# Effects of Vibratory Compaction

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ABSTRACT: Aspects governing the execution of vibratory compaction projects are discussed. The importance of careful planning and implementation is emphasised. Recent developments of vibratory compaction methods are presented. Design charts help to assess the suitability of soils for vibratory compaction. A hypothesis is advanced considering various factors governing the emission of vibrations from a vertically vibrating probe. It is shown that as a result of vibratory compaction, horizontal stress increase significantly and changes the stress conditions, which result in a permanent overconsolidation effect. Overconsolidation due to vibratory soil compaction is at present not taken into account in geotechnical design. The findings are illustrated with results from field measurements.

## 1 SOIL COMPACTION METHODS

Soil compaction requires geotechnical competence and careful planning on the part of the design engineer. Also the contractor must have experience from the use of vibratory compaction equipment. Each compaction method has its advantages and limitations, and thus optimal application conditions. The selection of the most suitable method depends on a variety of factors, such as: soil conditions, required degree of compaction, type of structure to be supported, maximum depth of compaction, as well as site-specific considerations such as sensitivity of adjacent structures or installations, available time for completion of the project, competence of the contractor, access to equipment and material etc.

It is increasingly common to award soil compaction projects to the lowest bidder. However, after completion of a project, this may not always turn out to be the best choice, as a too low price increases the risk that the required compaction effect is not achieved, or that the time schedule is exceeded. The compaction effect depends on several factors, which can be difficult to verify after compaction. It is thus important to apply high standards of field monitoring, quality control and site supervision during all phases of the project.

Soil compaction is a repetitive process and much can be gained from properly planned and executed compaction trials. The most important factors, which should be established and verified at the start of the project, are:

- required compaction energy at each compaction point,
- spacing between compaction points,
- duration of compaction in each point,
- ground settlements due to compaction (in compaction point and overall settlements),
- time interval between compaction passes (time for reconsolidation of soil),
- verification of the achieved compaction effect by field measurements and penetration tests,
- potential increase of compaction effect with time after compaction,
- ground vibrations in the vicinity (effects on adjacent structures and installations),
- effect on stability of nearby slopes or excavations,
- monitoring of equipment performance and review of safety aspects.

## 2 VIBRATORY COMPACTION METHODS

A variety of soil compaction methods have been developed and these are described in detail in the geotechnical literature, e.g. Mitchell (1982), Massarsch (1991), Massarsch (1999), and Schlosser (1999). In this paper, emphasis is placed on new compaction concepts. In particular, the effect of vibratory compaction on the compacted soil and of vibration propagation from the compaction probe to the surrounding soil is discussed.

Vibratory compaction methods can be classified according to the location of energy transfer from the source to the soil.

### 2.1 *Vibratory Equipment*

The first vibrators, which were developed for pile driving applications, came into use some 60 years ago in Russia. During the past decade, powerful and sophisticated vibrators have been developed for specific foundation applications, such as pile and sheet pile driving and soil compaction. These vibrators are usually hydraulically driven. Modern vibrators can generate centrifugal forces of up to 4 000 kN. The maximum displacement amplitude can exceed 30 mm. These enhancements in vibrator performance have opened new applications to the vibratory driving technique, Massarsch (1999). Recently, vibrators with variable frequency and variable static moment (displacement amplitude) have been introduced. These vibrators can be controlled electronically to adapt the vibration frequency and vibration amplitude to the varying compaction requirements.

### 2.2 *Surface Vibratory Compaction*

The compaction energy can be applied to the soil at the ground surface by steady state vibrations. The highest compaction effect is achieved in a zone close to the ground surface, but decreases usually with depth. The effective depth of compaction is difficult to assess and is influenced by a variety of factors, such as the geotechnical conditions, the type and quality of equipment, compaction procedure etc. In general, it can be assumed that the depth of influence corresponds to the diagonal length of the compaction plate. The densification effect decreases approximately linearly with depth below the centre of the compaction plate. The degree of compaction is affected by the dynamic and static force, the number of compaction cycles and the vibration frequency.

Surface compaction can be carried out with a heavy steel plate, activated by one or several powerful vibrators, cf. Fig 1.

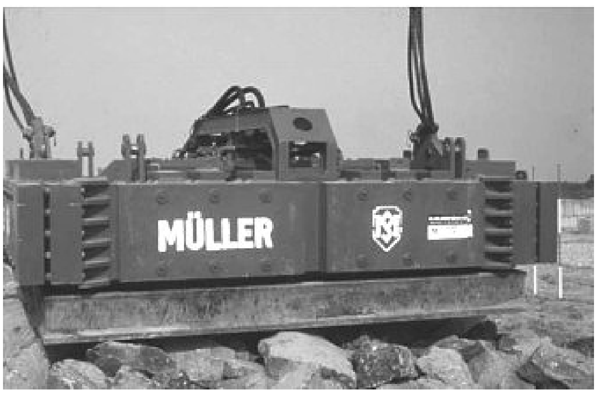


Figure 1. Heavy vibratory compaction plate

This compaction method is being used increasingly, especially for marine and off-shore applications and has become economical due to the availability of powerful hydraulic vibrators.

