# GEO TECH -II

# USE OF VIBRO COMPACTION TO INCREASE SHEAR STRENGTH OF GRANULAR SOIL

## UW-11-CE-BSC-010

**DATE OF SUBMISSION**
**15TH JAN 2014**

**SUBMITTED TO:**

**BRIG (R.) DR.NASRULLAH ABEER**

**SUBMITTED BY:**

**KHALID REHMAN**

**UW-11-CE-BSC-010**

**DATE OF SUBMISSION**

**15th-JAN-2014**

**DEPARTMENT OF CIVIL ENGINEERING**

# ABSTRACT

Planning and execution of deep vibratory compaction of natural and man-made fills requires recognition of fundamental soil aspects, such as the compactability of soils. Design is usually based on cone penetration tests and carried out with equipment specially developed for deep vibratory compaction, in particular, using variable frequency vibrators. The features of different, purpose-built types of compaction probes are described and the most important factors governing the compaction process are presented, such as vibration frequency—an important parameter as it influences probe penetration—and can enhance compaction by means of resonance effects during the compaction phase. Vibratory compaction generates lateral stresses, which result in a permanent increase of the horizontal earth pressure and over consolidation.

## ➢Introduction:

Vibro-compaction is a ground improvement method that uses a specialized vibrating probe for in-situ subsurface compaction of loose sandy or gravelly soils at depths beyond which surface compaction efforts are effective(see Figure 14-6). The vibrating probe densifies loose granular, cohesionless soils by using mechanical vibrations and, in some applications, water saturation to minimize the effective stresses between the soil grains which then allows the soil grains to rearrange under the action of gravity into a denser state.

Generally, vibro-compaction can be used to achieve the following enhanced soil performance or properties:

- Increased soil bearing capacity
- Reduced foundation settlements
- Increased resistance to liquefaction
- Compaction to stabilize pile foundations driven through loose granular materials
- Densification for abutments, piers and approach embankment foundations
- Increased shear strength
- Reduced permeability

- Filling of voids in treated areas

The vibrator is hung from a crane cable or, in some instances; it is mounted to leads in a similar fashion as foundation drilling equipment. The vibrator penetrates under its self-weight (or crowd of the machine if mounted in leads) and, at times, with assistance from the action of water jets. The goal is that the vibration and water imparted to the soils transforms the loose soils to a more dense state.

