XIII ICSMFE, 1994, New Delhi, India / XIII CIMSTF, 1994, New Delhi, Inde

RECENT EXPERIENCES AND DEVELOPMENTS OF THE RESONANT VIBROCOMPACTION TECHNIQUE

EXPERIENCES ET DEVELOPPEMENTS DU COMPACTAGE EN VIBRATION RESONANTE

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SYNOPSIS : In many cases of improvement of cohesionless soils, the improvement requirements vary over the soil profile, especially when some layered variable densities are distinghuished. In the case of soild densification by resonant vibrocompaction, a specially designed low dynamic stiffness compaction probe is used, achieving a more efficient transfer of vibration energy at the interaction with the surrounding soil.
In the paper, data will be given and analysed on recent experiences with the resonant vibrocompaction techniwue for densifying study layered soil behind a large quay wall ; moreover, the sensitiviy of the compaction effeciency to the frequency change, as compared to other compaction techniques will be discussed.

INTRODUCTION

The densification of granular soils using dynamic methods has been discussed largely in literature. An overview of the various possibilities of heavy temping, soil blasting, vibroflotation, vibrocompaction, and resonant compaction methods has recently been presented in a report to the Seminar on "Soil Dynamics and Geotechnical Earthquake Engineering - 26-29 July 1992, Lisbon, Portugal".

Resonant compaction soil improvement techniques have been applied for same years in problems related to liquefaction potential reduction, foundation of structures, pile length reduction, slope stability improvement, etc...

VIBRATORY COMPACTION

Loose granular deposits can be most suitably densified, up to great depths, by vibratory compaction techniques. Among those methods, vibroflotation and casing driving with soil replacement, and certainly vibratory probes (vibro-wings, Y- or double Y-shaped probes) at constant or varying frequencies (resonant vibratory compaction) and applied shear strains larger than about 0.1 % up to 10 %, are the most well-known procedures.

Vibratory probes in contrast with vibroflotation techniques use heavy vibrators clamped at the upper end of long steel probes, which can be either suspended at a crane or guided by a mast. The probe is excited in the vertical direction and the vibration energy is transmitted to the surrounding soil along the whole length of the probe. The soil is compacted mainly as a result of vertically polarized waves. Water jetting is normally not required, which makes the method simple to execute. Different types of compaction probes were developed in Japan, North America and Europe, Massarsch (1991). The geometric shapes of simple probes such as steel tubes or H-beams is not very efficient for soil compaction. Therefore, special probe shapes were developed for soil compaction. In loose to medium dense saturated sands the strong ground vibrations result in a sudden increase of pore water pressure in a soil column surrounding the vibrating probe which can be considered leading to a state of cyclic mobility of the soil mass. Whenever the sand in its original density was loosely enough packed, so real liquefaction can even occur.

Commonly used vibrocompaction probes are the Swedish Vibrowing Massarsch (1982), the stiff Franki (Tristar) Y-profile and the more flexible double-Y shaped probe (MRC-profile), Fig. 1 and 2.

The Franki Y-probe (Fig. 1) has three long steel plates 500 mm wide and 20 mm thick which are attached to a long steel rod 15 m - 20 m long, at 120° to each other. Additional steel ribs 300 mm x 50 mm x 10 mm are welded on to the two sides of each plate at 2 m intervals in order to improve further the efficiency of the probe. A motor driven vibrator mounted on top of the probe delivers vertical vibrations with frequencies in the range 10 to 30 Hz.

The degree of soil improvement that can be achieved for a given soil deposit depends mainly on the power of the vibrator, the duration of compaction, the vibration amplitude and frequency, the rate and sequence of insertion and withdrawal of the probe and the spacing between the points of insertion. Also the geotechnical conditions are of importance such as the fines content (permeability) of the soil deposit, the depth of compaction, the initial density of the soil and the location of the ground water level.

The efficiency of the densification is usually monitored by electric CPT carried out before and after densification, measurement of porewater pressures set up, measurements of vibration velocities next to the probes, settlements and the overall ground subsidence evaluation, etc... Field measurements provide valuable information on the increase of soil stiffness, and reduced compressibility. In terms of soil parameters, this is generally reflected as increases in the angle of internal friction ϕ ; shear modulus G ; elastic modulus, E ; and decreases in compression index C_c. Furthermore, soils improved by vibro-compaction and vibro-replacement have shown increased resistance to liquefaction.

