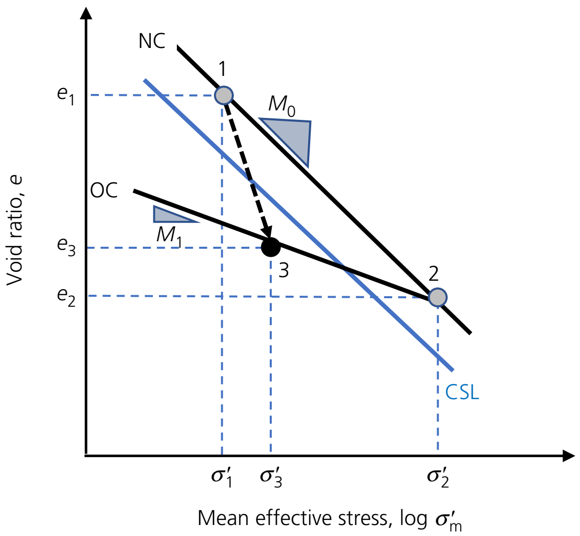

Figure 4. Conceptual description of changes of void ratio with mean effective stress, showing conditions prior to compaction (1), during maximum loading (2) and after compaction (3), according to the critical-state concept, adapted from Mayne *et al.* (2009). The figure shows the void ratio before compaction e_1 and after compaction e_3, as well as soil modulus before compaction (M_0) and after compaction (M_1)

2.4 Critical-state concept illustrating compaction

Critical-state soil mechanics is a widely accepted concept for describing the behaviour of soil in a void ratio–stress space. A detailed discussion of the critical-state concept is beyond the scope of this paper. Regarding the behaviour of sandy soils, reference is made to the geotechnical literature (Been *et al.*, 1992). The critical-state concept is useful to illustrate the compaction of sandy soil when transformed from a normally consolidated to an overconsolidated state. Figure 4 shows, conceptually, the soil response due to compaction in a void ratio–mean effective stress diagram. Prior to compaction, a normally consolidated (NC) loose sand is assumed. Point 1 has a void ratio e_1 and corresponding vertical effective stress σ'_1. In response to loading, the sand will compress (the void ratio will reduce) along the line labelled M_0. After compaction, the void ratio has reduced to e_3 and corresponding vertical effective stress σ'_3. Point 3 now lies below the critical-state line (CSL) and thus the sand has become preloaded (overconsolidated (OC)). In response to a static load, the sand will now compress along the line denoted M_1 and the deformation due to a static load will be much smaller than that before compaction.

3. Measurement of horizontal stress

The two methods to measure changes in horizontal stress used in this review of compaction projects are the CPT and the DMT. Both methods can detect changes in horizontal stress.

3.1 CPT

The CPT has become the most widely used in situ testing method in connection with the design and monitoring of vibratory compaction projects. The CPT measures the cone resistance q_c, the sleeve resistance f_s and – in the case of the CPTU – also the pore water pressure u. The generally applied correction of the cone resistance with respect to the pore water pressure q_t is not necessary in the case of soil compaction projects, where the cone resistance is significantly higher than the pore water pressure (thus $q_t \approx q_c$). Therefore, in this paper, the uncorrected cone resistance q_c will be used for convenience. The friction ratio R_f (the ratio of the sleeve resistance to the cone resistance) can be used to identify the soil type in the form of a soil behaviour type (SBT) chart, as suggested by Robertson (1990) and Lunne *et al.* (1997) for example. It is important to appreciate that changes in horizontal stress will result in changes in sleeve resistance and will thus also affect the friction ratio. This limitation of the soil behaviour index I_c, as suggested by Robertson (2009), was noted by Nguyen *et al.* (2014) and can result in a reduction of the measured I_c value and a corresponding decrease of apparent fines content. However, it is impossible for the vibratory compaction process to produce a decrease in fines content. Nguyen *et al.* (2014) performed extensive CPTs, SPTs and soil sampling during vibro-replacement (stone column) projects, and compared I_c values and fine contents of the soil before and after ground improvement. They proposed a correction method to compensate for the shift in I_c and to maintain the same fines content in pre- and the post-treatment CPT-based liquefaction analyses.

The primary objective of the work described in this paper was to determine changes in horizontal stress following different types of vibratory compaction. The change in horizontal stress can be estimated from (Mayne and Kulhawy, 1982)

$$1. \quad \frac{K_1}{K_0} = \frac{f_{s1}}{f_{s0}} \frac{\tan \phi'_0}{\tan \phi'_1}$$

where K_0 is the earth stress coefficient before compaction, K_1 is the earth stress coefficient after compaction, f_{s0} is the sleeve resistance before compaction, f_{s1} is the sleeve resistance after compaction, ϕ'_0 is the friction angle before compaction and ϕ'_1 is the friction angle after compaction.

The increase in friction angle can be estimated from the cone resistance, as suggested by Lunne *et al.* (1997). For practical purposes, however, it can be assumed that, due to compaction, the friction angle increases by approximately 5°. This effect can be considered by a correction factor (0·85), included in Equation 1

$$2. \quad \frac{K_1}{K_0} \cong 0{\cdot}85\, \frac{f_{s1}}{f_{s0}}$$

Using Equation 2, it is possible to estimate the change in horizontal stress by sleeve resistance measurements.

3.2 DMT

The DMT consists of a flat pressure cell that is pushed into the ground in 0·2 m intervals. At each level, the lateral earth stress is measured according to a standardised procedure. Thereafter, the membrane is expanded laterally by 1·2 mm and the soil resistance stress is recorded. From these two measurements, cell pressures p_0 (before inflation) and p_1 (after inflation) are determined, and the material index I_D, horizontal stress index K_D and the dilatometer modulus E_D can be calculated from (Marchetti *et al.*, 2001)

3. $$I_D = \frac{p_1 - p_0}{p_0 - u_0}$$

4. $$K_D = \frac{p_0 - u_0}{\sigma'_{v0}}$$

5. $$E_D = 34{\cdot}7(p_1 - p_0)$$

where u_0 is the hydrostatic pore water pressure and σ'_{v0} is the pre-insertion overburden stress. From the horizontal stress index, the change in horizontal stress due to compaction can be determined as

6. $$\frac{K_1}{K_0} \approx \frac{K_{D1}}{K_{D0}}$$

where K_0 is the earth stress coefficient before compaction, K_1 is the earth stress coefficient after compaction, K_{D0} is the horizontal stress index before compaction and K_{D1} is the horizontal stress index after compaction.

3.3 Accuracy of horizontal stress measurements

The measurement of horizontal stress in granular soils (silt, sand or gravel) is difficult. Empirical correlations have been developed where in situ tests (CPTs or DMTs) have been correlated to the horizontal effective stress based on calibration chamber tests (e.g. Baldi *et al.*, 1986, 1989; Lee *et al.*, 2011). Robertson (2016) showed that it should be possible to estimate the horizontal earth stress coefficient K_0 based on a CPT or, preferably, a combination of CPT and DMT. However, for settlement analyses, an important question is whether a soil deposit has become preloaded (overconsolidated) as a result soil compaction. It can be generally assumed that, prior to compaction, the soil is close to normally consolidated. This assumption is conservative because the increase in horizontal stress will be highest in loose soils and lower in compact soils.

Sleeve resistance measurements are subject to some uncertainty due to the change in effective stresses along the friction sleeve behind the penetrating cone. There is also a risk of arching of stresses around the penetrating sleeve. In very loose granular soils, very low values of sleeve resistance have been measured. This aspect needs to be considered when interpreting sleeve resistance measurements. However, with well-calibrated equipment, it is possible to obtain a continuous profile of sleeve resistance before and after compaction, from which the increase in horizontal stress can be estimated (Robertson, 2016).

The horizontal stress index from DMT investigations (K_D) has the advantage that measurements are made by a flat blade that is less affected by arching of stresses in the horizontal direction. The ratio given by Equation 6 can be considered a more reliable parameter than the CPT-based ratio in Equation 2, as the DMT measures the horizontal stress directly. However, DMT measurements are made at larger depth intervals than when using the CPT. Therefore, it is recommended to base the assessment of horizontal stress changes on several CPT and/or DMT measurements.

The accuracy of horizontal stress measurements based on in situ tests is still an unresolved issue, in particular if derived from the CPT (sleeve resistance). The DMT has the advantage that stresses and stress changes can be measured directly in the horizontal direction during the test. However, as will be shown by the case histories presented later in the paper, both the CPT and the DMT provide valuable information regarding changes in horizontal stress due to vibratory compaction.

4. Effect of preloading

Several theories and analytical methods have been developed to explain and/or analyse the residual horizontal earth stress induced by soil compaction. Common to all of these is the concept that compaction represents a form of preloading wherein stresses resulting from a temporary or transient loading condition are retained to some extent following removal of this peak load. Early on, Rowe (1954) proposed that compaction could be interpreted as the repeated application and removal of a static surcharge and suggested that virtually all peak soil stresses induced by surcharge loading would be retained after surcharge removal. These considerations also apply to deep compaction of granular soils, which should be recognised, as stated by Massarsch and Fellenius (2002).

4.1 Horizontal stress in normally consolidated soil

The horizontal effective stress σ'_h, in normally consolidated soil can be estimated from the well-known relationship

7. $$\sigma'_h = K_0 \sigma'_v$$

where σ'_v is the vertical effective stress and K_0 is the earth stress coefficient at rest. In normally consolidated friction soil,

K_0 can be estimated according to the simplified relationship (Jaky, 1948)

8. $$K_0 \approx 1 - \sin \phi'$$

where ϕ' is the effective friction angle. In uncompacted friction soil ($\phi' \approx 33°$), a typical value of $K_0 = 0{\cdot}43$ can be assumed.

4.2 Horizontal stress in overconsolidated soil

The OCR, which describes the degree of preloading of a soil deposit, can be defined by

9. $$\text{OCR} = \frac{\sigma'_\text{p}}{\sigma'_{\text{v}0}} = \frac{\sigma'_{\text{v}0} + \Delta\sigma'}{\sigma'_{\text{v}0}}$$

where $\sigma'_{\text{v}0}$ is the vertical effective stress, σ'_p is the preloading stress and $\Delta\sigma'$ is the preloading margin ($\sigma'_\text{p} - \sigma'_{\text{v}0}$). The value of the OCR is based on the vertical effective stress and can therefore vary significantly, especially at shallow depth. Based on extensive investigations of laboratory tests by Mayne and Kulhawy (1982), the following relationship was found

10. $$\frac{K_1}{K_0} = \text{OCR}^\beta$$

where K_0 is the earth stress coefficient at rest (normally consolidated), K_1 is the earth stress coefficient (preloaded) and β is an empirical stress exponent. The OCR can thus be calculated from

11. $$\text{OCR} = \left(\frac{K_1}{K_0}\right)^{1/\beta}$$

The horizontal stress ratio can be estimated from Equation 2. In the literature (Massarsch and Fellenius, 2002), values of the stress exponent have been proposed for different soil types, ranging between 0·30 and 0·48. Massarsch and Fellenius (2018) re-evaluated the DMT investigations reported by Lee *et al*. (2011) in a calibration chamber, and found a conservative value of the stress exponent of $\beta = 0{\cdot}48$ ($1/0{\cdot}48 = 2{\cdot}1$), which, in the case of DMT results, yields

12. $$\text{OCR} = \left(\frac{K_{\text{D}1}}{K_{\text{D}0}}\right)^{2\cdot1}$$

where $K_{\text{D}0}$ is the horizontal stress index before compaction and $K_{\text{D}1}$ is the horizontal stress index after compaction.

5. Case studies

The results of five case studies were re-analysed. In each project, a different vibratory compaction method was used to improve primarily granular soils: (*a*) dynamic compaction by falling weight (Gdansk, Poland); (*b*) vibroflotation (Gdynia, Poland); (*c*) VibroWing (Värnamo, Sweden); (*d*) TriStar compaction (Annacis Island, Canada) and (*e*) resonance compaction (Antwerp, Belgium). In all five cases, the results of CPT and DMT investigations prior to and after treatment were reported. The main objective of this study was not to compare or evaluate the efficiency of the respective vibratory compaction methods, but to investigate whether – and if so, by how much – the horizontal stress increased as a result of vibratory compaction. The case histories described project conditions with limited research resources, which in some cases limited the extent of the field investigations. This limitation was aggravated by the variability/heterogeneity of soil conditions, which in some cases should have justified more extensive field investigations. However, the evaluation of actual compaction projects reflects the limitations encountered by geotechnical engineers. The results of the in situ tests were re-analysed without adjusting the reported measurement values.