Extensive investigations have been performed in connection with off-shore soil compaction projects, Nelissen (1983). It was found that the compaction effect depended on the vibration frequency and the dynamic interaction of the plate-soil system. Based on field trials on land and on the seabed, the optimal compaction parameters could be established.

Surface compaction is often used in combination with deep vibratory compaction, in order to increase the densification effect in a zone from the ground surface to approximately 3 m depth.

### 2.3 *Deep Vibratory Compaction*

The most efficient way to densify deep deposits of granular material is to introduce the compaction energy at depth, i.e in the soil layer that requires densification. The energy can either be applied by vertical or horizontal vibration, or a combination thereof. Several deep compaction methods have evolved during the past decades and are used for a variety of applications.

#### 2.3.1 *Vibro-Rod*

The Vibro-Rod method exists in several different variations, (Massarsch, 1991 and Schlosser, 1999). A compaction probe is inserted in the ground with the aid of a heavy, vertically oscillating vibrator, attached to the upper end of the compaction rod. The insertion and extraction process is repeated several times, thereby gradually improving the soil. Different types of compaction probes have been developed, ranging from conventional tubes or sheet pile profiles to more sophisticated, purpose-built tools. The Vibro-Rod method was initially developed in Japan, where a slender rod was provided with short ribs. The rod was vibrated, using conventional (often electric) vibratory pile driving equipment.

The so-called VibroWing method was developed in Sweden and is a further improvement of the Vibro-Rod method. An up to 15 m long steel rod is provided with about 0.8 to 1,0 m long radial wings, at a vertical spacing of approximately 0.5 m. The vibratory hammer is usually operated from a piling rig, Fig. 2. The frequency of the vibrator can be varied to fit the conditions at a particular site. The duration of vibration and rate of withdrawal of the probe is chosen, depending on the permeability of the soil, the depth of the soil deposit and the spacing between compaction points. The duration of compaction, the grid spacing and number of probe insertions are chosen empirically or are determined by field tests. The maximum depth of compaction depends on the capacity of the vibrator and size of the piling rig and is on the order of 10 to 15 m.

Figure 2. VibroWing method

a) MRC compaction equipment

b) MRC compaction probe

Figure 3. Resonance compaction method using variable frequency vibrator and flexible compaction probe

### 2.3.2 *Resonance Compaction*

The resonance compaction method (MRC) is similar to the Vibro-Rod method but uses the vibration amplification effect, which occurs when the vibrator, the compaction probe and the soil are vibrating at resonance. In this state, ground vibrations are strongly amplified and the efficiency of vibratory soil densification increases, cf. Fig. 3. A heavy vibrator with variable frequency is attached to the upper end of a flexible compaction probe. The probe is inserted into the ground at a high frequency in order to reduce the soil resistance along the shaft and the toe. When the probe reaches the required depth, the frequency is adjusted to the resonance frequency of the vibrator-soil system, thereby amplifying ground vibrations.

The probe is oscillated in the vertical direction and the vibration energy is transmitted to the surrounding soil along the entire probe surface. At resonance, the soil layer vibrates "in phase" with the compaction probe. At this state, vibration energy is transferred very efficiently from the vibrator to the compaction probe and to the surrounding soil, as the relative movement between the compaction probe and the soil is very small. This aspect is an important advantage, compared to conventional vibratory compaction methods. The resonance frequency depends on the dynamic and static mass of the vibrator, the mass and dynamic properties of the compaction probe and on the soil conditions. At resonance, which occurs typically between 10 and 20 Hz, the required compaction energy decreases. In this phase of soil compaction, the oil pressure of the vibrator decreases, which reduces fuel consumption and wear on the vibratory equipment.

The compaction probe is an essential component of the MRC system and is designed to achieve optimal transfer of compaction energy from the vibrator to the soil, c.f. Fig. 3a.

The probe profile has a double Y-shape, which increases the compaction influence area. Reducing the stiffness of the probe further increases the transfer of energy to the surrounding soil. This is achieved by openings in the probe, cf. Fig. 3 b. The openings also have the advantage of making the probe lighter and thereby providing larger displacement amplitude during vibration, compared to a massive probe of the same size.

Figure 4 shows how the vertical vibration velocity, measured on the ground surface, varies as a function of the vibration frequency. During probe penetration and extraction, a high vibration frequency (around 30 Hz) is used, which does not cause significant ground vibrations. During compaction, the speed of the vibrator is reduced to the resonance frequency of the probe-soil system. At resonance, ground vibrations are strongly amplified, by a factor of 3 to 4. The probe and the surrounding soil vibrate in phase, resulting in an efficient transfer of compaction energy.