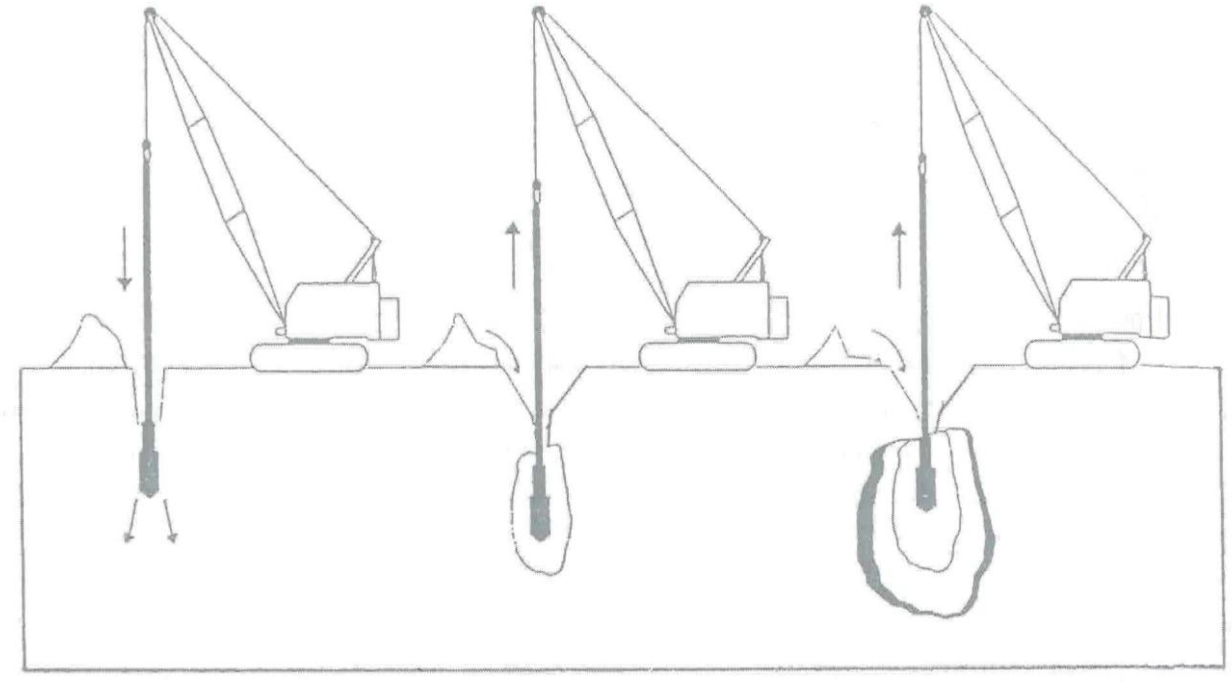


**Fig. (14-6)**

# ➢COMPACTABILITY OF SOILS

One of the most important questions to be answered by the geotechnical engineer is whether or not—and to which degree—a soil deposit can be improved by dynamic methods (vibratory or impact compaction). Mitchell (1982) identified suitable soil types according to grain size distribution and indicated that most coarse-grained soils with a "fines content" (amount of particles smaller than 0.06 mm, Sieve #200) below 10 % can be compacted by vibratory and impact methods. However, compaction assessment based on grain-size curves from sieve analysis has the disadvantage that, in order to obtain a realistic picture of the geotechnical conditions, a large number of soil samples and sieve analyses is required—larger than what is usually considered justifiable for a routine foundation project Going back to a site in order to obtain additional samples is impractical due to time constraints. Moreover, obtaining representative soil samples may prove to be difficult and costly because the soils at such sites are usually loose and water-saturated. Moreover, soil lenses and layers of importance for the assessment may not be evident from the inspection of soil samples obtained intermittently. It is therefore preferable to base the assessment of compactability on results of the CPT, as these measurements present continuous soil profiles reflecting variations in soil strength and compressibility, and, in the case of the piezocone, also variations in hydraulic conductivity of the soil.

Massarsch (1991) proposed that the compactability of soils can be classified as “compactable”, “marginally compactable”, and “not compactable”. Figure 1 presents a conventional soil classification chart with the friction ratio along the abscissa and the cone resistance (qt) along the ordinate. (It should be noted that the diagram assumes homogeneous soil conditions. Layers of silt and clay can inhibit the dissipation of excess pore pressures and, therefore, reduce the compaction effectiveness).

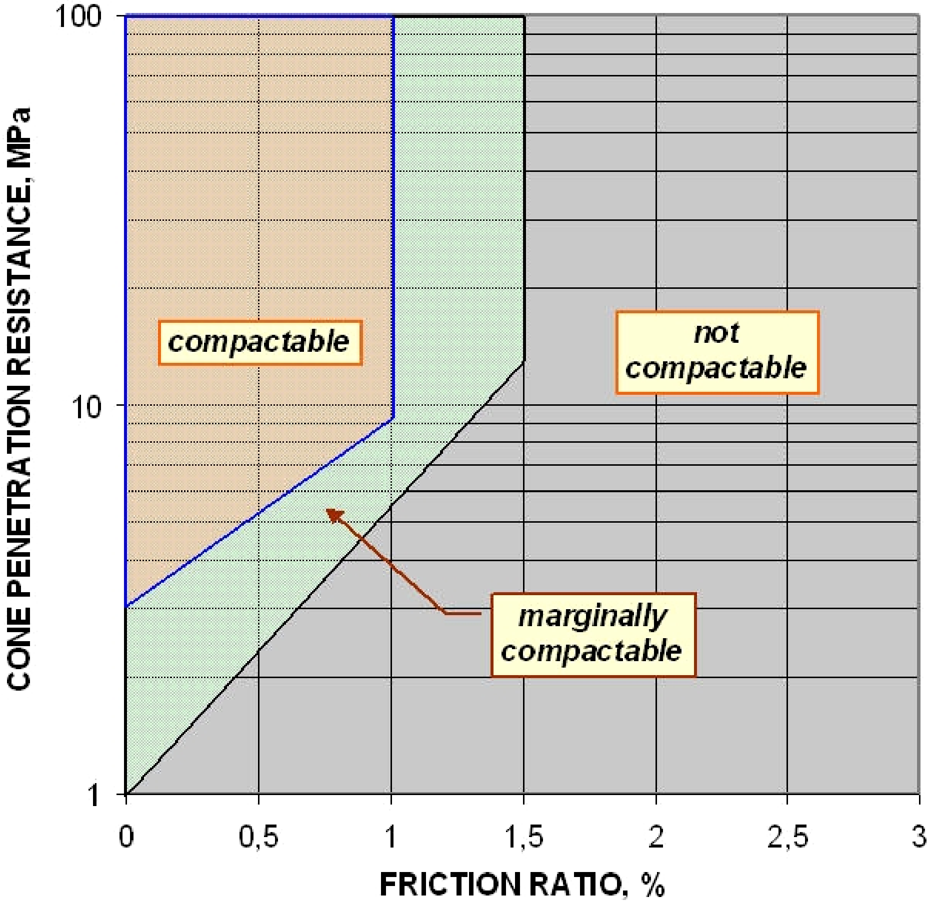


*Fig. 1. Soil classification for deep compaction based on CPT data. After Massarsch, (1991).*