The tendency of a soil to generate excess pore pressure during undrained loading is correspondent to the volume changes that occur during drained loading. Loose soils tend to contract upon shearing and, if loading is too quick for drainage to occur, generate excess pore pressures. For soils that derive all strength from confinement, this generation of excess pore pressures can lead to a condition of zero effective stress (when $\sigma = u + \delta_u$), resulting in loss of strength and fluid-like behavior with only residual resistance to deformation.

Fig. 1. The Y-probe on the test site.

Fig. 2. The double Y-probe on the test site.

RESONANT COMPACTION

Over the years, the deep vibratory compaction technique has been largely improved by the introduction of the resonance vibro-compaction concept, the basic principles of which have been discussed in several papers. In these references, case studies are reported which document the practical experience gained from a variety of projects, where resonance compaction successfully has been applied to solve the foundation problems, such as the problem of loose saturated sands (liquefaction), the reduction of pile length for bridge foundations, foundations for tanks and other heavy structures, quay walls, harbour projects, the improvement of slope stability etc..., Franki (1986), Massarsch and Vanneste (1988), Wiesner (1983), Massarsch (1991), Neely and Leroy (1991).

The key features of the resonant compaction technique are the use of a specially designed compaction probe and of a heavy vibrator with variable operating frequency on top of the probe. Vibration excitation of the probe is in the vertical direction only. After probe insertion, the frequency of the vibrator is adjusted to the resonant frequency on the soil layer, thereby amplifying the ground response. An important advantage of resonant compaction, compared to other vibratory methods, is that the whole soil layer oscillates simultaneously during compaction. Moreover, because of the special design of the probe and the possibility to adjust the compaction frequency to the resonant frequency of the soil layer, an optimal transfer of vibration energy to the surrounding soil can be achieved, resulting in a more efficient compaction process.

Recently very promising improvements of the resonant compaction method have been introduced within the MRC concept. This concept overcomes a number of limitations of the former used equipment by the development of a harmonized unit, comprising a modern vibrator, a flexible double-Y-profile (FLEXI-probe) and an electronic process control unit, Fig. 2.

The vibrator can vary the frequency continuously during operation without reduction of operating speed of the diesel engine (centrifugal force of up to 4000 kN) and is attached to the top end of the flexible probe. Usually, everything is guided by a mast to assure vertical insertion of the probe. Vibration excitation of the probe is in the vertical direction only. The patented FLEXI probe has specially been designed to achieve optimal transfer of compaction energy from the vibrator to the soil. This is obtained by the reduction of the dynamic stiffness of the probe, together with the increase of the interaction area of the profile. Finally, the electronic monitoring system, which continuously records all essential compaction parameters, such as vibrator frequency, probe penetration depth, ground vibration velocity, power supply etc..., allows the recording of the actually performed compaction process, displays relevant information of the process as well as instructions to the operator of the compaction machine, and delivers a complete report of the work performed to the site inspector and the engineer.

The capacity of the vibrator must be chosen with respect to the specific project requirements, such as soil type, initial soil density, required degree of compaction and penetration depth. The vibration amplitude required to compact the soil can be determined from a semi-empirical relationship between initial cone penetration resistance, vertical ground acceleration and soil layer depth, Fig. 3.

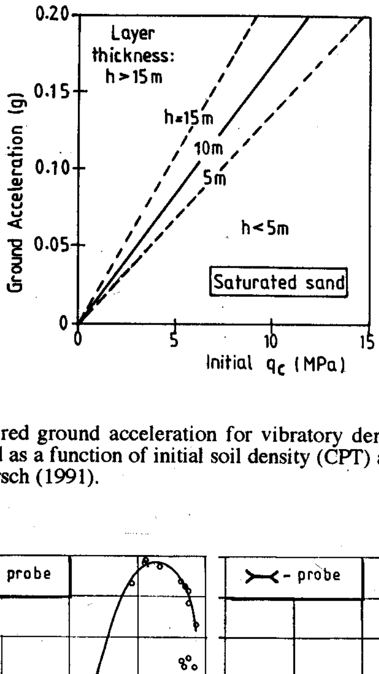

Fig. 3. Required ground acceleration for vibratory densification of saturated sand as a function of initial soil density (CPT) and soil layer depth, Massarsch (1991).