5.1 Evaluation method of case histories

The five projects covered a wide range of soil conditions and were carried out in different parts of the world. Details of the projects and the employed compaction methods are given in the respective references. In order to reduce the influence of soil layering and minor variations in measurement results, the running geometric average of the measured CPT and DMT values was determined over a depth interval of 400 mm. From the CPT investigations, the cone resistance q_c and the sleeve resistance f_s were determined. The friction ratio R_f and the SBT chart (Robertson, 1990) were used to illustrate the soil type before and after treatment. The ratio of cone resistance and sleeve resistance after treatment was then compared with the values prior to compaction. From the sleeve resistance ratio, the OCR was calculated according to Equations 2 and 11. In the case of DMT measurements, the material index I_D and the measured horizontal stress index K_D were derived first. Thereafter, the horizontal stress index after treatment was compared with the value prior to compaction. From the horizontal stress ratio, the OCR was determined using Equation 12.

5.2 Dynamic compaction – Gdansk, Poland

In the Vistula delta near Gdansk, Poland, compaction tests were performed using a falling weight, as described by Kurek and Balachowski (2015). The soil consisted of sand with embedded layers of organic material. Down to 6 m depth, loose layers of fine and medium sand were encountered, with a silt content below 6%. Organic material occurred in layers between 6 and 16 m depth. The depth of the groundwater table is not mentioned in the reference but – based on CPT results – is estimated to approximately 3 m below the ground surface. Deep compaction was performed using a mass of 16 t, dropped from 18 m height. Soil treatment was carried out in two passes. During the first pass, a rectangular grid of 7·5 m × 7·5 m was used. Eight days after the first pass, the soil was compacted in the intermediate points of the grid. The required compaction energy of 1500 kJ/m^2 was achieved by 13 blows. The compaction effect was measured by CPT and DMT investigations before treatment and 1 d and 14 d after treatment.

The cone resistance q_c and the sleeve resistance f_s prior to and 14 d after treatment are shown in Figure 5. Both q_c and f_s increased after dynamic compaction between 1·5 and 6·0 m depth. A fine-grained layer occurred at 5 m depth (see Figure 6). The increase in q_c was low in this layer while f_s showed a more distinct increase. It is interesting to note that q_c and f_s continued to increase during the time between 1 and 14 d after compaction.

Figure 6 shows that – with the exception of the fine-grained layer at 5 m depth – the soil deposit was rather homogeneous. Because the increase in q_c was higher than that of f_s, the friction ratio decreased, which would suggest a change in soil type. However, the soil type did not change during dynamic compaction. Therefore, a change in friction ratio due to compaction needs to be interpreted with caution.

The effect of compaction on the sleeve resistance, and thus on horizontal stress, is shown in Figure 7. Also shown is the OCR value calculated according to Equation 11, assuming a stress exponent of $\beta = 0{\cdot}48$. Due the variability of soil properties down to 1·5 m depth, values in this zone were disregarded.

It is apparent that the sleeve resistance increased between 2 and 6 m depth by a factor of approximately 2–4. This increase in horizontal stress resulted in a significant preloading effect, with OCR values between 2 and 15. It is important to interpret the OCR value cautiously, as this ratio is affected by low vertical effective stress values. Usually, for settlement analyses, it is recommended to calculate the preloading stress rather than to use the OCR.

The material index determined from DMT measurements is shown in Figure 8. Prior to compaction, the soil can be generally classified as sand, similar to the CPT results shown in Figure 6. After compaction, the DMT soil classification shows a decrease in the material index, corresponding to an increase in friction ratio. However, this observation does not imply any change in soil type but is purely a result of the I_c interpretation method, which is affected by changes in horizontal stress.

The horizontal stress index was very low prior to treatment but increased significantly due to dynamic compaction and continued so during the following 14 d. The DMT results are similar to those of the CPT results shown in Figure 5. However, the increase in horizontal stress index was more pronounced in the

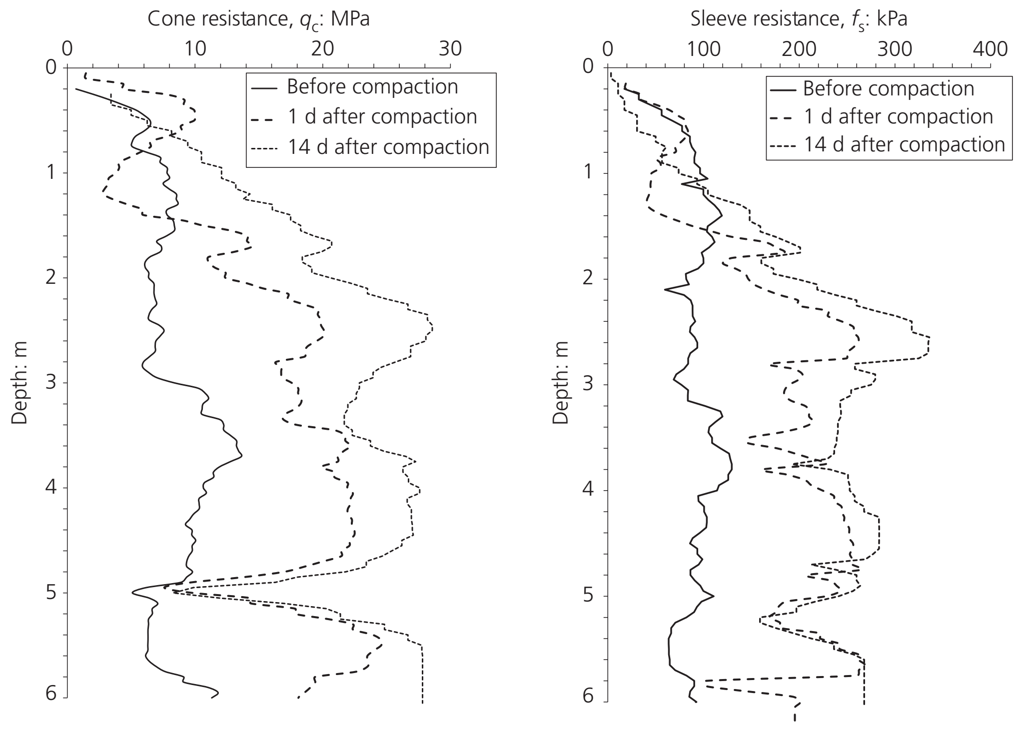

Figure 5. Gdansk, Poland: cone resistance and sleeve resistance prior to compaction and 1 d and 14 d after dynamic compaction (data from Kurek and Balachowski (2015))

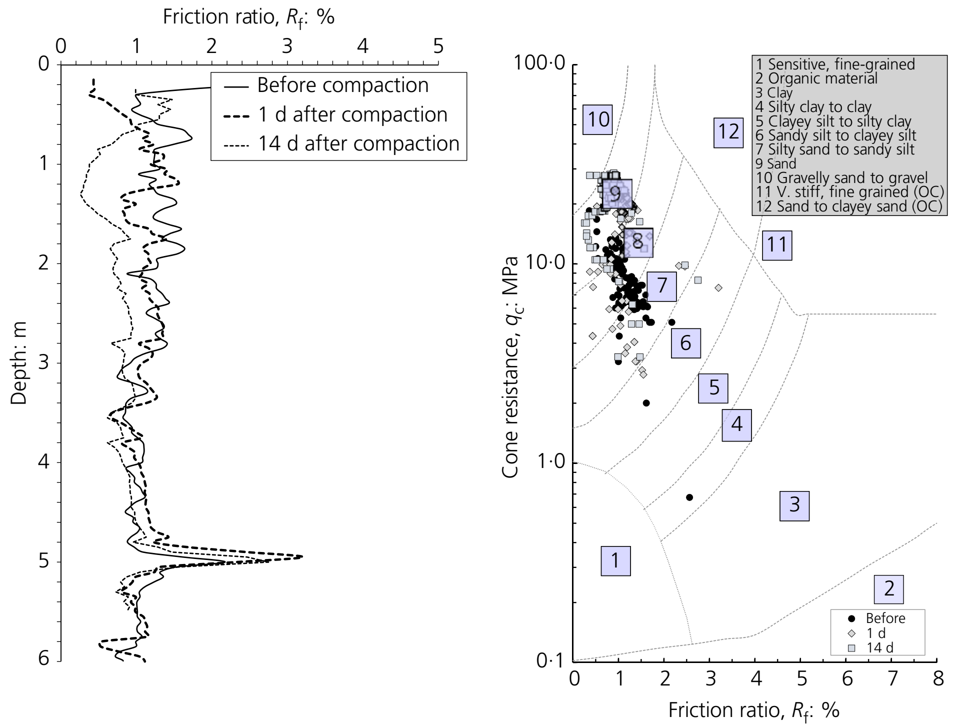

Figure 6. Gdansk, Poland: friction ratio and SBT chart before treatment and 1 d 14 d after dynamic compaction (data from Kurek and Balachowski (2015))

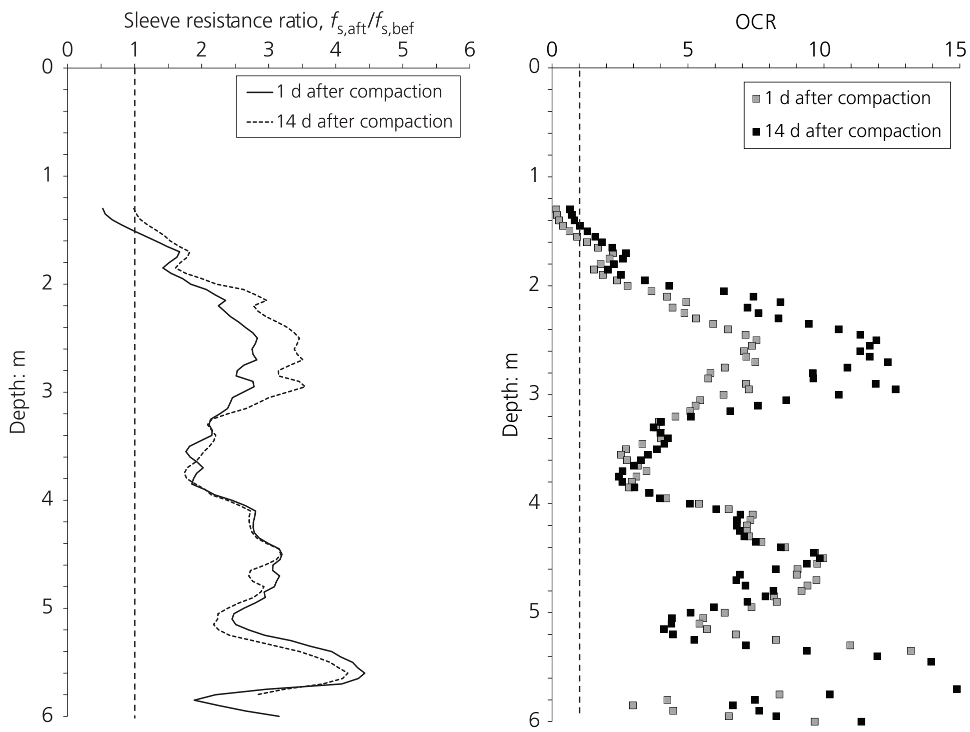

Figure 7. Gdansk, Poland: change in sleeve resistance after compaction and resulting increase in OCR, determined from sleeve resistance (Figure 5)

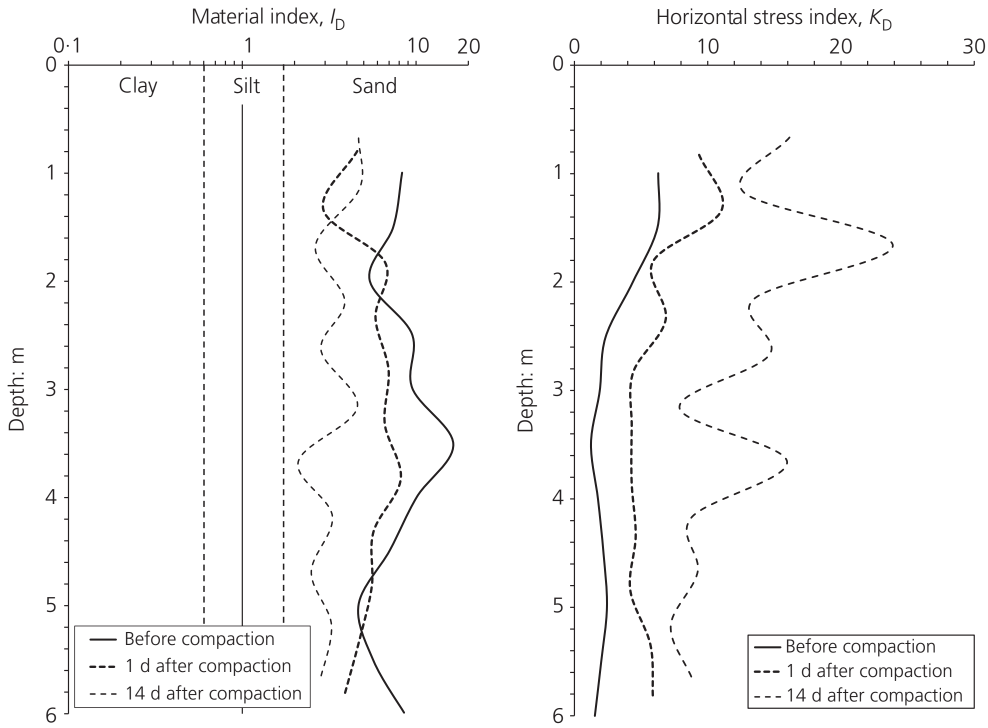

Figure 8. Gdansk, Poland: material index and horizontal stress index measured prior to compaction and 1 d and 14 d after dynamic compaction (data from Kurek and Balachowski (2015))

DMT measurement compared with of the sleeve resistance from the CPT.