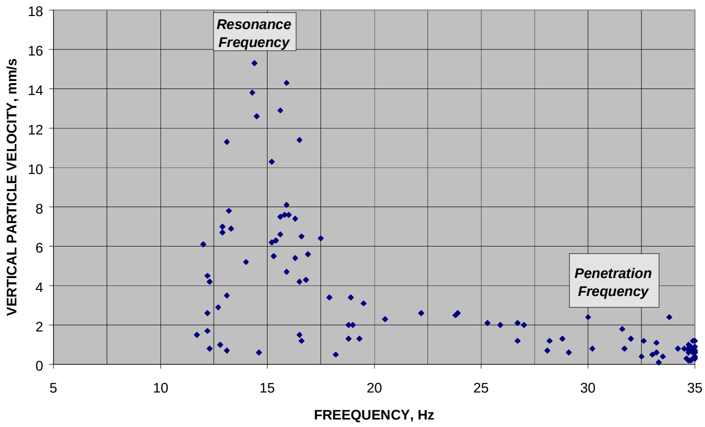


Figure 4. Vertical ground vibration velocity at a distance of 4 m from the compaction probe during probe penetration and resonance compaction

The dynamic response of the soil deposit during compaction can also be used to monitor the compaction effect. With increasing densification of the soil layers, the resonance compaction frequency rises. Also the ground vibration velocity increases and soil damping is reduced. With the aid of vibration sensors placed on the ground surface, the change in wave propagation velocity can be determined, which reflects the change of soil stiffness and soil strength, Massarsch (1995).

### 2.3.3 *Vibroflotation*

This method was invented in Germany more than 60 years ago, and its development has continued mainly there and in North America, where it was introduced in the 1940's. The equipment consists of three main parts: the vibrator, extension tubes and a supporting crane, Fig. 5.

Figure 5. Vibroflotation equipment with water jetting

Vibroflotation is the most widely used deep compaction method and extensive experience has been accumulated over the past 30 years. The vibrator is incorporated in the lower end of a steel probe. The vibrator rotates around the vertical axis to generate horizontal vibration amplitude. Vibrator diameters are in the range of 350 to 450 mm and the length is about 3 - 5 m, including a special flexible coupling, which connects the vibrator with the extension tube.

Units developing centrifugal forces up to 160 kN and variable vibration amplitudes up to 25 mm are available. Most usual Vibroflotation probes are operating at frequencies between 30 and 50 Hz. The extension tubes have a slightly smaller diameter than the vibrator and a length dependent on the depth of required penetration.

The Vibroflotation is slowly lowered to the bottom of the soil layer and then gradually withdrawn in 0.5-1.0 m stages. The length of time spent at each compaction level depends on the soil type and the required degree of compaction. Generally, the finer the soil, the longer the time required achieving the same degree of compaction. In order to facilitate penetration and withdrawal of the equipment, water jetting is utilized with a water pressure of up to 0.8 MPa and flow rates of up to 3000 l/min. The water jetting transports the fine soil particles to the ground surface and by replacing the fines with coarse material, well-compacted soil columns are obtained.

There is a fundamental difference between the Vibro-rod and the vibroflotation system. In case of the Vibro-rod (and the resonance compaction system), compaction is caused by vertically polarised shear waves, which propagate as a cylindrical wave front from along the entire shaft of the compaction probe. In addition, also horizontal compression waves are emitted, as will be discussed later. In the case of resonance compaction, a significant amount of energy can be generated at the lower end of the compaction probe (Krogh and Lindgren, 1997).

In the case of vibroflotation, the soil is densified as a result of horizontal impact of the compaction probe at the lower end. The compaction action is primarily in the lateral direction and gives rise to compression waves. Thus, it is not possible to create soil resonance using a Vibroflotation probe. The compaction zone is limited to the length of the compaction probe and the soil is improved in steps during extraction of the probe.

## 3 COMPACTABILITY OF SOILS

An important question to be answered by the geotechnical engineer at every soil compaction project is, to which degree a soil can be improved by vibratory compaction and the required compaction. Mitchell (1982) classified soils with respect to the grain size distribution. Most granular soils with a content of fines (particles < 0,064 mm) less than 10 % can be compacted by vibratory and impact methods. The disadvantage with an assessment of compaction based on the grain size distribution is that a large number of soil samples are required to obtain a realistic picture of the geotechnical conditions. Due to the loose state of the soil prior to compaction, it is difficult and costly to retrieve representative soil samples. The compaction is also affected by soil layering, which may not be apparent from the inspection of a limited number of soil samples. It is therefore preferable to assess the compatibility by the cone penetration test, CPT.

With CPT, detailed and reliable information of the soil strength and the soil layering is obtained. Massarsch (1991) has proposed that the compactability of soils can be based on the cone resistance and on the friction ratio, Fig. 6.

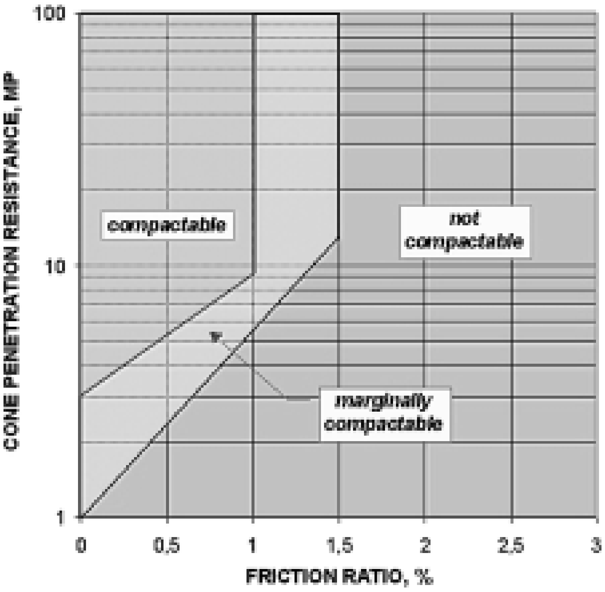


Fig. 6. Soil classification for assessment of deep compaction based on CPT (Massarsch, 1991).