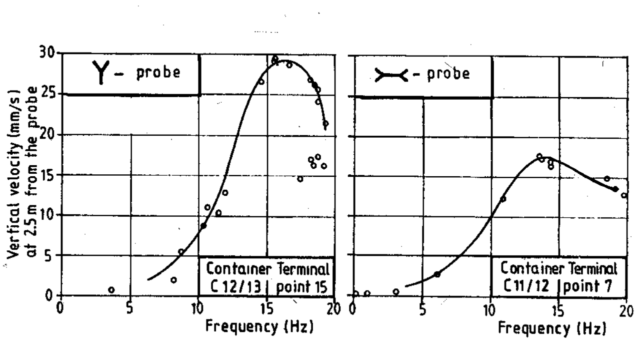

Fig. 4. Frequency spectrum-vertical particle velocity peaks, for the two probes.

The resonance frequency of a soil layer is rather difficult to predict reliably from theory, but is relatively simple to measure directly on site through seismic measuring techniques. The ground response during the on- or off-switching of the probe vibrator is measured by velocity transducers at a distance from the compaction probe. The equivalent frequency spectrum (Fig. 4) indicates that the resonance of the relevant soil layer to be densified occured in this case study around 15 Hz for both probes. It also can be seen that at resonance the vertical vibration amplitude is strongly amplified up to much higher values than at the other operating frequencies.

Frequency analyses of ground response at the start of a densification often show in addition to the fundamental vibration mode also several of the higher vibration modes, suggesting that soil layers of varying stiffness exist. With progressing compaction, the resonance frequency increases and higher vibration modes tend to disappear, indicating more homogeneous soil conditions. The resonance frequency can be readily determined at any stage of soil compaction, and makes it possible to adapt the vibrator frequency to the optimal operating conditions.

GEOTECHNICAL REQUIREMENTS FOR VIBRATORY COMPACTION

Under present practice, the efficiency of the soil improvement and even the liquefaction potential of mechanically improved site is typically evaluated through the use of in situ tests particularly the Standard Penetration Test and Cone Penetration Test, and recently even dilatometertests, DMT. When CPT is used, the data are either converted to equivalent SPT values, or used directly to assess liquefaction using CPT-based evaluation methods, eg. Robertson and Campanella (1985). It must be noted however that these correlations were developed from natural sites where no ground improvement has been performed. When soils are subjected to mechanical modification, variables associated with pre-straining, such as horizontal stresses and time effects (aging), may not be adequately represented by SPT and CPT results. An example of a CPT and DMT evaluation at the test site discussed in this paper, is shown in Fig. 5a,b. Measurements of pore pressure ratios with a piezocone (CPTU) with the porous element behind the tip show loose untreated soils generating high excess pore pressures during penetration. Well densified soils, on the other hand, exhibit pressures below hydrostatic and even negative, indicating a tendency for the soil to dilate during shear.

Vibratory compaction should be used only in granular, free-draining soils with an "effective" particle diameter d_{10} (corresponding to 10 % of the grain size curve) larger than approximately 0.03 mm. Grain size curves are useful but can usually only be obtained from disturbed samples at certain depth intervals. Thus, they may not be representative for the entire soil deposit, especially if the soil is stratified. Even relatively thin silt and clay layers in a sand deposit can significantly affect the drainage conditions and reduce the densification effect. Therefore, it is advisable to also use in situ testing methods such as the static cone penetration test (CPT) with sleeve friction measurements. Good compaction results can generally be expected, when the friction ratio (local sleeve friction as percentage of point resistance, F_R in %) from electric cone penetration tests is lower than about 1 %. When the friction ratio exceeds 1.5 %, then vibratory compaction is usually not efficient.