# ➢EXECUTION OF DEEP VIBRATORY COMPACTION

The vibratory compaction process consists of the following three elements, which need to be adapted to the site conditions and densification requirements, in order to achieve optimal performance:

- **Compaction equipment**: compaction probe, vibrator and power pack, and base machine.
- **Compaction process**: compaction point grid and spacing, vibration frequency, and mode of probe insertion and extraction.
- **Process control and monitoring**: production control and verification of densification effect. The main elements of vibratory compaction equipment are shown in Fig. 3.

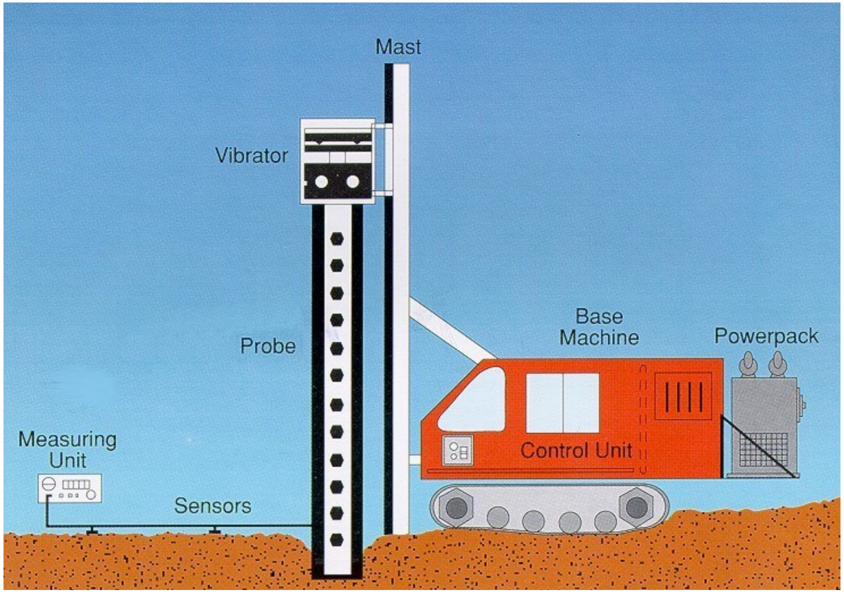


*Fig. 3. Main elements of vibratory compaction equipment (resonance compaction system).*

- **Compaction Equipment**

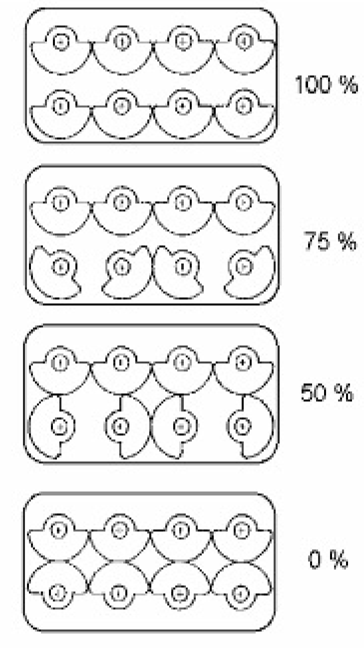
The compaction equipment includes the following components: vibrator with powerpack, compaction probe and base machine (carrier).

- **Vibrator Characteristics**

Modern vibrators are hydraulically driven and the vibration frequency can be varied during operation. The vertical oscillation of the vibrator is generated by counter-rotating eccentric masses.