The effect of compaction on horizontal stress is shown by the horizontal stress index ratio in Figure 9. The DMT measurements confirmed that horizontal stresses increased immediately after compaction (1 d) and continued to do so in the following time period.

The increase in horizontal stress was more pronounced in the DMT measurements than the CPT investigation. The horizontal stress ratio after 1 d was similar to the sleeve resistance ratio, as shown in Figure 7. However, a much more pronounced increase in horizontal stress was measured in the following 13 d by the DMT. The OCR was estimated based on Equation 12. One day after compaction, the OCR varied typically between 2 and 10, but increased during the following days to values exceeding 30. However, as already stated, a large increase in OCR needs to be interpreted with caution.

5.3 Vibroflotation – Gdynia, Poland

In the vicinity of the President harbor in Gdynia, several buildings were founded on Holocene soil, consisting of loose sand with organic layers and seams. The soil layer to be treated was loose to medium dense and had a silt content lower than 7%. The groundwater table was located about 1 m below the ground surface. Project details and the results of field trials were reported by Balachowski and Kurek (2015). Vibroflotation was used as the ground treatment method. A compaction probe with a power of 120 kW was used, operated at a constant frequency of 30 Hz. The displacement amplitude of the horizontally oscillating poker (above the ground) was 20 mm. Compaction was carried out in a rectangular grid with 3 m × 3 m spacing. Before and after treatment, CPT and DMT investigations were performed in the centre points of the rectangular grid. The results of the CPT investigations before and after compaction are shown in Figure 10.

It is apparent that, between 2 and 9 m depth, both the cone resistance q_c and the sleeve resistance f_s increased due to compaction with the exception of a layer between 3 and 4 m depth. After compaction, an increase in q_c was detected at 2–3 m depth and 4–8·5 m depth, with very high values between 4·5 and 7·5 m depth. The very low values of q_c and f_s after compaction down to 2·5 m depth are suspect and have been disregarded. The occasional decrease in f_s after compaction is considered to reflect the heterogeneity of the soil deposit rather than a loosening effect. Below 9 m, no increases in q_c and f_s were detected. The variation of the friction ratio with depth before and after compaction and the SBT chart are shown in Figure 11.

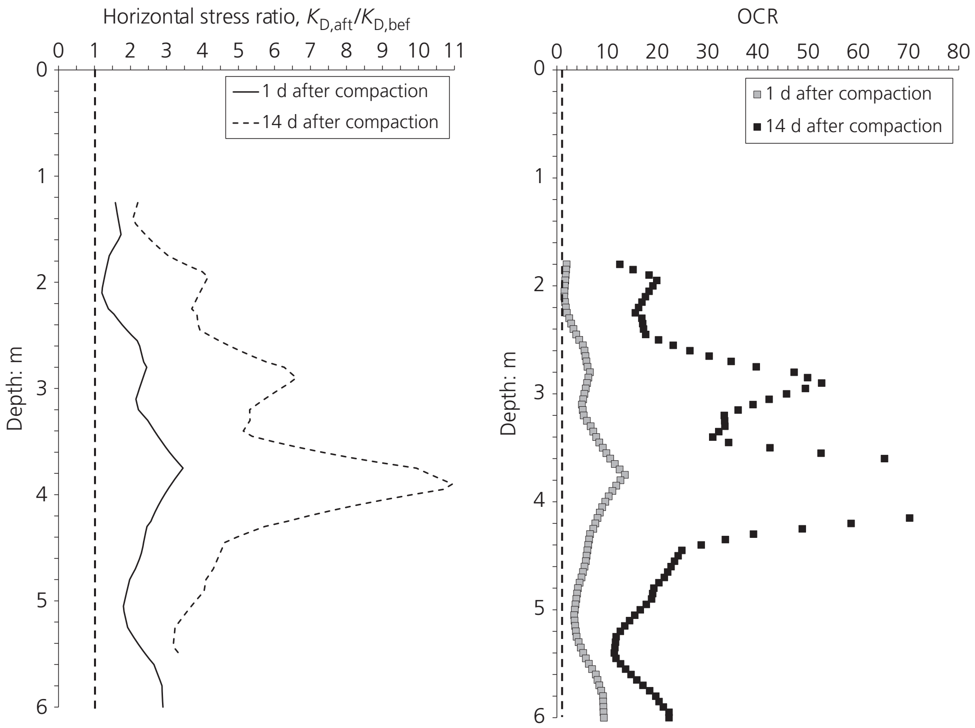

Figure 9. Gdansk, Poland: change in horizontal stress due to compaction and resulting increase in OCR, determined from horizontal stress index (Figure 8)

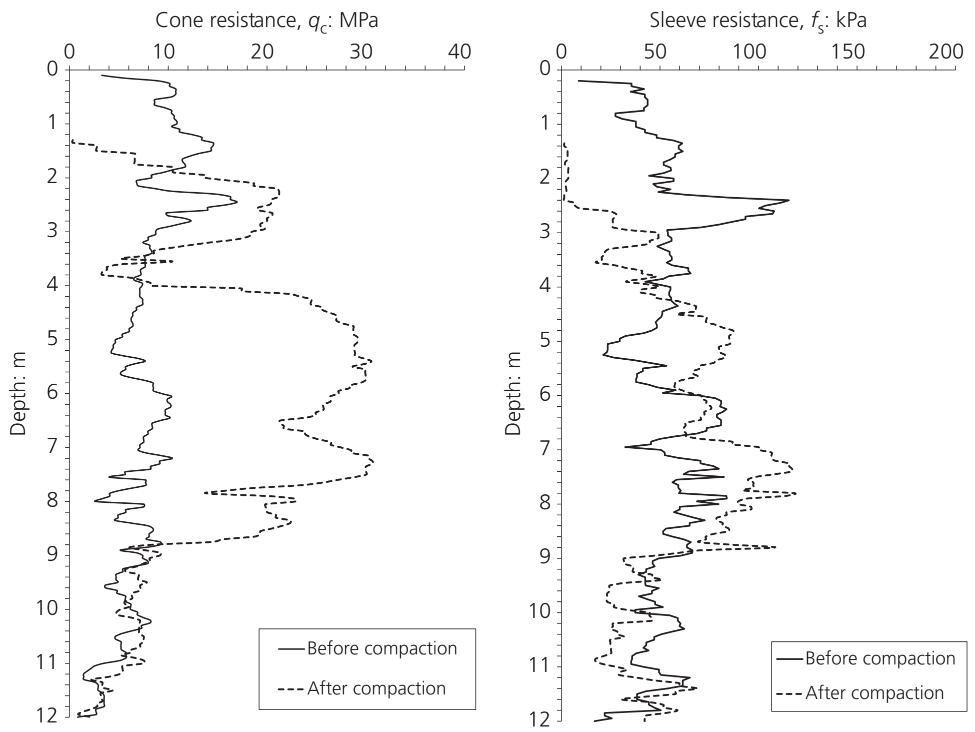

Figure 10. Gdynia, Poland: cone resistance and sleeve resistance prior to compaction and after vibroflotation compaction (data from Balachowski and Kurek (2015))

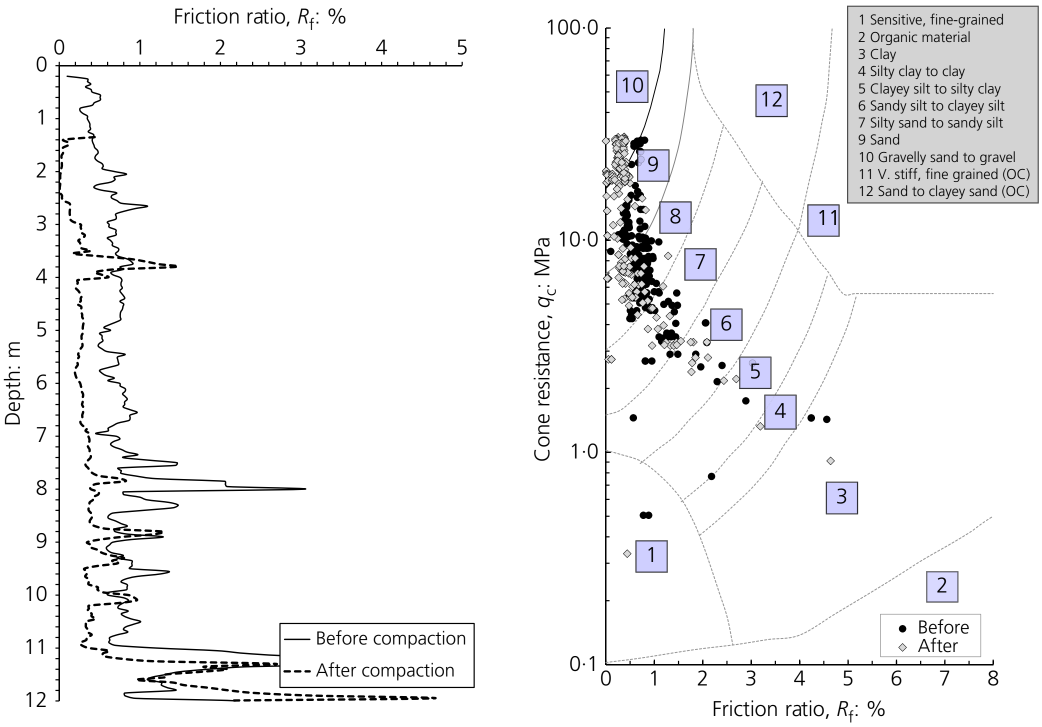

Figure 11. Gdynia, Poland: friction ratio and SBT chart before and after treatment by vibroflotation (data from Balachowski and Kurek (2015))

Due to the much stronger increase in cone resistance compared with the sleeve resistance, the friction ratio decreased. However, this change in friction ratio does not imply that the soil had become more granular. The same effect can be observed in the SBT chart.

The sleeve resistance ratio is shown in Figure 12, as determined from the sleeve resistance measurements (Figure 10). The values between 4 m and 9 m depth are considered reliable while the sleeve resistance down to 3 m (the zone above the groundwater table) was unrealistically low. In the layer between 4 and 7 m depth, the sleeve resistance ratio ranged between 1 and 3. The corresponding OCR is also shown in Figure 12. Again, only values between 4·5 and 8 m depth are considered reliable. OCR values <1 are not considered realistic and do reflect the variability of soil conditions. Inspection of the cone resistance after compaction confirmed that the soil deposit between 4 and 8·5 m was compacted. This was also confirmed by the DMT measurements (horizontal stress index; see Figure 13).

The results of the DMT investigations are shown in Figure 13. Similar to the friction ratio from the CPT in Figure 11, the DMT classifies the soil as sand. The material index decreased due to compaction, suggesting that the soil had become more fine-grained. However, as stated above, this conclusion of change in soil type is misleading and is caused by the stronger increase in horizontal stress. The horizontal stress index was very low before compaction, but increased significantly after treatment down to a depth of about 8 m.

Figure 14 shows the horizontal stress ratio and the derived OCR. Compared with the CPT results, the DMT results showed a consistent increase in horizontal stress between 2·0 and 8·5 m depth. This strong increase is partly due to the very low K_D values prior to compaction, which magnified the horizontal stress ratio. Consequently, OCR also became very large, and this needs to be interpreted with judgement. However, it is apparent that compaction resulted in a significant increase in horizontal stress.