Pore pressure measurements performed in connection with cone penetration tests - CPTU - can provide additional information concerning soil stratification and the existance of even thin, fine-grained layers. Soil with excess pore water pressures higher than about 10 % are often not suitable for vibratory compaction. It is also important to establish the level and variation of the ground water in connection with a soil compaction project. Usually, dry soils or soil layers with negative pore water pressures are more difficult to densify than saturated soils and need to be identified carefully. The effect of thin impermeable seams in a soil deposit can be evaluated by measuring the permeability in situ. Soils suitable for vibratory compaction should have a permeability higher than approximately 10^{-6} m/s.
Another factor of great practical importance for the design of vibrocompaction is the aging effect which can occur even several weeks after

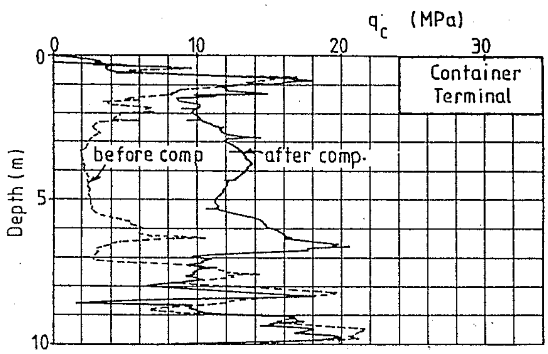

Fig. 5a. Typical CPT before and after resonant compaction.

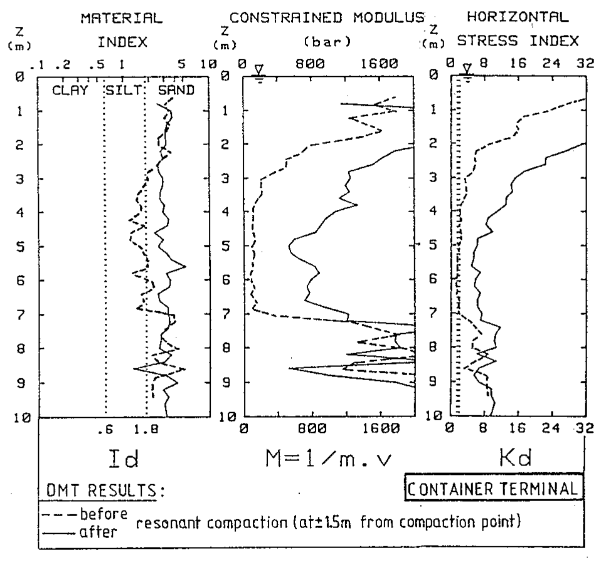

Fig. 5b. Typical DMT rest before and afer resonant compaction.

soil compaction. A large number of well-documented case histories suggests that also granular soils show a marked aging behavior, i.e. that the engineering properties can improve by 50 tot 100 % over a period of few weeks, Schmertmann (1991). The soil strengthening and stiffening effects can be explained by increased soil friction and should be considered when the time of penetration testing after compaction is choosen. Mitchell (1986) has compiled several case histories from soil improvement projects in different parts of the world where significant soil stiffening with time has been observed. Massarsch (1991) reported a case where after vibratory compaction of a silty sand, the cone penetration resistance increased within one week by almost 50 %. Based on experience from compaction projects in different soil conditions, at least 5 days should be allowed for recovery of soils after compaction. In the case of larger projects it is recommended to establish the time effect by penetration tests at different time intervals after compaction.

ADDITIONAL PRACTICAL CONSIDERATIONS

For resonant compaction, as in the case of heavy tamping and blasting of cohesionless material, the final higher degree of relative density guarantees a more dilative deformation behavior. This implies a much higher resistance to liquefaction, since one mostly has to deal in such dense cohesionless soils with the phenomenon of cyclic mobility, Castro (1976), Van Impe ~~(1982). As reported~~ by R.A. López et al (1992), Mitchell et al (1976) studied the effects of pre-straining and soil fabric on liquefaction potential. This research determined that soils prepared to the same relative density do not necessarily exhibit similar undrained cyclic behavior. For example, soils densified by vibratory procedures produced no preferred axis of particle orientation, and exhibited better static and cyclic performance than soils prepared to the same density.