- **Vibrator and Powerpack**

The first vibrators for pile driving were developed some 60 years ago in Russia and have since been used extensively on foundation projects world-wide. Conventional vibrators can change the operating frequency by throttling the hydraulic pressure on the powerpack. In order to avoid a loss of hydraulic power when the frequency is reduced, a pump system was developed which maintains the power of the vibrator independently of the operating frequency. The pumps can be electronically controlled and the operating frequency of the vibrator can be adjusted at all stages of the compaction process. During the past decade, very powerful vibrators have been developed for foundation applications, such as pile and sheet pile driving and soil compaction. These vibrators are hydraulically driven, which allows continuous variation of the vibrator frequency during operation. Moreover, modern vibrators can generate a centrifugal force of up to 4,000 kN (400 tons), and the maximum displacement amplitude can exceed 30 mm. These enhancements in vibrator performance have opened new applications to the vibratory driving technique, and in particular to soil compaction. Figure 5 shows the operating principles of a vibrator with variable frequency and variable eccentric moment (“static moment”), with eight eccentric masses, arranged at two rows of four masses at separate rotation levels. During any stage of vibrator operation, the position of the lower row of masses can be changed relative to that of the upper row, thereby affecting the static moment and the displacement amplitude. This makes it possible to start up the vibrator to the desired frequency without vibration. Once the operating frequency has been reached, the eccentric moment is gradually increased to the desired intensity of



vibrations.

***Fig. 5. Operating principle of vibrator with dual rows of eccentric masses, allowing variation of the static moment (displacement amplitude).***

- **Compaction Probe**

The compaction probe is an important component of the vibratory compaction system. The probe is inserted in the ground with the aid of a heavy, vertically oscillating vibrator, attached to its upper end. Different types of compaction probes have been developed, ranging from conventional pile (H-bream), tubes, or sheet pile profiles, to more sophisticated, purpose-built probes (Terra probe, Vibro-rod, and Y-probe), Fig. 6

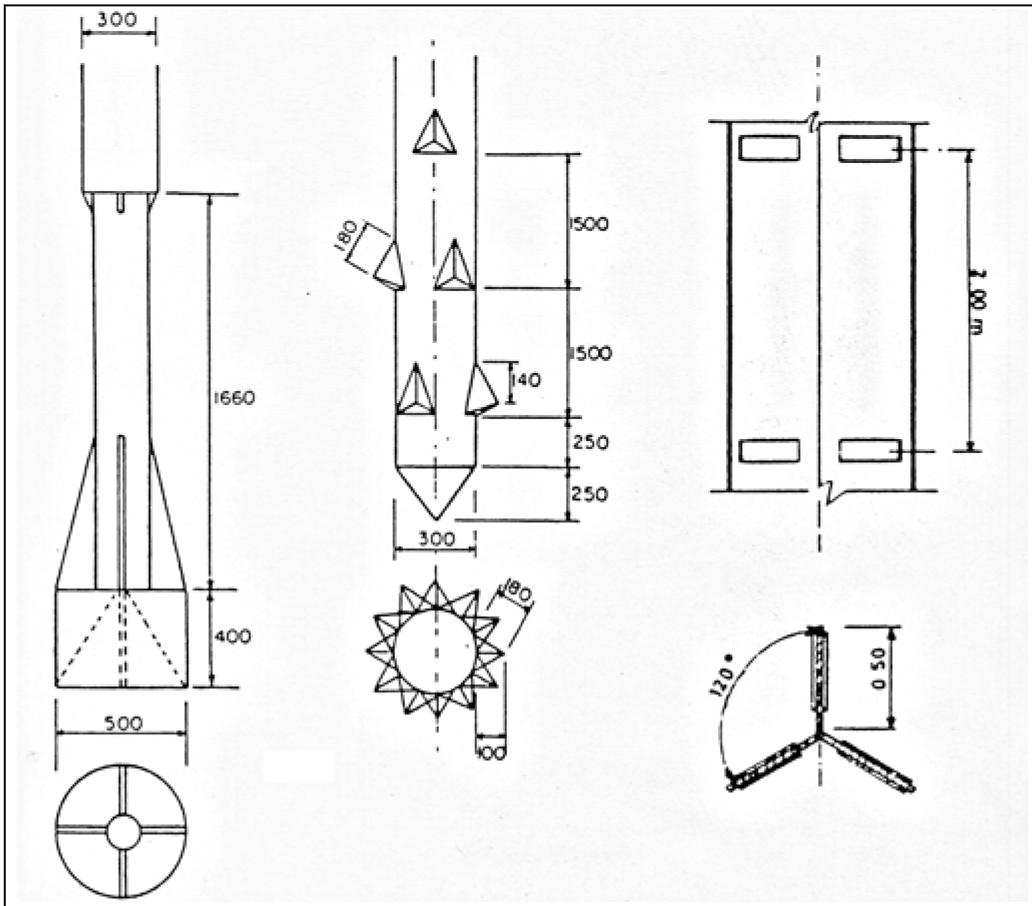


***Fig. 6. Examples of compaction probes (from let to right: Terra probe, Vibro-rod and Y-probe).***

## ➢Compaction Process

The compaction process is an important element of deep vibratory compaction and can influence the technical and economical results significantly. However, in practice, this aspect is not appreciated. The compaction process requires that the following parameters are chosen:

- compaction point spacing,

- vibration frequency,
- probe penetration and extraction, and
- duration of compaction.