5.4 VibroWing – Värnamo, Sweden

The VibroWing method was used to improve the soil conditions for building foundations in the city of Värnamo in southern Sweden. The project was described by Jendeby (1992). The subsoil consisted of silty, very loose sand. The ground surface was almost horizontal and the groundwater table was located 3 m below the ground surface. Instead of a more expensive pile foundation, the designer chose a slab foundation on improved ground. In order to optimise the compaction process, compaction trials were performed prior to the start of the project. The VibroWing method is described by Massarsch and Broms (1983). The compaction probe consisted of an 11 m long tube with horizontal 0·8 m wide wings, attached at 2 m distance. The vibrator was a Tomen VM-5000

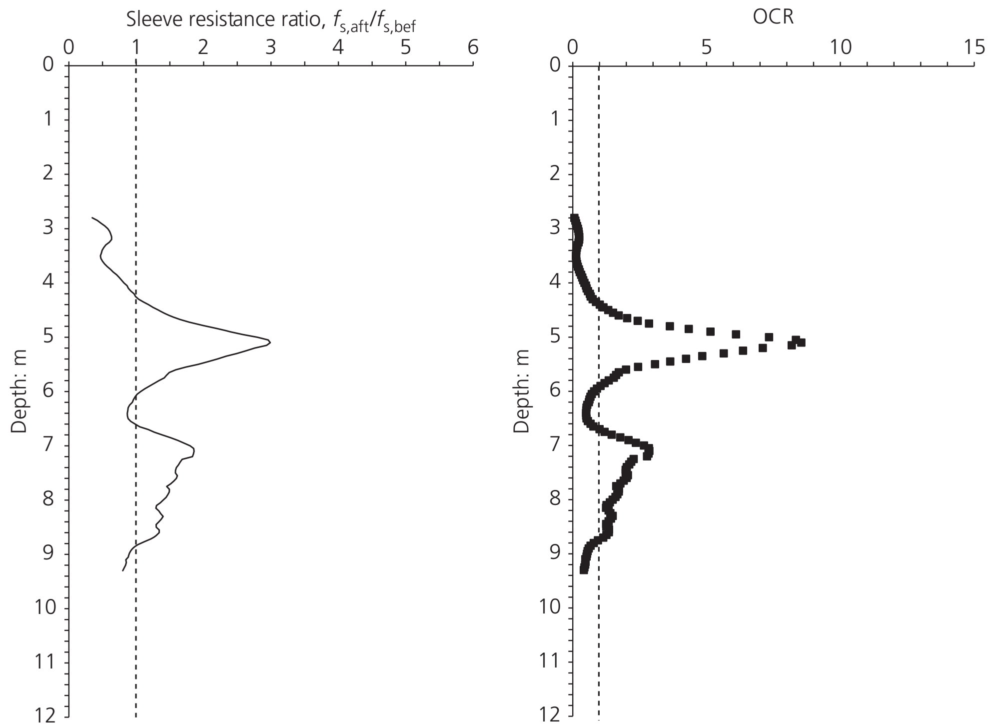

Figure 12. Gdynia, Poland: change in sleeve resistance after compaction and resulting increase in OCR, determined from sleeve resistance (Figure 10)

type, operated at a frequency of 20 Hz. Compaction was carried out in a triangular grid at 2·2 m distance to a depth of 8 m. The duration of compaction at each point was about 8 min. After deep vibratory compaction, the surface was treated by a vibrating plate with a size of 2·5 × 3·0 m, as described by Massarsch and Broms (1983). For vibratory plate compaction, the same vibrator was used as for the VibroWing treatment.

The soil compaction process was monitored by CPT and DMT measurements prior to compaction, 2 d after VibroWing compaction and 3 months after the vibratory plate treatment. The CPT results are shown in Figure 15.

Prior to compaction, the cone resistance was low, especially above the groundwater table (at 3 m depth), but increased gradually with depth. However, the sleeve resistance down to 5 m depth was unrealistically low and was neglected. Therefore, the pre-compaction sleeve resistance was not used to determine the increase in horizontal stress, as it would give unacceptably high improvement values.

Following VibroWing compaction, the cone resistance and sleeve resistance increased gradually with depth. However, the increase in the upper soil layer was considered insufficient and it was decided to improve the upper layer by compaction using a vibratory plate, which was moved repeatedly in an ironing movement over the ground surface. From Figure 15, it can be concluded that vibratory plate compaction improved the soil down to a depth of about 3·5 m. This depth corresponds approximately to the side length of the compaction plate. It should be noted that this strong increase in cone resistance and sleeve resistance occurred in the layer above the groundwater table – a zone that is usually difficult to compact. This zone is usually affected by the increase of effective stress due to the capillary rise. The friction ratio and SBT chart are shown in Figure 16.

Due to the unrealistically low sleeve friction (resulting from measurement or equipment error), the friction ratio before compaction was unreasonably low and is therefore not shown. Figure 16 shows a layer of silt and clay at 1 m and 5 m depth, respectively. This explains the relatively low increase in cone resistance and sleeve resistance after VibroWing compaction in Figure 15.

The increase in sleeve resistance after surface compaction by the vibrating plate is shown in Figure 17.

As the depth of compaction by the vibratory plate was limited to about 3·5 m, the sleeve resistance ratio increased only in the upper soil layer. However, it is surprising that vibratory plate compaction resulted in such a strong increase in horizontal stress, by a factor exceeding 10.

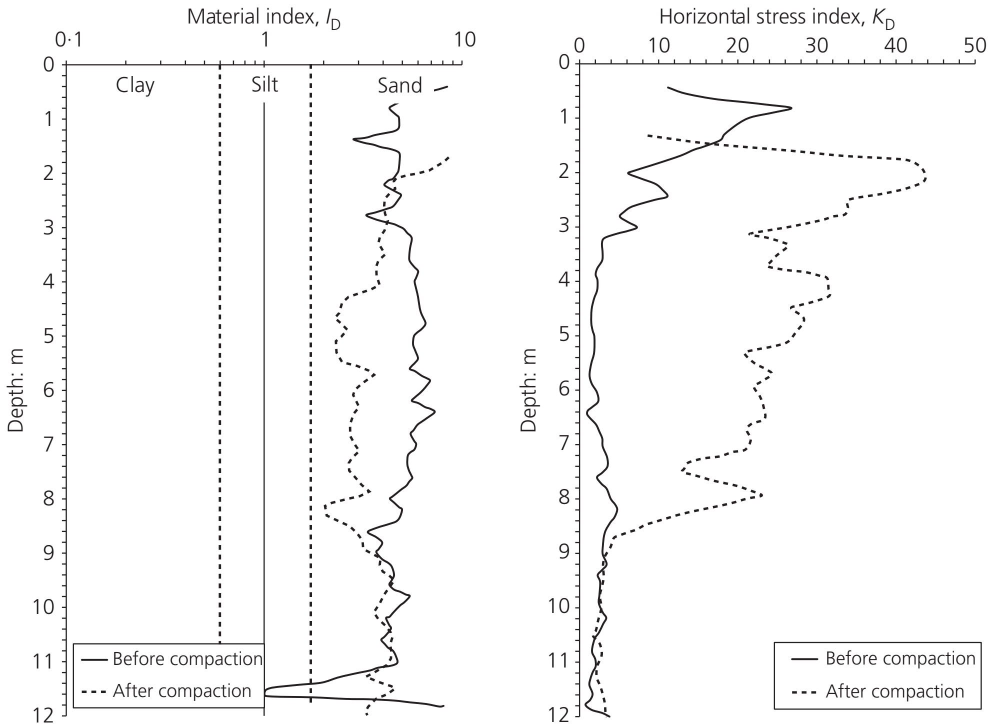

Figure 13. Gdynia, Poland: material index and horizontal stress index measured prior to and after compaction (data from Balachowski and Kurek (2015))

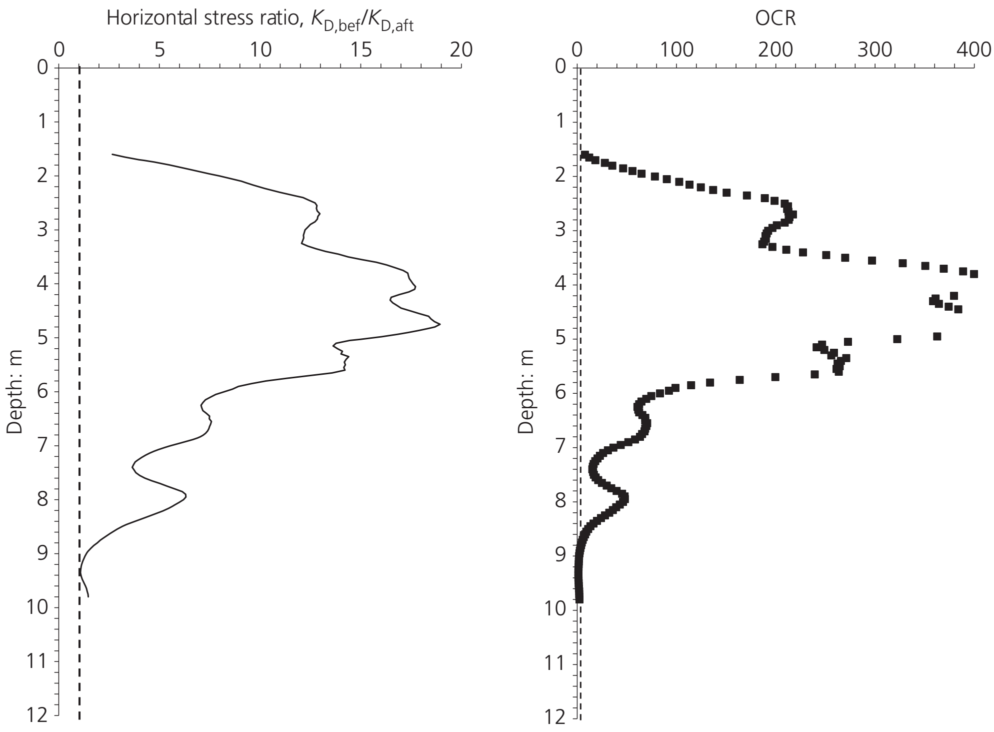

Figure 14. Gdynia, Poland: change in horizontal stress due to compaction and resulting increase in OCR, determined from horizontal stress index (Figure 13)

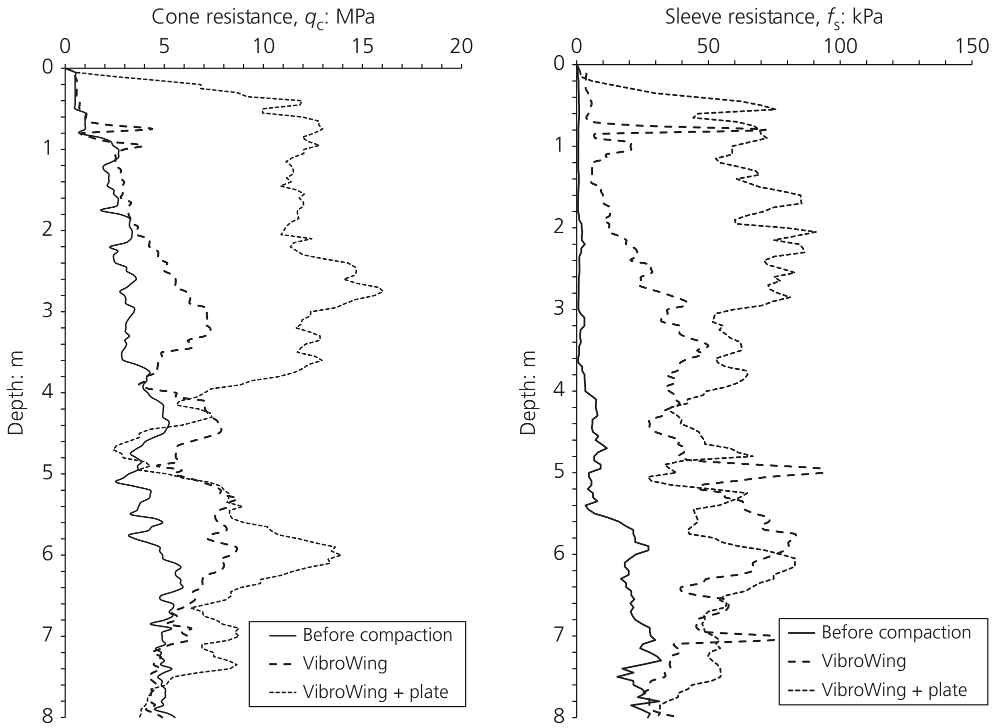

Figure 15. Värnamo, Sweden: cone resistance and sleeve resistance prior to compaction, 2 d after VibroWing treatment and 3 months after vibratory plate compaction (data from Jendeby (1992))