Four important parameters must be determined before the start of the compaction work : the interdistance of compaction points, the compaction time at each point, the mode of probe movement (insertion and extraction) and the compaction points' sequence. The grid spacing ranges typically between 1.5 and 4.5 meters depending on the shape, size and stiffness of the probe. The duration of each compaction energy at a given point depends on the layer thickness, grid spacing, degree of soil improvement required and varies typically between a few minutes up to half an hour.

Two examples of compaction procedures at our test site of the container terminal are shown in Fig. 6.

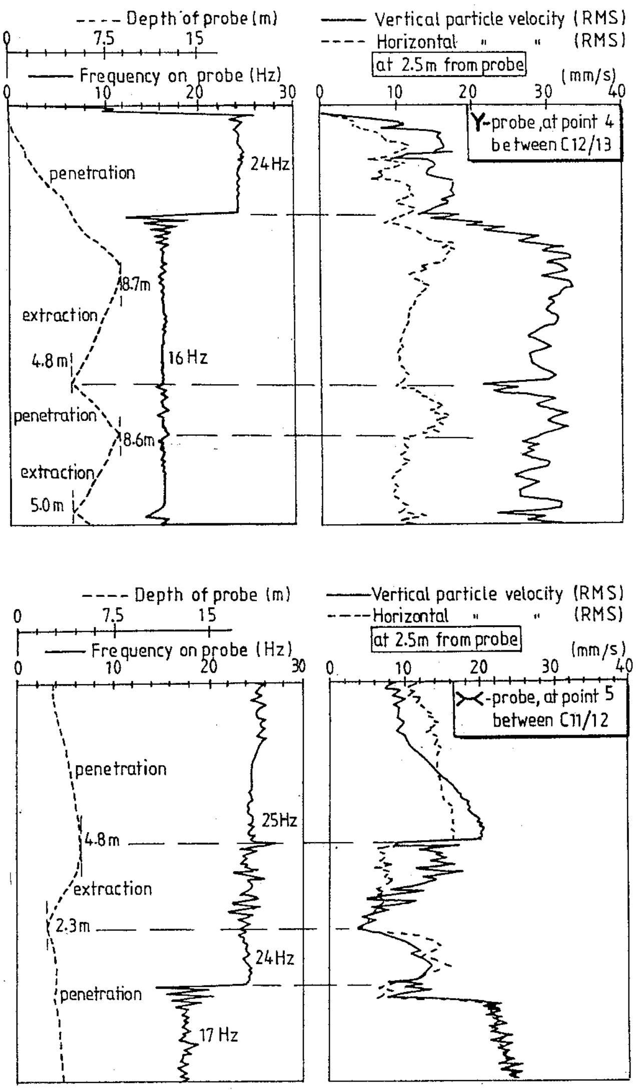

Fig. 6. Part of resonant compaction procedure at container terminal test site.

For the mode of probe insertion and extraction, in the layer to be compacted, plays an important role, the optimal procedure should be monitored with the aid of vibration sensors on the ground surface. They indicate the ground response during all probe movements. Fig. 6 show partly, the vertical and horizontal vibration velocities (RMS-values) during penetration, change of frequency, penetration and extraction of the probes in an easily drained partially saturated sand layer. Initially, during the probe penetration from the surface, the vibration amplitudes increase. Lowering the frequency envolves a larger soil volume in the densification process and increases the vibration velocities. During the step-wise extraction of the probe, the vibration amplitudes also show peaks, but generally of a lower level than during insertion.

The vibration attenuation can be approximately estimated from the equation :

$$A_2 = A_1 \sqrt{\frac{R_1}{R_2}}.e^{-\alpha(R_2-R_1)} \qquad (1)$$

where A_1 and A_2 are the vibration amplitudes at the respective distances R_1 and R_2 from the probe. The coefficient of wave attenuation α is a measure of the soil damping, depending on the vibration frequency and the dynamic soil properties. Fig. 7 shows the results at the test site of the relationship between the vertical vibration acceleration (velocity) and the distance from the vibrating probe to the measuring devices on the soil surface. The attenuation coefficient α for vibratory compaction varies in saturated clean sands typically between 0.05 and 0.10 m^{-1}. In partially saturated to dry sands α can rise to 0.5 m^{-1}.