- **Compaction Point Spacing**

Normally, a triangular pattern of compaction points is chosen. However, by using a double Y-shaped compaction probe, which has an almost rectangular influence area, a rectangular pattern of compaction grid points is possible, which reduces the number of required compaction points by approximately 13 percent. It should be noted that the spacing between compaction points needs to be chosen also with respect to practical considerations, such as the overall geometry of the site, the reach of the compaction machine, and the number of compaction passes. It is generally advantageous to perform compaction in two passes, as this will result in more homogeneous soil densification. This aspect is of particular importance when impervious layers of silt or clay exist in the soil deposit to be compacted. Such soil deposits are usually prone to augment liquefaction in the intermediate soil layers, as the impervious layers prevent or reduce the vertical flow of water and thus affect the dissipation of excess pore water pressure during earthquakes. A similar situation occurs during vibratory compaction of loose, water-saturated soil deposits and reduces compaction efficiency. However, if compaction is carried out in two passes, the probe will create drainage channels during the first pass, resulting in more efficient compaction during the second pass. What spacing between compaction points to assign depends on several factors, such as the geotechnical site conditions prior to compaction, the required degree of compaction, the size of the compaction probe (influence area), and the capacity of the vibrator. It is generally advantageous to use a smaller spacing with a shorter duration of compaction rather than a larger spacing with longer duration. This will result in more homogeneous compaction of the soil deposit. The spacing between compaction points ranges typically between 1.5 and 5 m.

## ➢Vibration Frequency

The vibration frequency is an important parameter of vibratory soil compaction and should be chosen with care. During insertion and extraction, it is desirable that the shaft resistance along the probe is as small as possible. This is achieved by using a high frequency—higher than about 30 Hz. Ground vibrations are then low and most of the vibration energy is converted into heat along the shaft of the probe and little energy reaches the soil body. In contrast, during the compaction phase, the objective is to transfer the energy generated by the vibrator along the vertically oscillating compaction probe to the surrounding soil as efficiently as possible, which is achieved when the probe is vibrated in resonance with the soil—usually about 15 to 20 Hz. Resonance between the vibrator-probe-ground system, leads to amplification of the ground vibrations, as the probe and soil move “in phase” with little or no relative displacements occurring—achieving efficient transfer of the vibration energy to the ground. It should be noted that in this state, probe penetration will become slow or stop completely. Figure 9 shows the vertical vibration velocity on the ground surface, measured by a vibration sensor (geophone) at a distance of 4 m from the compaction probe. The resonance frequency depends on several factors, such as the mass of the vibrator, the length and size of the compaction probe, and the shear wave velocity of the soil. The resonance frequency will increase with increasing shear wave velocity, reflecting a change of soil stiffness and soil strength, Massarsch (1995). Figure 10 shows measurements during different phases of soil compaction, where the hydraulic pressure in the vibrator system, the operating frequency, the depth of

probe penetration, and the vertical vibration velocity on the ground measured at a distance of 4 m are shown. When the vibrator frequency is tuned to the resonance frequency of the vibrator probe- ground system, the probe oscillates in phase with the adjacent soil layers. Ground vibrations increase markedly, while the required compaction energy (hydraulic pressure) is low. At higher frequencies, the probe oscillates relative to the adjacent soil layers and ground vibrations decrease, while the required hydraulic pressure increases significantly.