The diagram assumes uniform soil conditions. Layers of silt and clay can reduce, however, the effectiveness of the compaction. The CPTU, where the excess porewater pressure is measured, can also be used to determine the soil stratification and the occurrence of less permeable silt and clay layers.

Fig. 7 presents the classification boundaries proposed by Massarsch (1991) together with soil type boundaries proposed by (Eslami and Fellenius, 1997; 2000) in a soil classification chart with the cone stress as a function of the sleeve friction.

The numbered areas in Fig.7 denote soil type, as follows:

1 = Very Soft Clays or Sensitive Soils
2 = Clay and/or Silt
3 = Clayey Silt and/or Silty Clay
4b = Sandy Silt and Silt
4a = Fine Sand and/or Silty Sand
5 = Sand to Sandy Gravel

There is good agreement with between the two charts, Fig. 6 and 7. However, Fig. 7 is preferred as it covers a wider range of soils and also indicates soil type.

## 4 COMPACTION MECHANISM IN SAND

Although extensive information is available in the literature concerning the application of different soil compaction methods, little is mentioned about the mechanism, which causes the rearrangement of soil particles and densification.

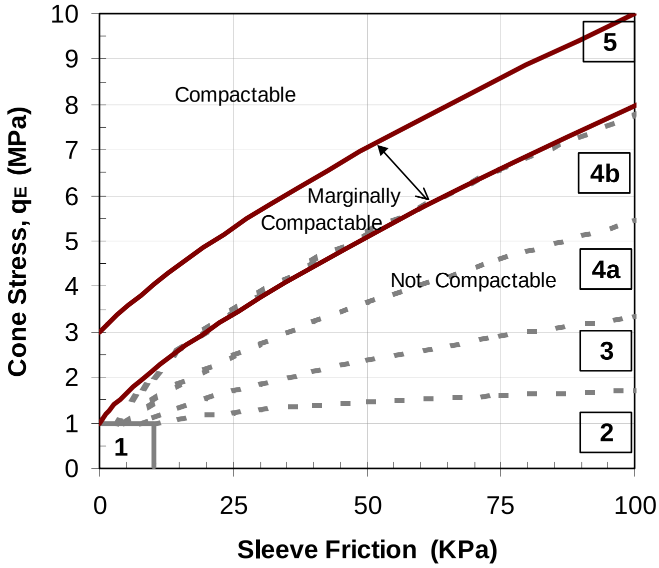


Figure 7. Soil classification for deep compaction with soil type boundaries per Eslami-Fellenius (1997; 2000)

An attempt is made to describe the factors, which are considered important for the densification process. To obtain a better understanding of the compaction process, it is necessary to consider the stress strain behaviour of granular soils.

### 4.1 *Energy transfer from compaction probe to soil*

Different types of energy sources can be used for soil densification. However, the basic mechanism, governing the energy transfer from the vibrating source to the surrounding soil, is in principle similar. The resonance compaction probe is used as an example, as the vibration energy is mainly transmitted to the surrounding soil along the shaft of the probe. However, a similar approach can also be used for assessing other compaction methods.

An important question for the prediction of ground vibrations caused by vibratory compaction is, whether there exists an upper limit to the vibration energy, which can be transmitted from the probe to the surrounding soil. In the plastic zone at the interface between the soil and the compaction probe, the maximum shear stress can approximated by

$$\tau_f = v_{\max} Z_s = v_{\max} C_s^* \rho \qquad (1)$$

where $v_{max}$ is the maximum particle vibration velocity, $Z_s$ is the soil impedance and $\rho$ is the bulk density. The soil impedance is the product of the strain-dependent shear wave velocity, $C_s^*$ and the soil density $\rho$. Similar relationships can be used to assess the energy transfer at the base of the probe, Bodare and Orrje (1988). According to Eq. 1, the maximum vibration velocity, which can be transmitted to the soil in the plastic zone, can be estimated from

$$v_{\max} = \frac{\tau_f}{C_s^{*}\ \rho} \tag{2}$$

It should be noted that the shear wave velocity $C_s^*$ at large strains is significantly lower than the small-strain shear wave velocity, which is determined by seismic field tests. In Fig. 8, the reduction of the shear modulus with shear strain is shown Massarsch (1983). The tests were performed in a resonant column apparatus on a sample of dry sand of medium density. The shear modulus at different strain levels is divided by its maximum value to obtain a modulus reduction factor. From the shear modulus and the soil density, the shear wave velocity can be readily determined. The shear wave reduction factor is the square root of the shear modulus reduction factor. At a strain level of about 1 %, where the sand can be assumed to behave plastically, the shear wave velocity is only about 25 % of the maximum value. In the case of a medium dense sand, the shear wave velocity decreases thus from around 150 m/s to about 40 m/s. Thus, also the soil impedance decreases in the plastic zone – a fact that is generally neglected. This strain effect must be taken into consideration when assessing energy transfer from a vibration source to the surrounding soil.