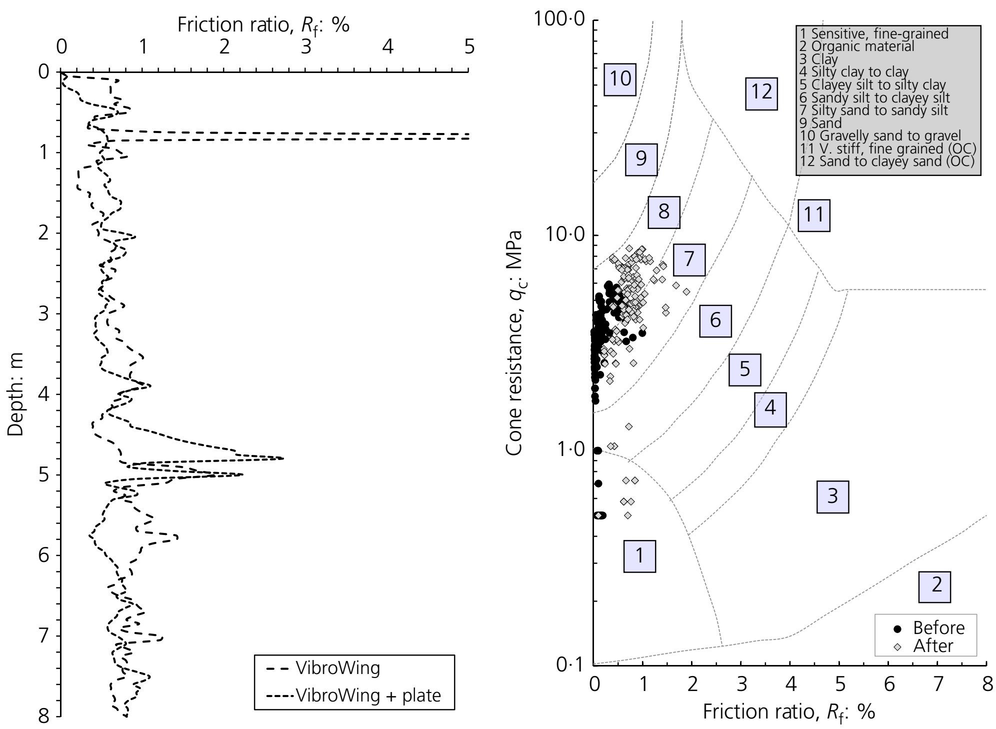

Figure 16. Värnamo, Sweden: friction ratio and SBT chart before and after treatment by VibroWing as well as 3 months after vibratory plate compaction (data from Jendeby (1992))

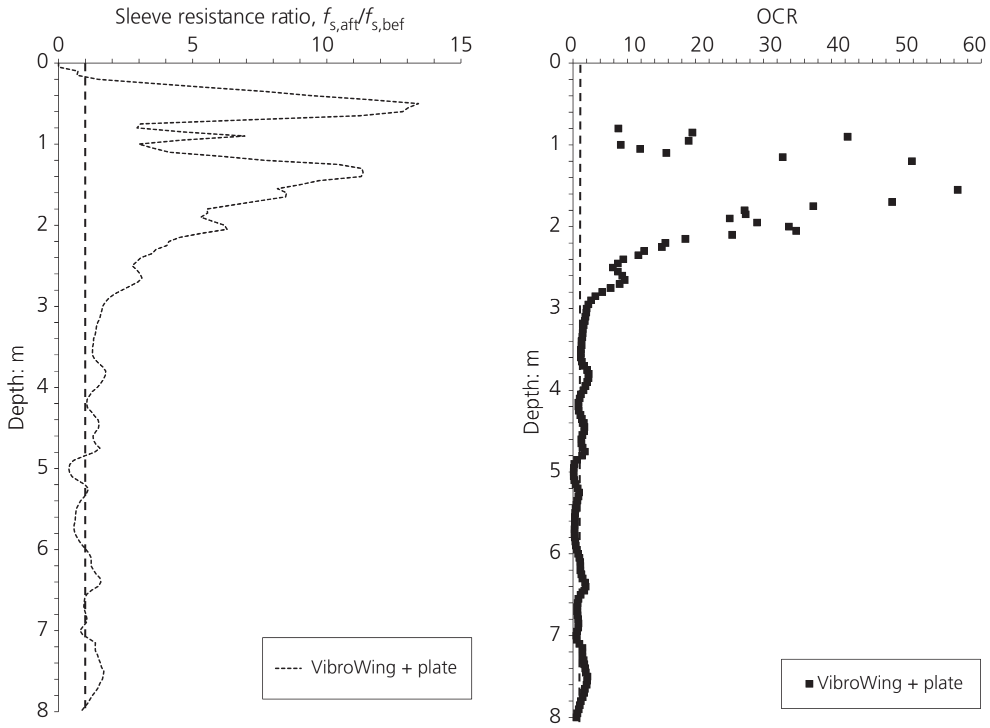

Figure 17. Värnamo, Sweden: change in sleeve resistance due to vibratory plate compaction and resulting increase in OCR, determined from sleeve resistance (Figure 15)

The results of the DMT measurements shown in Figure 18 are consistent with the CPT investigations (Figure 15). The material index indicates that, prior to compaction, the soil was primarily sand. After the VibroWing treatment, the material index increased down to about 2·5 m but changed little below that depth. However, after vibratory plate compaction (including the reconsolidation period), the material index decreased significantly down to 5 m depth, suggesting that the soil had become silty. However, the soil remained unchanged during treatment. Thus, the material index was affected by changes in horizontal stress, similar to the friction ratio in the SBT charts.

The horizontal stress index was very low prior to compaction, but there was a slight increase down to 5 m depth after the VibroWing treatment. However, after vibratory plate compaction, the horizontal stress index increased significantly down to 3·5 m depth.

Figure 19 shows the ratio of the horizontal stress index after VibroWing compaction and subsequent treatment by the compaction plate. It should be noted that the final DMT investigation was carried out 3 months later and was probably also affected by the reconsolidation in fine-grained layers. The horizontal stress ratio increased after VibroWing compaction between 2 and 7 m depth. The surface compaction by the vibratory plate increased the horizontal stress ratio to about 3 to 4. This increase is significant but lower than that determined from the sleeve resistance measurements (Figure 17). A possible reason for this difference could be the very low sleeve resistance measured prior to compaction. The OCR increased after VibroWing treatment but became significantly higher down to 3·5 m depth after surface compaction.

5.5 TriStar compaction – Annacis Island, Canada

TriStar compaction was used to improve potentially liquefiable sand deposits in the Frazer River near Vancouver (Brown, 1989). An extensive testing programme was carried out in connection with the project. The objectives of the in situ measurements were described by Massarsch and Fellenius (2018). The groundwater table was located approximately 2 m below the ground surface. The designer decided to improve the sandy and silty soil deposit to a depth of 11 m. Before compaction, extensive in situ tests were performed, including CPT and SPT. After completion of the project, researchers at the University of British Columbia investigated whether vibratory compaction resulted in a permanent change in horizontal stress and carried out CPT and DMT investigations 67 and 82 d after termination of the compaction. In order to obtain values of the pre-compaction conditions, DMT investigations were performed in a reference area with similar soil layering. However, the depth and thickness of the layers varied – an aspect that needs to be considered when interpreting the test results.

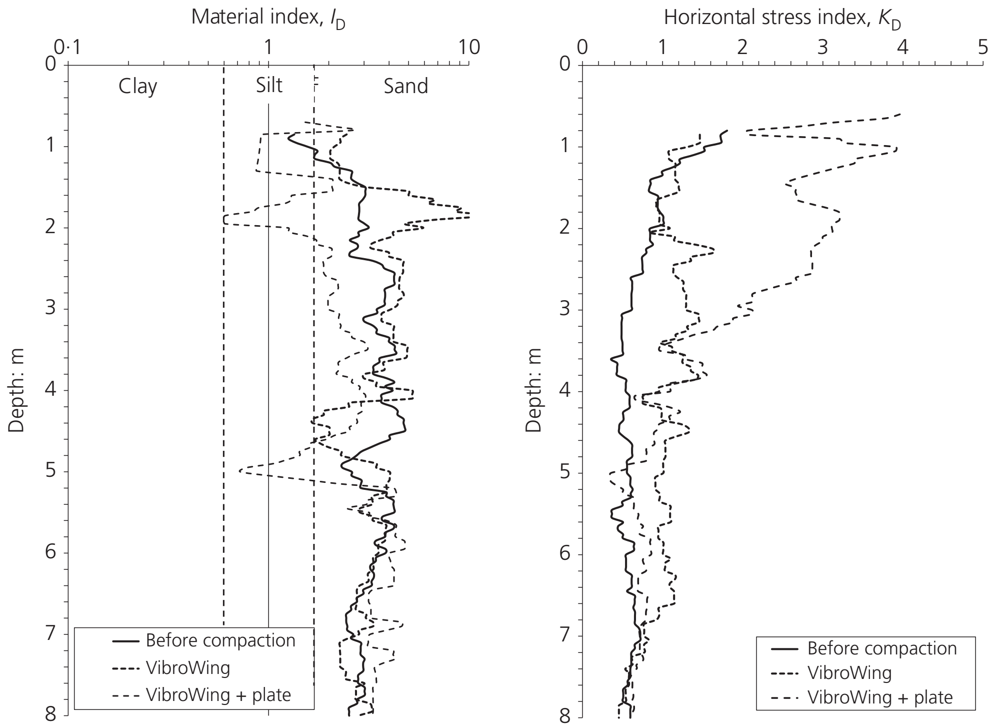

Figure 18. Värnamo, Sweden: material index and horizontal stress index measured prior to and after VibroWing and vibratory plate compaction (data from Jendeby (1992))

The results of the CPT investigations carried out before compaction and 67 and 82 d after treatment are shown in Figure 20. The cone resistance q_c and sleeve resistance f_s were low before compaction between 2 and 4 m depth. Increases in q_c and f_s can be observed after 67 d, with further increases after 82 d. These increases could have been caused by a time effect, but could also be explained by the variability of the soil conditions.

The friction ratio and the SBT chart are shown in Figure 21. It is apparent that several layers of fine-grained soil occurred in the sand deposit. The geotechnical conditions on the site were variable, which affected the comparison of in situ tests.

Figure 22 shows the sleeve resistance ratio and the derived OCR 67 and 82 d after treatment. The sleeve resistance increased significantly throughout the soil deposit, by a factor of 2–6. No significant time effect can be observed. Also, the OCR increased throughout the soil deposit, with the exception of a few soft soil layers with OCR $\approx$ 1.

The results of the DMT investigations are shown in Figure 23. Two tests were performed in each location with the dilatometer blade oriented in the north (N) and east (E) direction, to investigate whether there was a directional effect of the horizontal stress change. It should be noted that the tests, which simulated the pre-compaction conditions, were performed in a reference area, with similar but more variable soil conditions than in the compaction area. The material index suggests that the soil deposit consisted of silty sand with some fine-grained layers (silt and clay). Clay layers occurred before compaction at 2·5 m depth and after compaction at 4 and 6 m depth. This confirms the variability of the soil conditions, with fine-grained layers occurring at different depths.

The horizontal stress index was measured before and after treatment. High values of the horizontal stress index were measured in the surface layer down to 3·5 m depth. The horizontal stress index increased significantly after compaction down to 8 m depth, with the exception of two fine-grained layers at 4 and 6 m depth (see Figure 23). The direction of the stress measurement (north and east blade direction) appears not to have any notable effect on the results.

The ratio of horizontal stresses before and after compaction and the derived OCR are shown in Figure 24. The increase in horizontal stress varied between low values (<1) and 4. The low values occurred primarily in the two layers with high silt/clay content, and are most likely due to the variable soil conditions. The OCR values determined from sleeve friction measurements (Figure 22) were obtained in a different location. However, both the CPT and DMT measurements showed a similar trend, with a significant increase in the OCR after compaction.