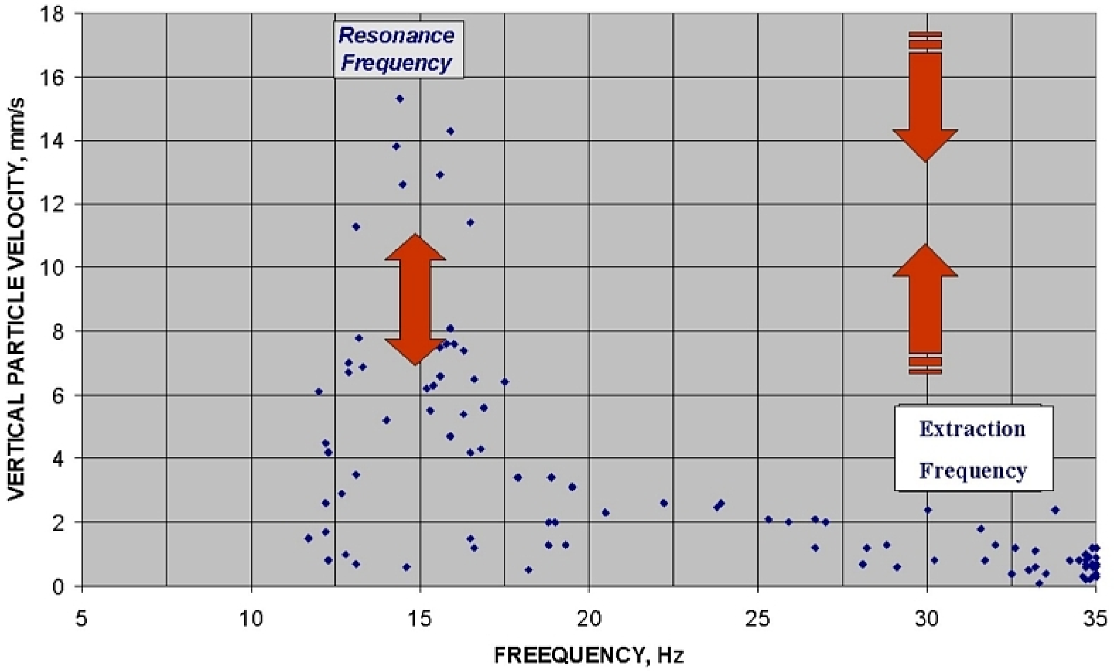


*Fig. 9. Ground vibration velocity during probe penetration and compaction measured at 4m distance from the compaction probe.*

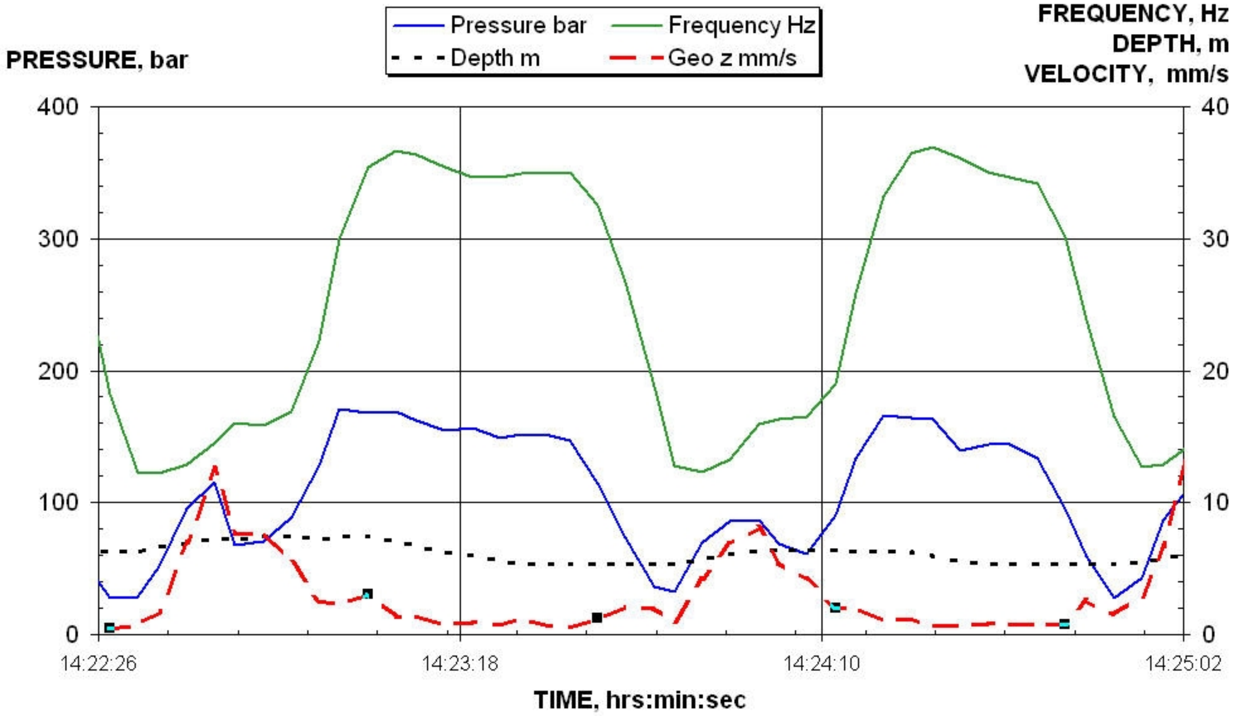


*Fig. 10. Vibrator performance during different compaction phases, cf. Fig. 9.*

## ➢Probe Penetration and Extraction

Deep vibratory compaction is a repetitive process, comprising of three main phases: insertion of the compaction probe to the required depth—densification of the soil— extraction of the compaction probe. The principle steps of the vibratory compaction process using variable frequency are shown in Fig. 12.