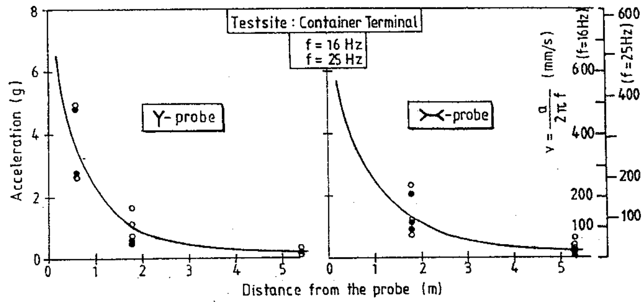

Fig. 7. Attenuation of ground acceleration with distance from the probes.

RESONANT COMPACTION RESULTS ON THE TEST SITE

A container terminal in Belgium, with large diameter caissons constituting the quay wall, was designed for a working load on top of the quay floor behind the caissons of 60 kN/m^2 The backfilling of the caisson quay wall with granular material had, for some reasons such as earth pressure reduction and settlement minimizing of the quay floor, to be densified. The aim of the densification work was to reach an overall mean cone resistance, after densification, of q_c = 6 MPa.

The layout of the compaction points with the mentioned techniques and the controlling CPT/DMT are indicated on Fig. 8. On the soil surface, vibration accelerations and settlements in many points of the testing area at 0.59 m, 1.76 m and 5.3 m of the densifying profile, were measured. Before and after the compaction work, a series of CPT and DMT results performed at the same locations, was gathered in order to analyze the efficiency and the fullfilling of the requirements of the densification.

For this particular test site in between caissons 11 and 13, soil compaction was carried out by Franki Foundations with a variable frequency vibrator (type Müller MS 50). The operating frequency of the vibrator can be varied between 10 and 30 Hz. The maximum oscillating amplitude is 22 mm at a centrifugal force of 1500 kN. For soil densification, 12 m long compaction probes (stiff Y-probe and double Y- or MCR flexible probe) were used.

Simultaneous with the densification work, a small research project was implemented in order to investigate more closely the efficiency of those different applied compaction methods (vibro-compaction using the Franki stiff Y-probe and flexible double Y-probe (MRC).

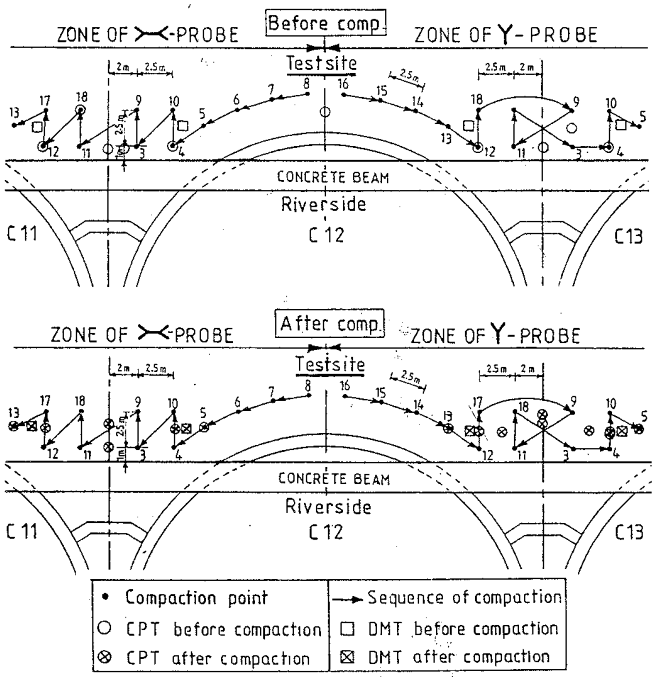

Fig. 8. Lay-out of the compaction points and the controlling CPT/DMT at the test site.