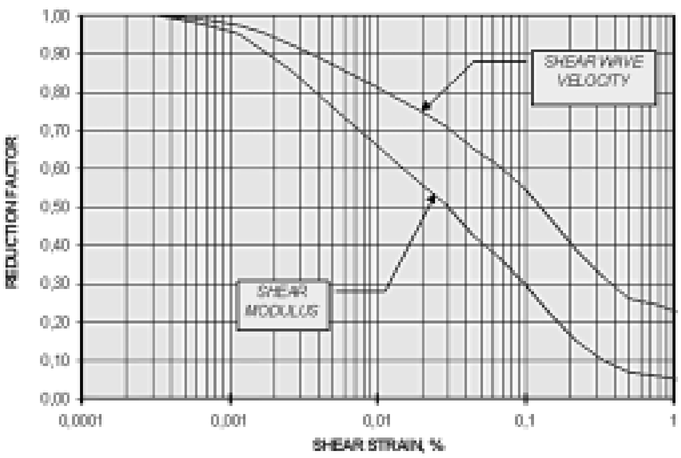


Figure 8. Reduction of shear modulus and shear wave velocity as a function of shear strain in a saturated sand

Assuming medium dense sand, a shear wave velocity at large strain of $C_s^*$ of 40 m/s and a bulk density of 2 t/m$^3$, it is possible to estimate from Eq. 2 the maximum vibration velocity which can be transmitted to the surrounding soil. The shear strength can be estimated from e.g. sleeve friction measurements using the CPT, and is in medium dense sand typically on the order of 100 kPa. The calculated maximum particle vibration velocity, which can be transmitted to the soil, is thus 1.2 m/s. This maximum vibration velocity can now be used to estimate vibration attenuation from the compaction probe.

An interative process can be used to estimate the shear strain level g, using the following relationship

$$\gamma = \frac{v_{\max}}{C_s^{*}} \tag{3}$$

The shear strain level adjacent to the compaction probe is approximately 1,25 % and is in good agreement with the assumed strain value. Clearly, the soil in the vicinity of the compaction probe is in the plastic state and it would be erroneous to use the small-strain shear wave velocity for calculating the soil impedance.

### 4.2 *Vibration propagation from the source to the surrounding soil*

Adjacent to a vertically oscillating compaction probe, three compaction zones can be identified:

1. elastic zone: where the shear strain level is below 10-3 %, and no permanent deformations can be expected,
2. elasto-plastic zone: where the strain level ranges between 10-3 and 10-1 %, where some permanent deformations will occur, and
3. plastic zone: where the soil is in a failure condition and is subjected to large strain levels >10-1 %.

These three zones are indicated schematically in Fig. 9. Also shown is the assumed attenuation of the vibration velocity (particle velocity) of the cylindrical wave front in the ground. In the plastic zone the vibration velocity is relatively constant and limited by the shear strength of the soil. The vibration amplitude attenuates rapidly in the elasto-plastic zone. In the plastic, and the elasto-plastic zone, the wave propagation velocity is strain-dependent and increases with distance from the energy source. In the elastic zone, the wave propagation velocity is constant, due to the limitation by the shear strength of the soil.

### 4.3 *Horizontal ground vibrations*

In the geotechnical literature is often assumed that in the case of vertically oscillating probes or piles, only vertical ground vibrations occur. However, in addition to a vertically polarised shear wave, which is emitted along the shaft of the compaction probe, also horizontal vibrations are generated. These are caused by the friction between the compaction probe and the soil, and cause horizontal stress pulses. These are directed away from the probe during its downward movement. The horizontal stress changes result in a compression wave and increased lateral earth pressure. This aspect will be discussed in the following sections.

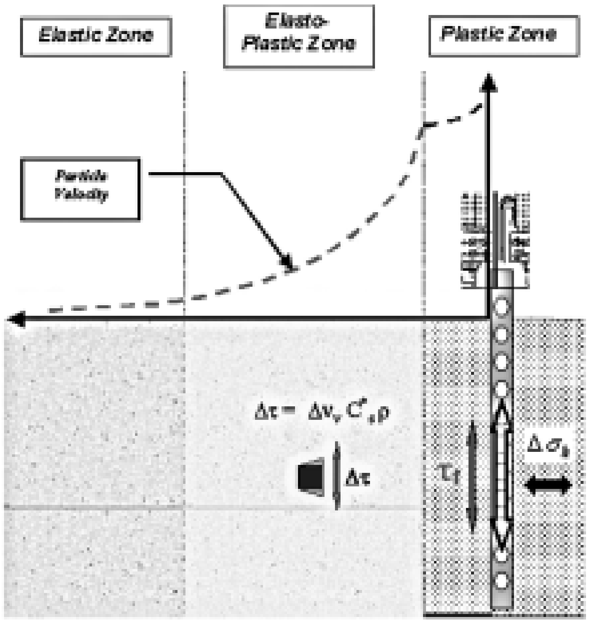


Figure 9. Transfer of vibration energy from the compaction probe to the surrounding soil

Fig. 10 shows the results of field measurements during vibratory compaction using the MRC system, Krogh & Lindgren (1997). Horizontally oriented vibration sensors (geophones) were installed at different levels below the ground surface, 2,9 m from the centre of the compaction probe. At the time of the vibration measurements, the tip of the compaction probe had passed the lowest measuring point.