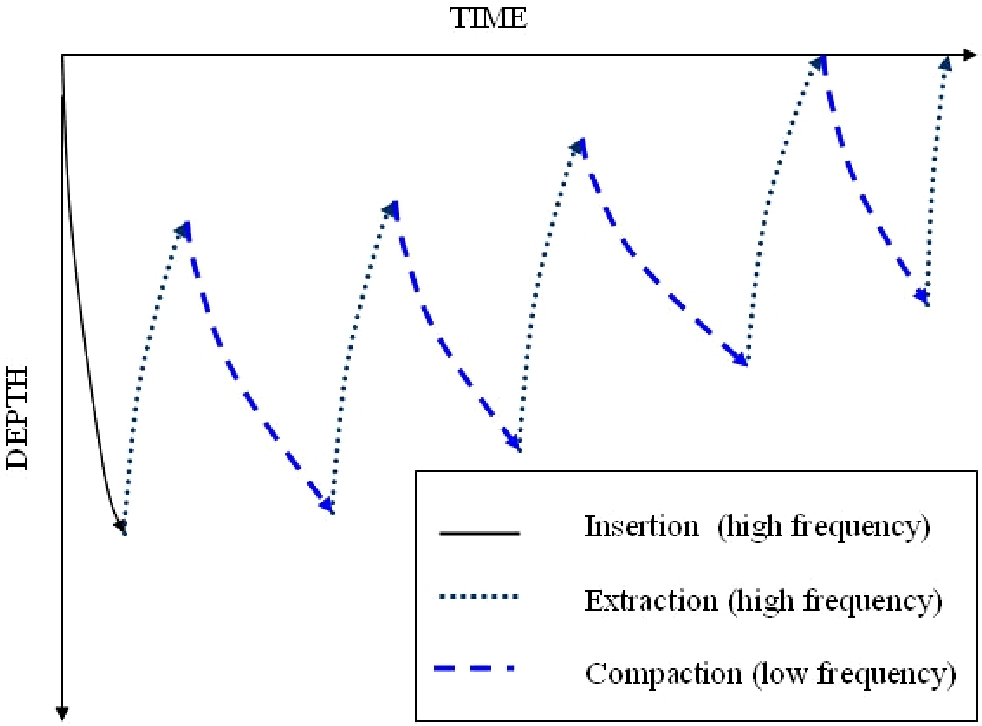


*Fig. 12. Principle of deep vibratory compaction using variable frequency concept.*

The most efficient compaction process is to insert the probe to the required depth as rapidly as possible at a high vibration frequency, followed by compaction of the soil at (or near to the) resonance frequency and, finally, to extract the probe at high vibration frequency. Compaction will be less efficient if the entire compaction process is carried out at a single frequency. Should a too high frequency be applied, most of the vibration energy will be converted into heat along the probe; and, should the vibration frequency be close to the system resonance frequency, probe penetration will be slow. Moreover, if the probe is extracted at the resonance frequency, the extraction force will be high and the compaction effect is destroyed (decompression). By recording the penetration speed of the compaction probe during insertion at a given vibration frequency, a record of the soil resistance is obtained in each compaction point. At a high vibration frequency, the probe penetration resistance is mainly influenced by the soil resistance at the probe tip.

This information can be compared with penetration test results and could serve to provide additional details on the geotechnical conditions of the site. As mentioned above, it is advisable to carry out deep vibratory compaction in two passes. During the second compaction pass, the probe is inserted in the diagonal point of the compaction grid, and the time required for the probe to penetrate the soil layer is again recorded. If the penetration speed at the start of the second compaction pass is the same as during the first pass, the grid spacing was too large. If the penetration speed during the second pass is much lower than during the initial phase, the point spacing was chosen correctly or, possibly, closer than necessary. Thus, the observations at the start of a compaction project or in a special pre-construction test phase can serve to decide on the optimum probe spacing to use. Indeed, deep vibratory compaction equipment can be used as a large-scale soil testing machine for assessing the liquefaction potential of a site.