Examples of the monitoring and quality evaluation of the compaction work at the test site, mainly done by CPT and dilatometer (DMT) before and after the compaction, are given in Fig. 9a,b. It can be seen that for both types of compaction probes, the requirement of reaching a mean cone resistance q_c-value of 6 MPa after the densification work, could be fullfilled rather easily. Gathering all CPT results in the densification area, one could also compare the average CPT cone diagrams before and after the densification (Fig. 10), reaching the same conclusions with respect to the densification quality. The DMT-results show the expected increase of the stiffness modulus and the horizontal stress index, indicating from the deformation point of view its usefullness in the control of the quality of compaction work.

Because of the individual scatter of CPT-results, which often occurs in sandy layers with thin seams of variable penetration resistances, it is sometimes advantageous, instead of going out from individual cone resistance comparison or from average cone resistance diagrams, to link the quality control to the comparison of the overall cone penetration energy before and after the compaction work.

For this purpose, one calculates the penetration energy E_c as :

$$E_c = \int_{z=0}^{h} q_{c,z} \cdot \omega_{cone} \, dz \qquad (2)$$

with $\omega_{cone} = 10^{-3}$ m^2

$q_{c,z}$ = electrical cone resistance at depth z, (in MPa).

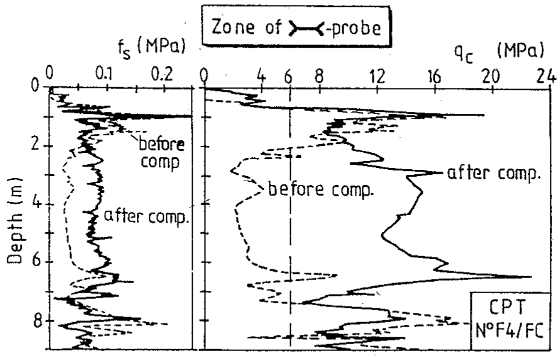

Fig. 9a. CPT cone and friction resistance comparison at container terminal before and after resonant compaction (C11/12).

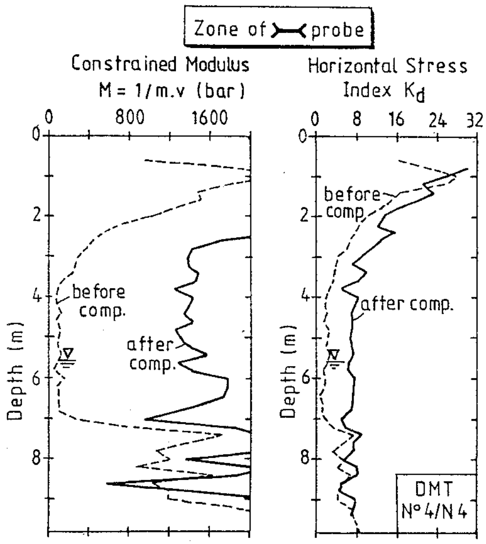

Fig. 9b. DMT-comparison before and after resonant compaction at container terminal (C11/12).

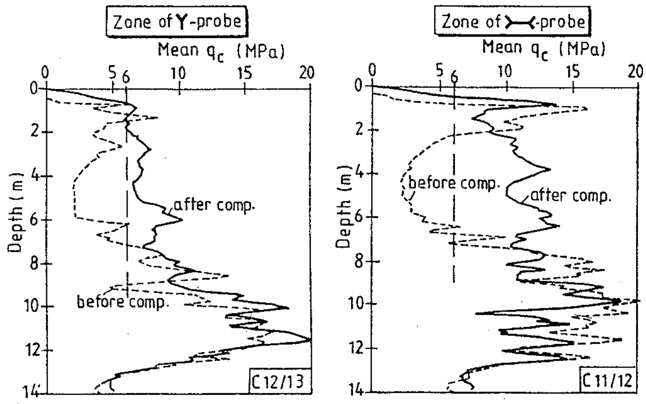

Fig. 10. Average densifying efficiency from cone resistances.

Such an analysis would allow to finally predict more reliably the expected improvement level Ec(after)/Ec(before) to the interdistance of the compaction (tribuary area) for a given probe, compaction input parameters and soil condition, Van Impe (1989).

Examples of such an energy comparison for this test site are shown in the Fig. 11.