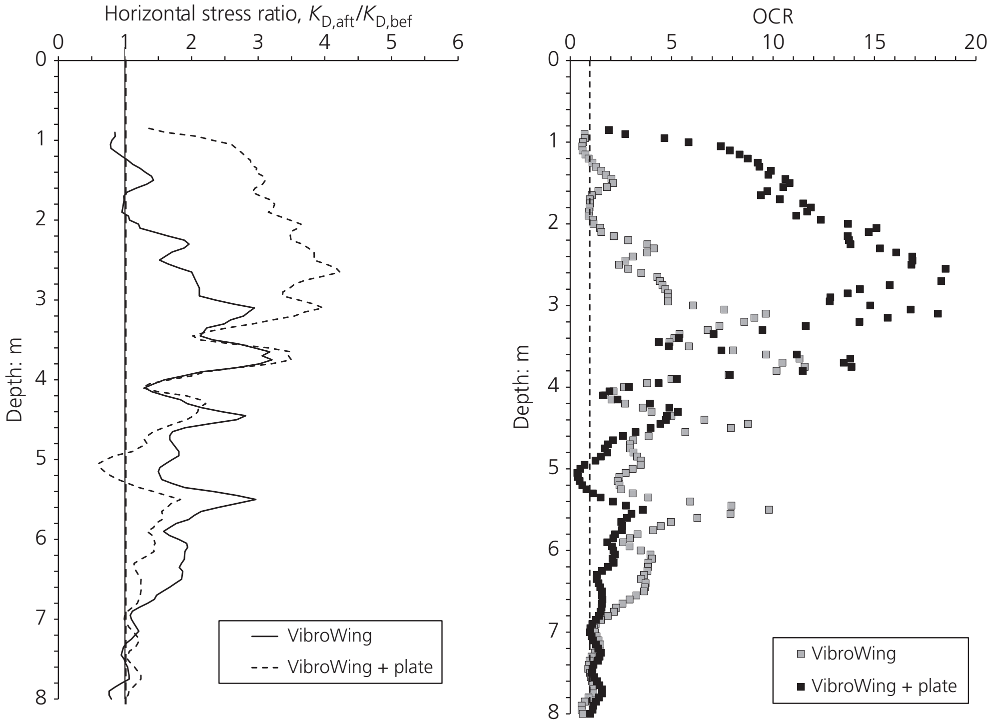

Figure 19. Värnamo, Sweden: change in horizontal stress due to compaction and resulting increase in OCR, determined from horizontal stress index (Figure 18)

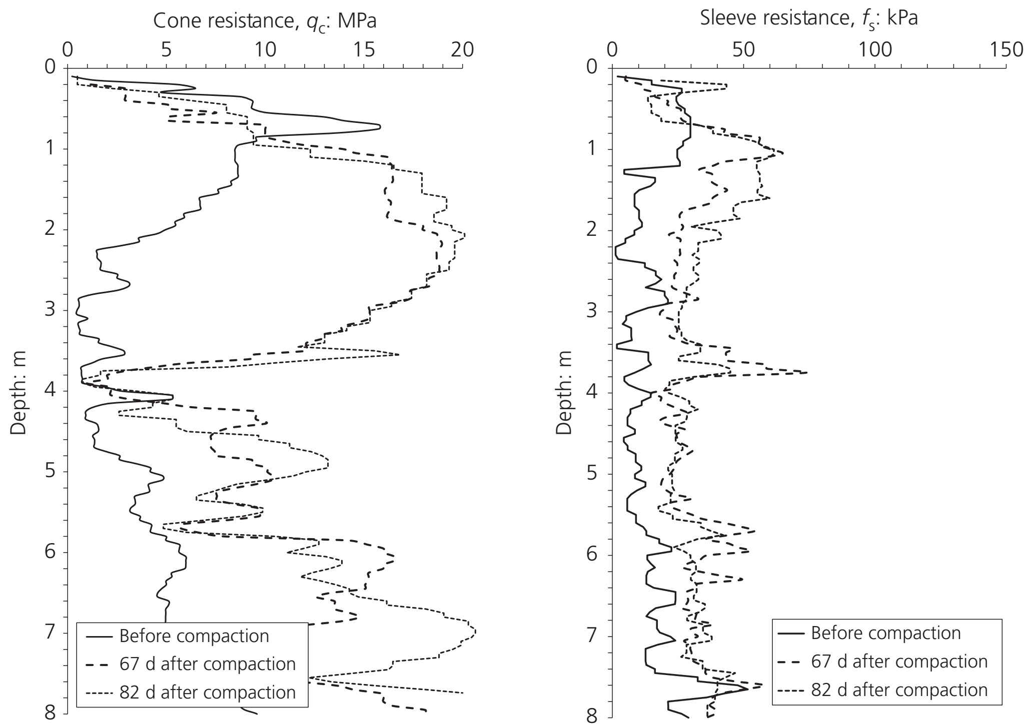

Figure 20. Annacis Island, Canada: cone resistance and sleeve resistance prior to compaction and after TriStar compaction (data from Massarsch and Fellenius (2018))

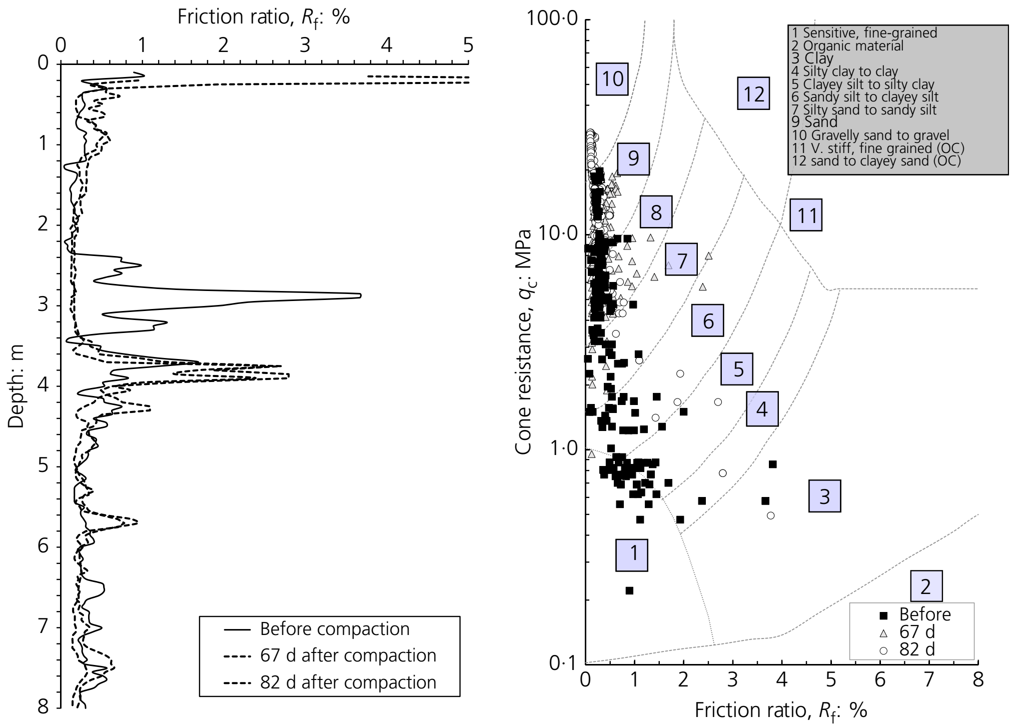

Figure 21. Annacis Island, Canada: friction ratio and SBT chart before and after treatment by TriStar compaction (data from Massarsch and Fellenius (2018))

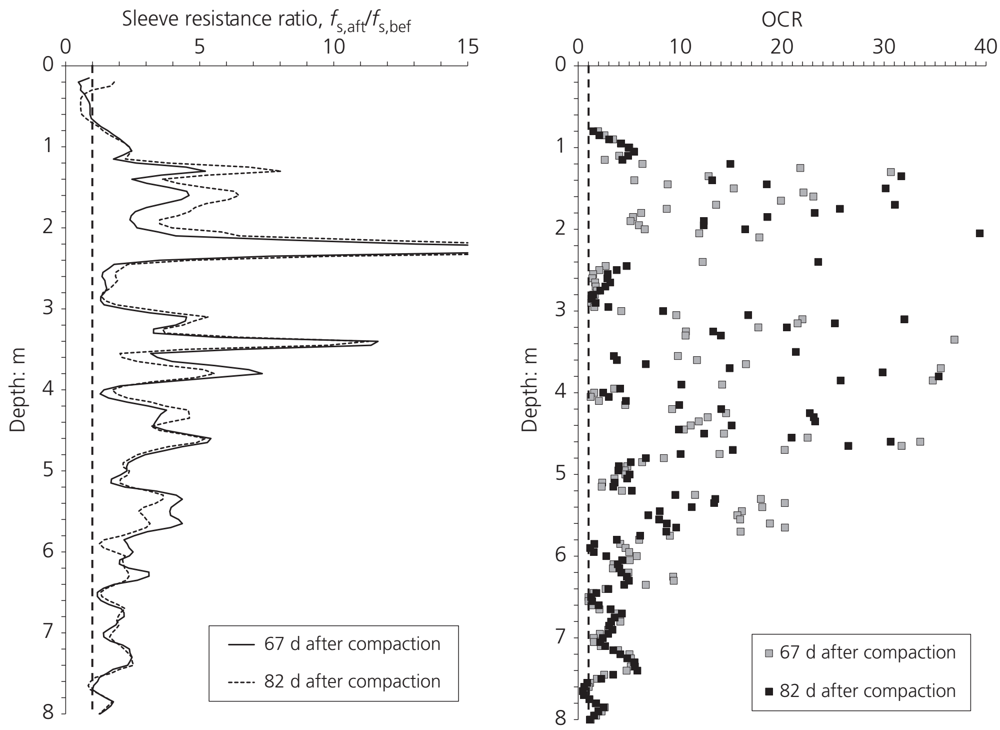

Figure 22. Annacis Island, Canada: change in sleeve resistance after compaction and resulting increase in OCR, determined from sleeve resistance (Figure 20)

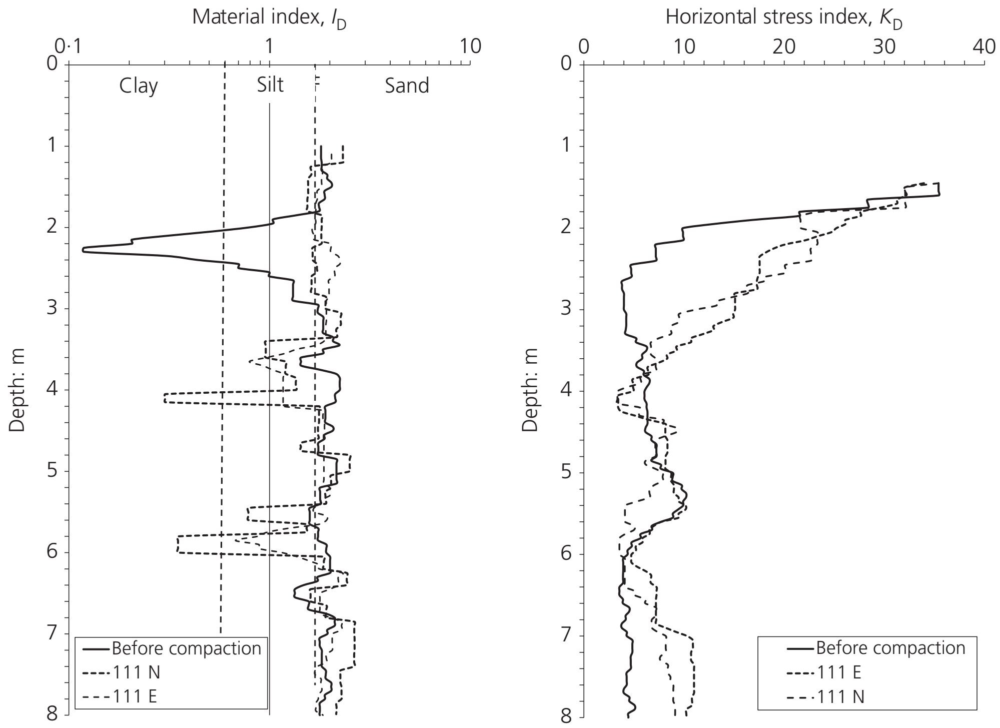

Figure 23. Annacis Island, Canada: material index and horizontal stress index measured prior to and 67 d after compaction at measurement point 111, E (east) and N (north) direction, respectively; (data from Massarsch and Fellenius (2018))

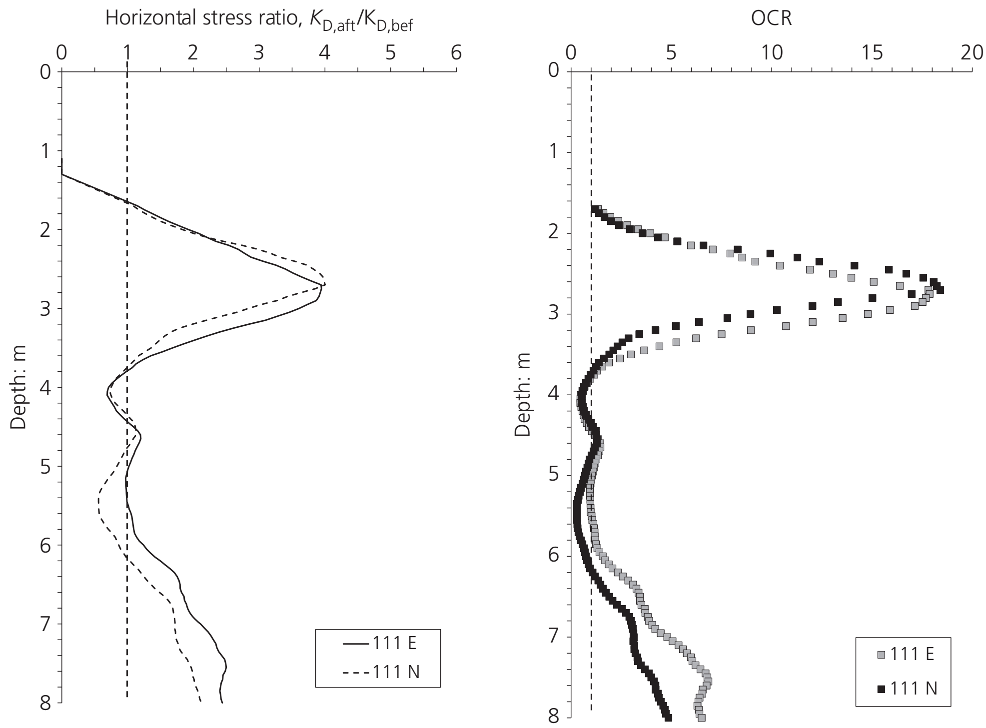

Figure 24. Annacis Island, Canada: change in horizontal stress due to compaction and resulting increase in OCR, determined from horizontal stress index (Figure 23)

5.6 Resonance compaction – Antwerp, Belgium

The resonance compaction method was applied in connection with the construction of a container harbour in Antwerp. The soil to be improved consisted of a 6–11 m thick sand fill placed behind a concrete retaining wall. The groundwater table was located approximately 5·5 m below the quay surface. The project was described by Van Impe *et al*. (1994). The objective of compaction was to reduce the risk of settlement from static loading (60 kPa) and from cyclic loading due to heavy vehicle traffic. In order to meet the requirements with regard to total and differential settlement, compaction was required to increase the cone resistance to at least 6 MPa. At the beginning of the project, compaction trials were performed using different compaction grid spacings, in the range 2–5 m. The duration of compaction varied between 10 and 15 min, depending on the compaction depth. In the trial area, the compaction depth was 7 m.