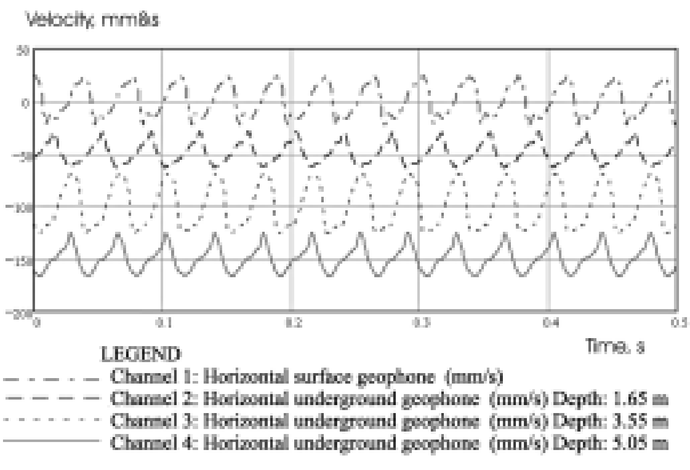


Figure 10. Horizontal vibration amplitude measured during resonance compaction, from Krogh & Lindgren (1997)

In spite of the vertically oscillating compaction probe, strong horizontal vibrations are generated. These were of the same order of magnitude as the vertical vibration amplitudes. It will be shown that as a result of vibratory compaction, the horizontal stresses increase in the soil. This compaction effect is of great importance as it changes permanently the stress conditions after compaction.

## 5 INCREASE OF LATERAL STRESS

An aspect of vibratory compaction, which is not generally appreciated, is the increase of the lateral stresses in the soil due to vibratory compaction. Sand fills (such as hydraulic fill) are usually normally consolidated prior to compaction. The lateral earth pressure increases significantly as a result of vibratory compaction, as shown by the measured sleeve resistance, Massarsch and Fellenius (2002). The sleeve friction $f_s$ can be approximated from Equation 4

$$f_s = K_0\ \sigma_v'\ \tan\left(\phi_a'\right) \tag{4}$$

where $\sigma_v'$ = effective vertical stress, $K_0$ = earth pressure coefficient, $\phi_a'$ = the effective sleeve friction angle at the soil/CPT sleeve interface. The ratio between the sleeve friction after and before compaction, $f_{s1}/f_{s0}$ can be calculated from Eq. 5

$$\frac{f_{s1}}{f_{s0}} = \frac{K_{01}\ \sigma'_{v1}\ \tan\left(\phi'_{a1}\right)}{K_{00}\ \sigma'_{v0}\ \tan\left(\phi'_{a0}\right)} \tag{5}$$

where $f_{s0}$ = sleeve friction before compaction, $f_{s1}$= sleeve friction after compaction, $K_{00}$ = coefficient of earth pressure before compaction (effective stress), $K_{10}$ = coefficient of lateral earth pressure after compaction (effective stress), $\sigma'_{v0}$= vertical effective stress before compaction, $\sigma'_{v1}$= vertical effective stress after compaction, $f'_{a0}$ = sleeve friction angle before compaction, $f'_{a1}$ = sleeve friction angle after compaction.

If it is assumed that the effective vertical stress, $\sigma_v'$, is unchanged by the compaction, the ratio of the lateral earth pressure after and before compaction, $K_{01}/K_{00}$ can then be estimated from the relationship according to Eq. 6

$$\frac{K_{01}}{K_{00}} = \frac{f_{s1}\ \tan\left(\phi'_{a0}\right)}{f_{s0}\ \tan\left(\phi'_{a1}\right)} \tag{6}$$

Equation 6 shows that the earth pressure coefficient is directly affected by the change of the sleeve friction and of the friction angle of the soil. The horizontal stresses can vary significantly within the compacted soil. The highest horizontal stresses are expected close to the compaction points and decrease with increasing distance. The initial stress anisotropy initiates a stress redistribution, which can to some extent explain the change of soil strength and of the stiffness with time.

### 5.1 *Case History*

Extensive field investigations were carried out in connection with a major land reclamation project, Fellenius and Massarsch (2001). CPTU tests were performed in a loose deposit of hydraulic fill, as well as at different time intervals following resonance compaction. Figure 11 shows the results of cone resistance and sleeve friction measurements prior to, and after compaction. The average of several CPT measurements has been used to determine the increase of cone resistance and sleeve friction.