## ➢Duration of Compaction

The duration of compaction in each point is an important parameter and depends on the soil properties prior to compaction, the required degree of densification, and the vibration energy transferred to the ground (intensity and duration). The optimal compaction grid spacing should be determined—at least in the case of larger projects— by compaction trials. As mentioned, in comparing the probe penetration speed during the first and the second compaction pass with penetration tests before and after compaction, the optimal compaction procedure can be established more reliably. In many cases, the same duration of compaction is applied during the first and second pass. However, it may be advantageous to vary the duration of compaction during the second pass. During the first pass, a uniform compaction procedure should be applied across the entire site. During the second pass, the compaction time should be varied in each point depending on the observed probe penetration speed. In loose, water-saturated sand deposits, the ground will liquefy during the initial phase of compaction. An example of ground liquefaction is shown in Fig. 13, where the ground water level was approximately 4.5 m below the ground surface. Shortly after densification had started, a zone adjacent to the compaction probe liquefied and ground water rose to the surface. During the liquefaction phase, the ground vibrations almost ceased as no energy was transferred from the probe to the soil. As the sand densifies, ground vibrations gradually increased again. During the second compaction pass, liquefaction did not occur. This is an indication that the soil deposit has become more resistant to liquefaction and can be used to verify the design specifications in the case of liquefaction mitigation.

*Fig. 13. Liquefaction of water-saturated sand during the initial phase of compaction. Note that the ground water level is 4.5 m below the ground surface.*

- **During the Vibro-Compaction process:**

• Sand and gravel particles are rearranged into a more dense state (higher relative density DR )

• A significant increase is achieved in the horizontal to vertical effective stress ratio

• Soil hydraulic conductivity (permeability) is significantly reduced

• Angle of internal friction is increased

- Settlement of the compacted soil mass (2 to 15%) is achieved

- Soil deformation moduli are increased

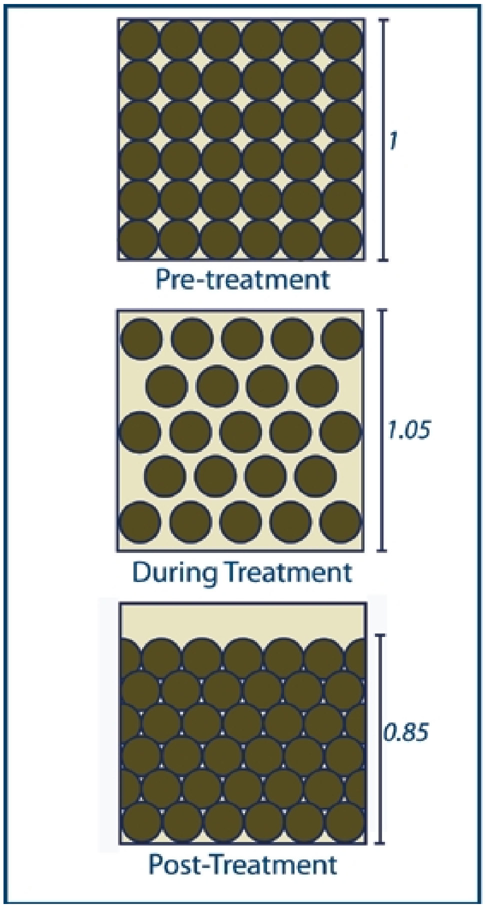


*Fig shows The Vibro-Compaction process rearranges sand and gravel particles into a more dense state. Backfill may be added during the process to maintain site elevation.*

## ➢ Conclusions

- Sand and gravel particles are rearranged into a more dense state (higher relative density DR)
- A significant increase is achieved in the horizontal to vertical effective stress ratio.
- Soil hydraulic conductivity(permeability) is significantly reduced.
- Angle of internal friction is increased.
- Settlement of the compacted soil mass(2 to 15 %) is achieved.
- Soil deformation module are increased.

## • Results

- Increased bearing capacity, permitting shallow foundation construction
- Settlement reduction under static and dynamic loading
- Near-elimination of differential settlement for large foundations
- Liquefaction mitigation
- Prevention of lateral spreading
- Reduction in soil permeability

# ➢References

- Eslami, A., and Fellenius, B.H., 1997. Pile capacity by direct CPT and CPTu methods applied to 102 case histories. Canadian Geotechnical Journal, Vol. 34, No. 6, pp. 880 898.
- Massarsch, K.R., 1991. Deep Soil Compaction Using Vibratory Probes. American Society for testing and Material, ASTM, Symposium on Design, Construction, and Testing of Deep Foundation Improvement: Stone Columns and Related Techniques, Robert C. Bachus, Ed. ASTM Special Technical Publication, STP 1089, Philadelphia, pp. 297 319.
- Massarsch, K. R. & Fellenius, B. H., 2001. Vibratory Compaction of Coarse-Grained Soils. Canadian Geotechnical Journal, Vol. 39. No. 3, 25 p.
- NYSDOT Geotechnical Design Manual

# ➢Site Reference

- http://www.fellenius.net/papers