Compaction was carried using an MS 50HFV hydraulic vibrator with an eccentric moment of 50 kg.m. The vibrator frequency was varied between 10 and 30 Hz. The maximum displacement amplitude of the vibrator prior to penetration was 26 mm. At the maximum frequency, the vibrator generated a centrifugal force of 1500 kN.

Resonance compaction takes advantage of the vibration amplification effect that occurs when the vibrator operates at the resonance frequency of the vibrator–probe–soil system. The operating frequency of the vibrator can be adjusted continuously with the aid of a monitoring and process control system. The vibration frequency is varied during the compaction process, using high frequencies during the penetration and extraction phases. The vibration response of the ground is measured by geophones placed in the vicinity of the compaction probe. The optimal compaction process is determined during field trials. The effect of compaction is verified by in situ tests before and after compaction. Application of the resonance compaction system has been described by Massarsch and Fellenius (2017b).

The results of the CPT investigation for the Antwerp site are shown in Figure 25. The cone resistance prior to compaction showed a stiff surface layer down to about 2 m depth. Below was loose sand to a depth of 8 m. After compaction, the cone resistance increased to 10–20 MPa, with the exception of a fine-grained layer as detected from the higher friction ratio (see Figure 26). The sleeve resistance indicated a similar soil profile, with a dense surface layer and low sleeve resistance below 2 m depth. After compaction, the sleeve resistance between 2·5 and 7·5 m depth increased from approximately 20 to 80 kPa, with the exception of the fine-grained layer at 6·5–7·5 m depth.

The variation of the friction ratio and the SBT chart are shown in Figure 26. It is interesting to note that, due to the stronger increase in the cone resistance compared with the

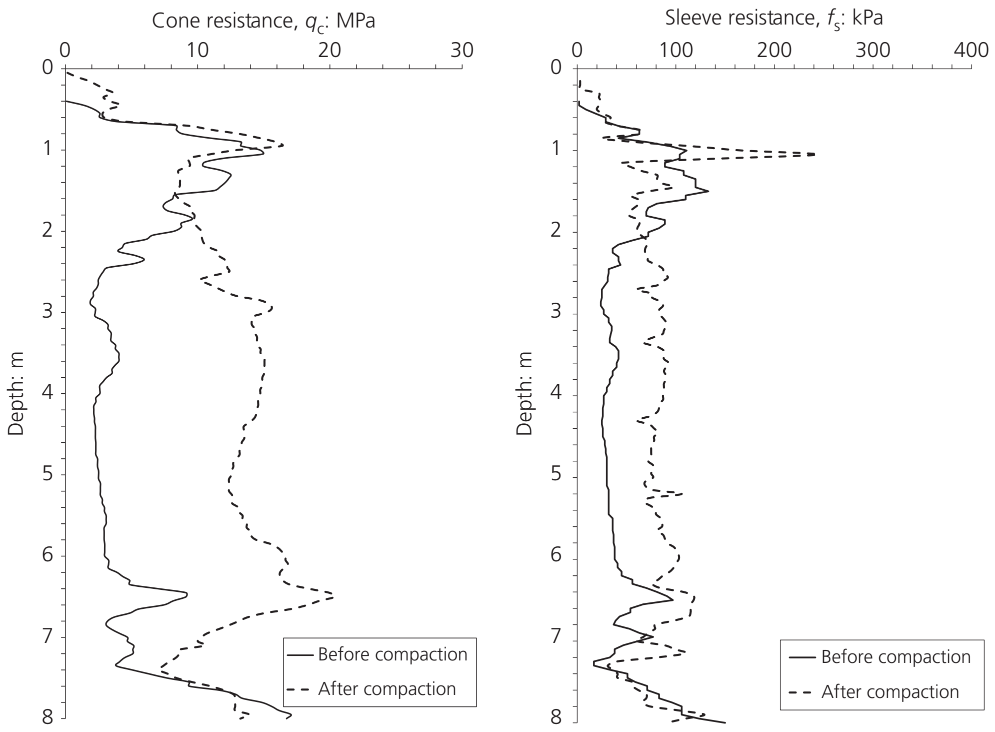

Figure 25. Antwerp, Belgium: cone resistance and sleeve resistance prior to and after resonance compaction (data from Van Impe *et al.* (1994))

sleeve resistance, the friction ratio decreased markedly after compaction, suggesting a change in material from silty to sandy soil. However, it is evident that the soil particle size did not change due to compaction. Thus, the change in friction ratio is merely a consequence of changes in horizontal stress.

Figure 27 shows the sleeve resistance ratio. The stiff surface layer was neglected in the evaluation. Below 2 m depth, the increase of sleeve resistance ratio ranged between 2 and 3, with the exception of a dense layer below 7·5 m depth, which was already very compact prior to treatment.

The OCR, derived from the sleeve resistance ratio before and after compaction, shows that the resonance compaction had a significant preloading effect (Figure 27). The low OCR values below 7 m depth are due to the overly conservative assumption that this already compact layer was normally consolidated. This is clearly not the case as can be seen from the high cone resistance and sleeve resistance values prior to compaction.

The results of the DMT investigations are shown in Figure 28. The material index before compaction was relatively low between 3 and 7 m depth, indicating a high silt content, which agrees with the friction ratio diagram (Figure 26). After compaction, however, the material index changed, indicating sandy soil and an apparent reduction in fines. As already stated, this effect is due to the change in horizontal stress, which affects the determination of the material index.

The horizontal stress index K_D was high in the upper layer down to about 2 m depth and very low in the loose soil down to approximately 7 m. K_D increased again in the dense bottom layer. After resonance compaction, K_D increased throughout the compacted soil deposit, with very high values in the layer down to about 3 m depth. The high K_D values in the top layer were likely due to the compaction effect caused by the movement of heavy construction equipment on site.

The change in horizontal stress based on DMT measurements is shown in Figure 29. The horizontal stress ratio increased on average between 2 and 5, and was thus somewhat higher than the increase determined from the sleeve resistance measurements. As a result of the high horizontal stress ratio, very high values of the OCR were derived, varying between 5 and 25.

6. Discussion and conclusions

Although it is difficult to determine in situ stresses accurately and, in particular, horizontal effective stresses in granular soil deposits, CPTs and DMTs can be used to measure changes in horizontal stresses. Based on the horizontal stress changes, empirical relationships can be used to estimate the extent of preloading (overconsolidation). The preloading effect is commonly expressed by the OCR, in spite of the fact that consolidation only occurs in fine-grained soil layers (silt and clay).

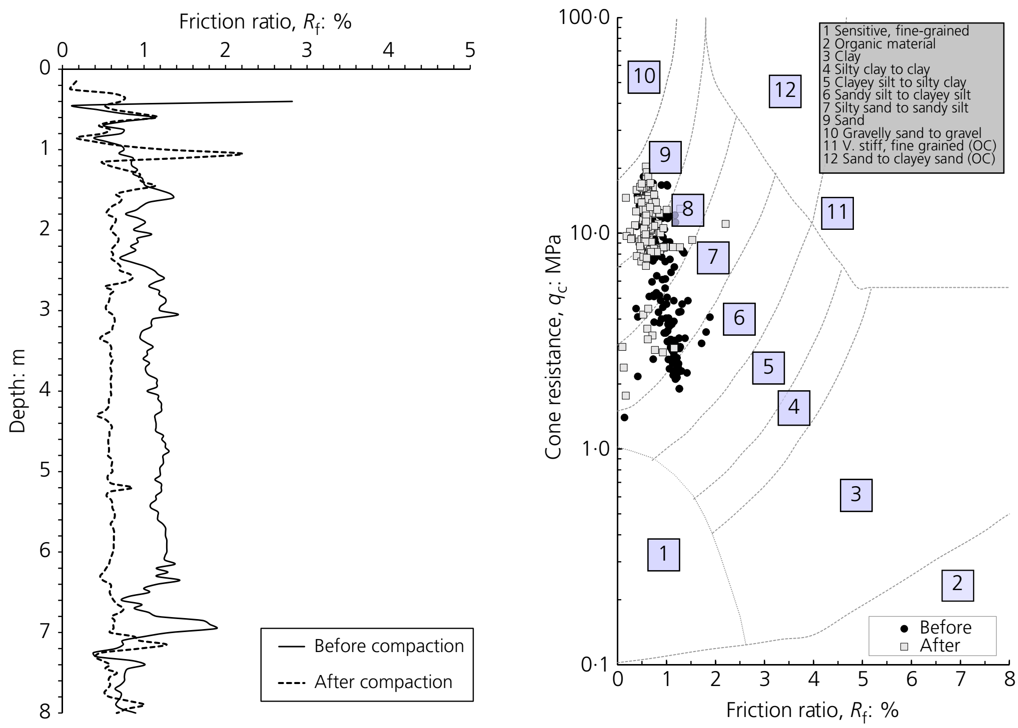

Figure 26. Antwerp, Belgium: friction ratio and SBT chart before and after resonance compaction (data from Van Impe *et al.* (1994))

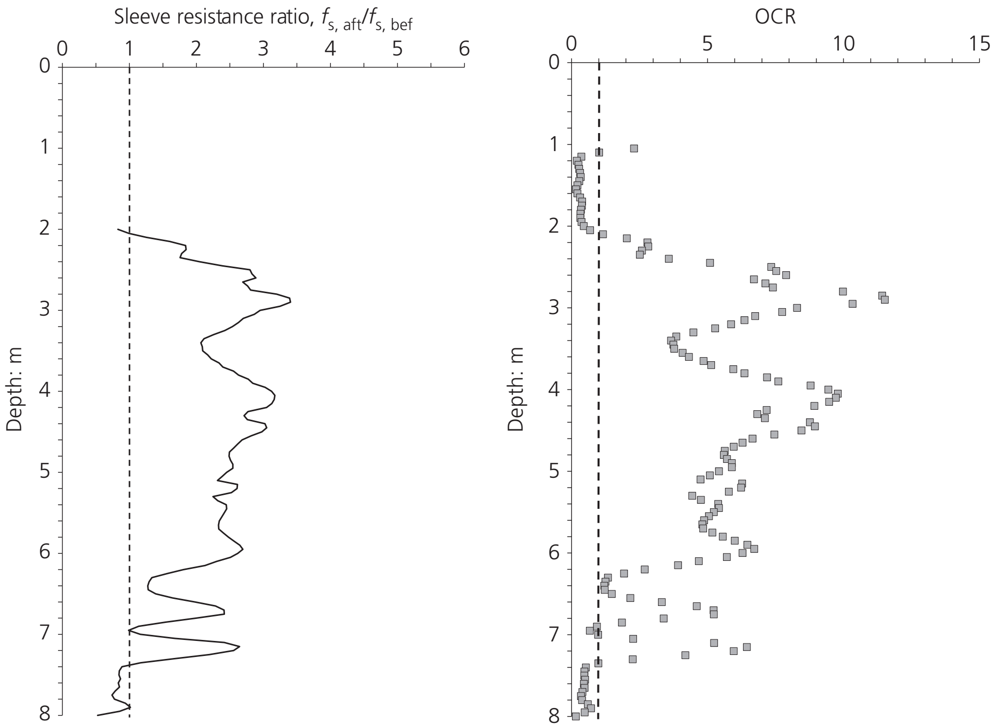

Figure 27. Antwerp, Belgium: change in sleeve resistance after compaction and resulting increase in OCR, determined from sleeve resistance (Figure 25)