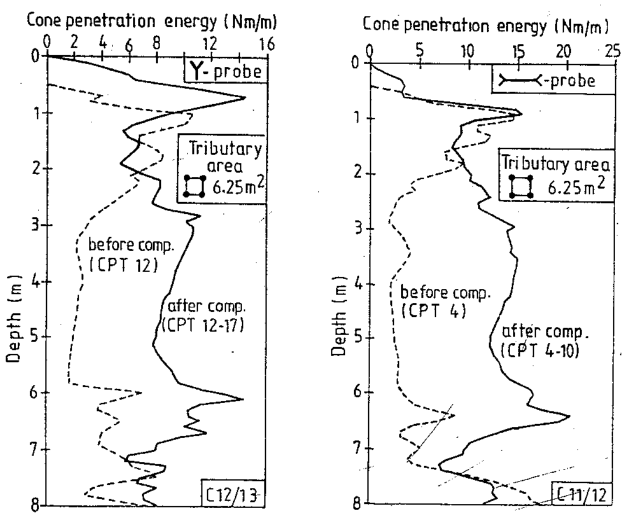

Fig. 11. Efficiency of the resonant compaction from the cone penetration energy at a given triburany area for the compaction points.

Another simple and very useful compaction control method goes out from the measurement of the soil surface settlements during compaction, Fig. 12. This Figure shows the final settlements and horizontal displacement vectors for various locations of the settlement measuring devices in between the compaction points. Fig. 13 shows how those settlement data match in an empirical group of curves correlating average settlements at the ground surface to the vibratory compaction specification and the initial CPT cone resistance of the compacted layer. The settlements indeed mainly depend on the initial soil density and the soil particle acceleration. The data of this test site, suggest that using the resonant compaction technique in sandy layers with initial cone resistances lower than or around 2.5 MPa, leads easily to settlements of 7 % and more of the initial thickness varying from 3.5 m to 4.5 m of the layer to be compacted.

CONCLUSIONS

From what has been discussed in this paper, it is obvious the resonant compaction technique has great potential in cohesionless soil improvement cases. The double Y-probe concept (MRC probe) including the advances for continuous monitoring of the compaction work through the electronic process control for the probe.

ACKNOWLEDGEMENT

We want to acknowledge the DOLSO-department of the Flemish Government, the Antwerp city, the main contractors and the owner of the Container Terminal for allowing us to set up this small research work.

Müller Geo-System provided the MRC process control system. The support and assistance of the personal of Müller Bautechnik and of Loster MCT is gratefully acknowledged.

We will thank also Mss. Minna Leppannen - Soil Mechanics Laboratory of Tampere University, Finland for helping, during her stage at the Ghent University Laboratory of Prof. Van Impe - analyzing the data.

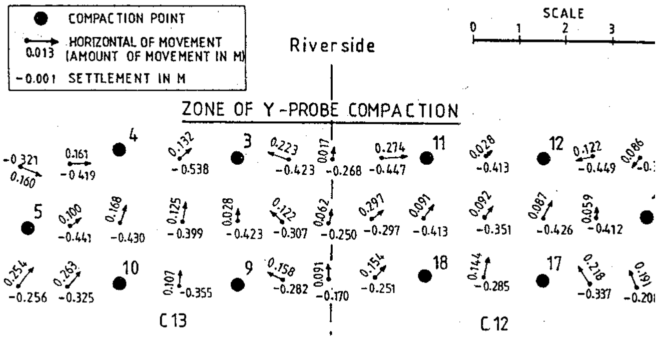

Fig. 12. Final settlements and horizontal displacement vectors for various locations of the settlement measuring devices in between the compaction points.

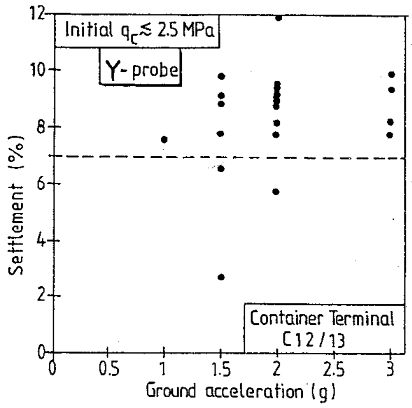

Fig. 13. Ground surface settlements due to resonant compaction.

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