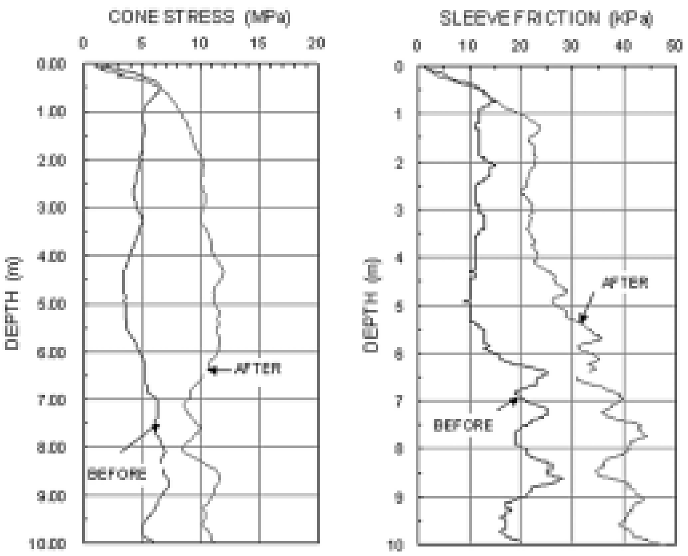


Fig. 11. Filtered average values of cone stress and sleeve friction from before and after compaction, Fellenius and Massarsch (2001).

The cone stress and the sleeve friction increased in the sand deposit as a result of the vibratory compaction. On average, the cone stress is doubled or higher, indicating efficient densification of the sand fill.  The specifications requirement of a cone stress of at least 10 MPa was satisfied. The effect of vibratory soil compaction on the stress conditions is also evidenced by increase in sleeve friction, on average about 2.5 times, which is about the same increase ratio as that of the cone stress. Thus the friction ration after compaction remained almost unchanged. This observation is in good agreement with experience reported in the literature and suggests, that in these cases, the horizontal stress has been increased.

The friction angle after compaction was not determined, but it is assumed that it is about 36°, which results in a sleeve friction ratio of 0.8. Inserting this ratio and the ratio of sleeve friction of 2.5 into Eq. 6 gives a ratio of earth pressure coefficient of 2.0.  Because the earth pressure coefficient prior to compaction, $K_{00}$, can be assumed to be 0.5, the earth pressure coefficient after compaction, $K_{01}$, is 1.0.

## 6 OVERCONSOLIDATION EFFECT

For many geotechnical problems, knowledge of the overconsolidation ratio is important. Empirical relationships have been proposed for the coefficient of lateral earth pressure of normally and overconsolidated sands and for the overconsolidation ratio, OCR,

$$\frac{K_{01}}{K_{00}} = OCR^m \tag{7}$$

where $K_{00}$ and $K_{01}$ are the coefficient of lateral earth pressure before and after compaction, respectively and m is an empirically determined parameter. Schmertmann (1985) recommended m = 0.42, based on compression chamber tests. Mayne and Kulhawy (1982) suggested $m = 1 - \sin(\phi)$. Jamiolkowski et al (1988) found that the relative density, $D_R$, influences m and that m varied between 0.38 and 0.44 for medium dense sand ($D_R$ = 0.5). Figure 12 illustrates the relationship from Eq. 7, which shows that even a modest increase of the lateral earth pressure increases the overconsolidation ratio significantly.

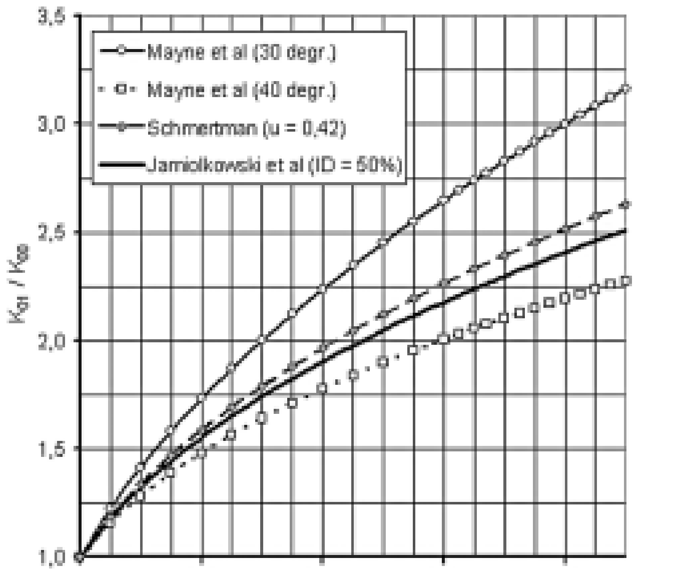


Fig. 12. Relationship between overconsolidation ratio and ratio of earth pressure coefficients for overconsolidated and normally consolidated sand, Fellenius and Massarsch (2001).

Sleeve resistance measurements reported in the literature and the above shown field tests show that the ratio $f_{s12}$ / $f_{s01}$ varies between 1,5 and 3,5, Massarsch and Fellenius (2002). If it is assumed that the effective friction angle increases due to compaction from on average 30 to 36 degrees, $K_{01}/K_{00}$ ranges according to Eq. 6 between 1.2 – 1.8. An average value of $K_{01}/K_{00}$ = 1.6 yields an overconsolidation ratio OCR according to Eq. 7 and Fig. 12 in the range of 2.5 – 4.0. This overconsolidation effect, which is generally neglected, is important for the analysis of many geotechnical problems.