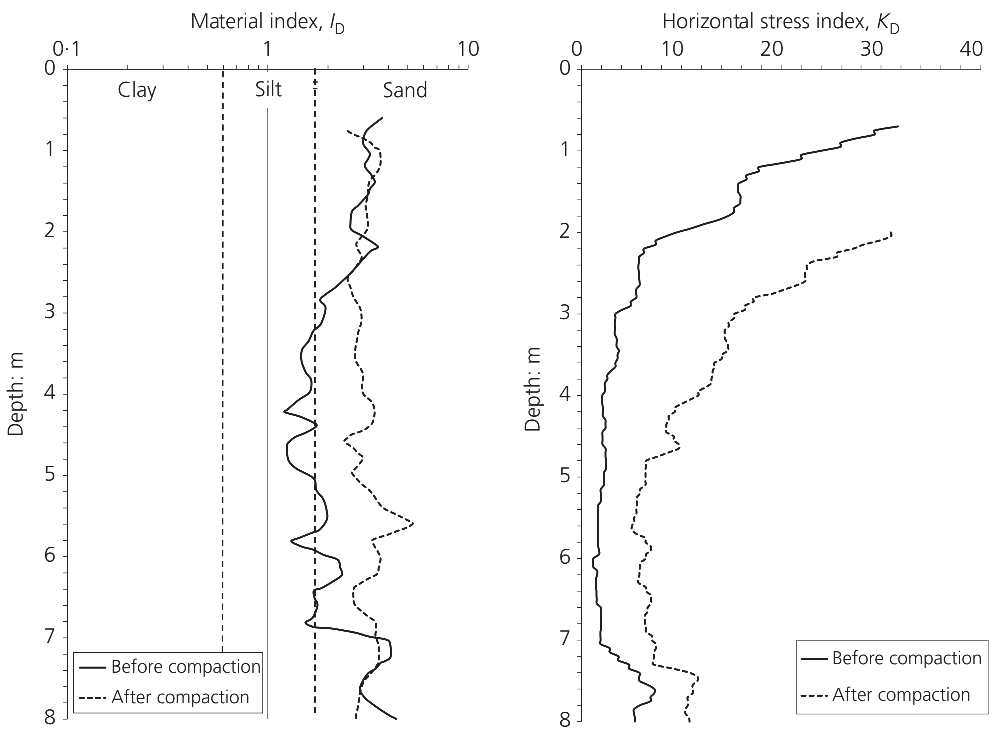

Figure 28. Antwerp, Belgium: material index and horizontal stress index measured prior to and after resonance compaction (data from Van Impe *et al*. (1994))

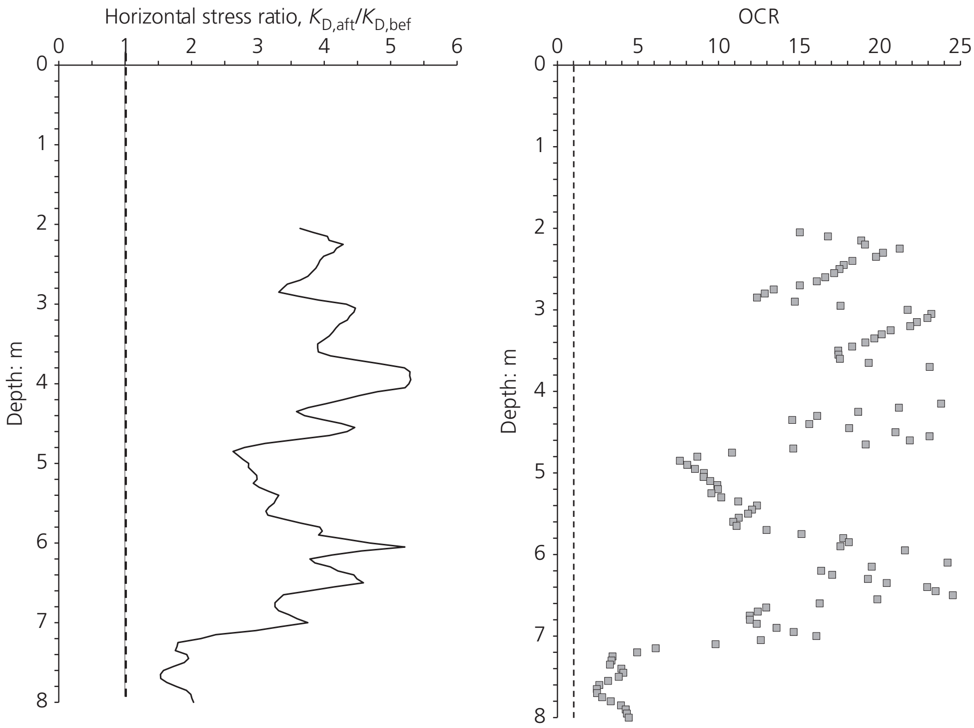

Figure 29. Antwerp, Belgium: change in horizontal stress due to compaction and resulting increase in OCR, determined from horizontal stress index (Figure 28)

Five case histories where different vibratory compaction methods were used have been reviewed. The tests were carried out in connection with actual projects and reflect the difficulties of limited research resources that are encountered by practising engineers. The site conditions were variable and represented a wide range of soil conditions encountered when applying deep vibratory compaction. In some cases, the results of in situ measurements are questionable and can be explained by the variability of soil conditions.

Two in situ testing methods (CPT and DMT) were used to measure change of horizontal stress as a result of different vibratory compaction methods, expressed in terms of the sleeve resistance f_s and the horizontal stress index K_D, respectively. Both methods have limitations with respect to measurement accuracy (related to instrument and test performance). Also, soil conditions and soil layering affect the accuracy of measurements. Moreover, a comparison of CPT and DMT measurements before and after treatment is affected by uncertainties regarding the location of the two testing methods on site prior to and after soil treatment. Thus, it is inevitable that a significant scatter of data occurs. For that reason, when comparing the test results from different sites and in order to eliminate to some degree variability of soil layering, the geometric average of measured values (over a depth interval of 0·4 m) was used in the comparisons. However, changes in the horizontal effective stress and the resulting preloading effect can have a significant impact on the static and/or cyclic soil response when subjected to loading.

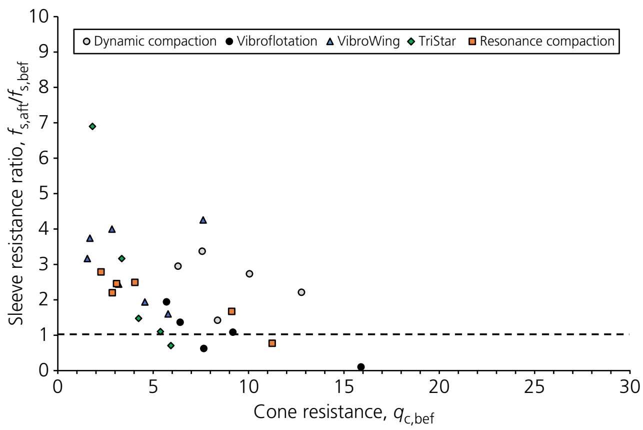

Figure 30. Sleeve resistance ratio as function of cone resistance prior to vibratory compaction

An important question was to determine whether CPT sleeve friction measurements could detect changes in horizontal stress after vibratory compaction. Figure 30 shows the sleeve resistance ratio (sleeve resistance after compaction divided by the value before compaction) as a function of cone resistance

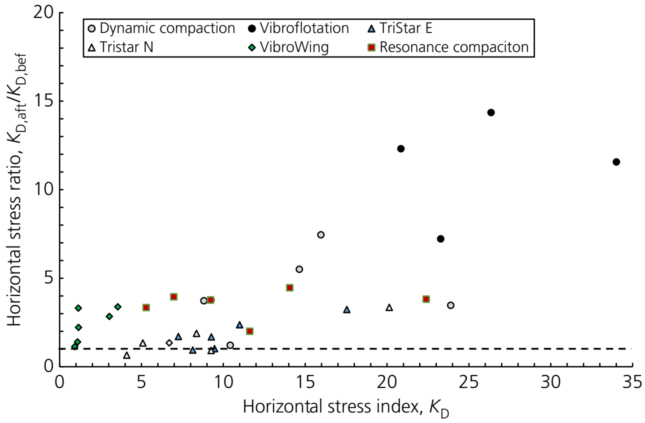

Figure 31. Horizontal stress index ratio as function of horizontal stress index prior to vibratory compaction

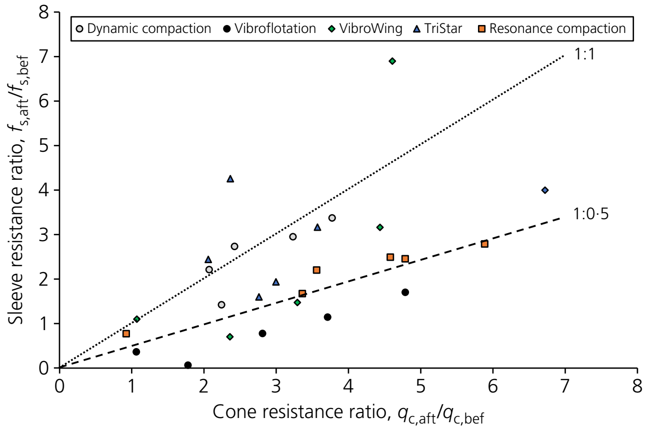

Figure 32. Comparison of cone resistance ratio with sleeve resistance ratio for five different deep vibratory compaction methods. Geometric average over 1 m depth intervals

prior to compaction for the different compaction methods employed.

With the exception of a few data points, all compaction methods showed an increase in sleeve resistance ratio, with values between 1 and 7. This trend was similar for all sites and for all compaction methods. It is not surprising that the highest increase in sleeve resistance was observed in loose soils, these having a low cone resistance (lower than 5 MPa). Consequently, in medium to dense soils, with a cone resistance exceeding about 10 MPa, high horizontal stresses exist prior to treatment and the increase in sleeve resistance is therefore low. In some cases with high cone resistance (>5 MPa), a loosening effect can even be observed.

A similar comparison was made for the DMT data and the results are summarised in Figure 31. The horizontal stress ratio is shown as a function of the horizontal stress index prior to treatment. With a few exceptions, the horizontal stress ratio increased by a factor of 1 to 4 up to a horizontal stress index of 10. At higher horizontal stress index values, a distinct increase in the horizontal stress ratio can be observed. This trend is contrary to the findings from the CPT data shown in Figure 30. This observation is surprising as soils with a high horizontal stress index prior to compaction are already likely to be dense and compaction would cause a smaller increase in horizontal stress. However, it should be noted that the high K_D values were measured primarily on one site where vibroflotation was used as the compaction method.

An interesting aspect of this study is the comparison of the increase in horizontal stress measured by sleeve resistance and cone resistance from CPT measurements. The results are summarised in Figure 32. It can be concluded that both the cone resistance and the sleeve resistance increased as a result of vibratory compaction. There is some scatter between different sites and compaction methods but the general trend is that the increase in horizontal stress measured by sleeve friction is consistent with the increase in cone resistance. The authors suggest the following relationship

13. $$\frac{f_{s,aft}}{f_{s,\,bef}} = R_h \frac{q_{c,aft}}{q_{c,bef}}$$

where R_h is an empirical factor ranging on average between approximately 0·5 and 1·0 (see Figure 32). Thus, it can be assumed that the increase in sleeve resistance is slightly smaller than the increase in cone resistance. The increase appears to depend to some extent on the vibratory compaction method. However, the number of data points is not sufficient to compare individual compaction methods.

The most important result of the present investigation is that, on all the investigated projects, horizontal stresses increased significantly as a result of soil compaction. The preloading effect caused by vibratory compaction can be expressed by the OCR. By definition, the OCR is the ratio between the maximum preloading stress and vertical effective stress after compaction and it is thus sensitive to variations in vertical effective stress. Especially at shallow depth, high OCR values and strong variations of OCR can occur. In some cases, OCR values <1 were obtained. Such values are not realistic, as can be determined from an inspection of cone resistance and lateral stress index measurements. Usually, OCR <1 can be expected in soil layers that are already dense prior to compaction. In other cases, surprisingly high values of the horizontal stress index were measured, resulting in unrealistically high OCR values. In order to avoid these strong variations, it is recommended to determine the preloading stress margin for design purposes.

Finally, it is recommended that both CPT and DMT measurements are used to determine the extent to which horizontal stresses increase in initial compaction trials. Thereby, significant savings can be made on vibratory compaction projects, with regard to settlement requirements and liquefaction.

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