### 6.1 *Change of Stress Conditions*

The stress conditions in loose, water-saturated sand will undergo a complex change of stress conditions during vibratory compaction. Energy is transmitted from the compaction probe to the surrounding soil at the tip as well as along the sides of the probe. The transmitted vibration energy depends on the capacity of the vibrator, the shear resistance along the probe and on the shape and size of the probe.

At the beginning of compaction of loose, water-saturated sand, the stress conditions will correspond to that of a normally consolidated soil. When the soil is subjected to repeated, high-amplitude vibrations, the pore water pressure will gradually build up and the effective stress is reduced. During the initial phase of compaction, the soil in the vicinity of the compaction probe is likely to liquefy. Whether or not liquefaction will occur, depends on the intensity and duration of vibrations and the rate of dissipation of the excess pore water pressure. If the soil deposit contains less permeable layers (e. g. silt and clay), these will increase the liquefaction potential. At liquefaction, the effective stresses and thus the shear strength of granular soils are zero. Although the probe continues to vibrate, the soil will not respond as only little vibration energy can be transmitted from to the soil. With time, the excess pore water pressure will start to dissipate. The rate of reconsolidation will depend on the permeability of the soil (and interspersed layers).

Figure 13 illustrates the change of effective stresses in a dry granular soil, which is subjected to repeated compaction cycles. During vibratory compaction, high oscillating centrifugal forces (loading and unloading) are generated (up to 2,000 kN) that temporarily increase and decrease the vertical and the horizontal effective stress along the compaction probe and at its tip. The initial stresses of the normally consolidated soil correspond to point (A). During the first loading cycle, the stress path follows the $K_{00}$-line to stress level (B). Unloading to stress level (C) occurs at zero lateral strain and horizontal stresses remain locked in. Each reloading cycle increases the lateral earth pressure, which can reach the passive earth pressure. At the end of compaction, stress point (D) is reached. The vertical overburden pressure is the same after compaction but the horizontal effective stresses have been increased. The lateral earth pressure after compaction can reach the passive value, $K_p$. The dynamic compaction has thus caused preconsolidation and increased the horizontal effective stress. The increase of the sleeve friction and the high lateral earth pressure as measured in the above presented case history, Fig. 11 can thus be explained by Fig. 13.

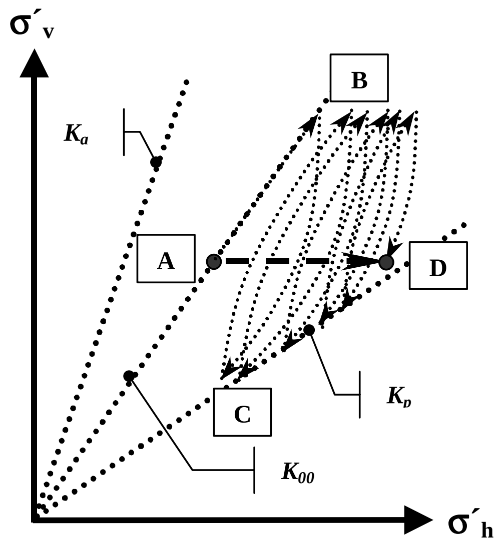


Fig. 13. Stress path of soil in the vicinity of a compaction probe during tow compaction phases; before (A), during first compaction phase (B, C, D and E) and during second compaction phase (E, F, G).

In the opinion of the author, Fig. 12 illustrates important aspects of vibratory compaction. The change of the stress conditions from a normally consolidated state to an overconsolidated state is influenced by several factors, such as the compaction method, the state of stress state prior to compaction and the strength and deformation properties of the soil. At MRC compaction, the vertically oscillating probe generates (as a result of friction between the probe and the soil) high, horizontally oscillating force, which is responsible for the high lateral earth pressure in the soil after compaction.

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## 8 SUMMARY

New developments in vibratory compaction have been made possible as a result of more powerful and sophisticated equipment. In spite of this positive development, many vibratory compaction projects are designed and executed without sufficient knowledge and understanding of the principles, which govern deep soil compaction.

The process of soil compaction using the Vibro-rod system is fundamentally different to that of Vibroflotation. In case of the Vibro-rod, compaction is due to shear waves and compression waves, which are transmitted from the shaft of the compaction probe to the surrounding soil. The Vibroflotation method uses compression waves to compact the soil. The resonance compaction method uses the vibration amplification effect to increase compaction efficiency.

Reliable charts are available to assess the compactability of soils. These are based on results of cone penetration tests, CPT with sleeve friction measurements.

A hypothesis is proposed which explains the mechanism of energy transfer from the compaction probe to the surrounding soil. An upper limit exists of the vibration amplitude, which can be transmitted in the plastic zone adjacent to the compaction probe.

As a result of vibratory compaction, high lateral stresses are created, which cause a permanent overconsolidation effect. This aspect should be taken into consideration when calculating settlements in vibratory-compacted soils.

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