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Vibratory plate resonance compaction

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1 INTRODUCTION

Deep soil compaction methods are generally effective below a depth of approximately 3 m, where the effective confining stress is sufficient to achieve soil densification. On the other hand, surface vibratory rollers have a limited depth effect and are effective down to maximum 1 m, due to the limited drum-soil contact area, as well as restrictions with respect to drum size and oscillating force. Vibratory plates can compact soil layers efficiently within the depth range of 1 to 4 m. In this presentation, the application of the resonance plate compaction method will be presented and its practical application illustrated by an example. In addition to the enhanced efficiency of compacting granular soils at the resonance frequency of the vibrator-plate-soil system, detailed monitoring of the compaction process makes it possible to determine in the field that the anticipated compaction effect is achieved.
Testing of vibratory plate resonance compaction dates back to investigations in the early 1950's. Converse (1952) used a dragged vibratory plate to compact loose sand in California. During field trials, a vibrator with a mass of approximately 4.5 tons and variable frequency (8 - 24 Hz) was used. The movement amplitude of the plate in the vertical and horizontal direction was measured, Fig. 1. One objective was to study resonance effects of the vibrator-plate soil system.

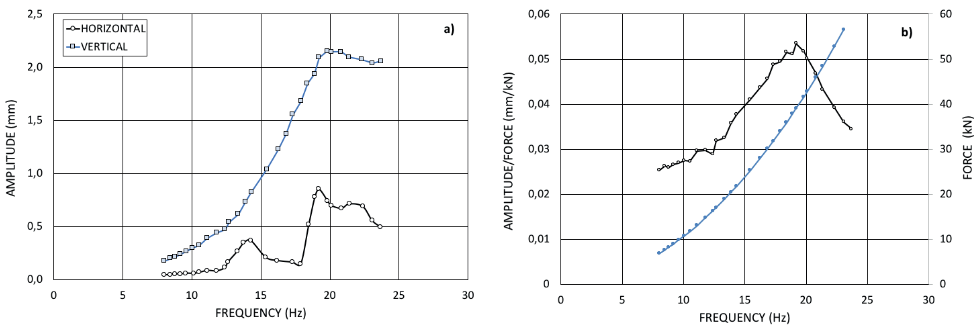

Figure 1. Effect of vibrator frequency on vertical displacement, data from Converse (1952). Influence of frequency on peak-to-peak amplitude. a) vibration amplitude as function of frequency, b) normalized vibration amplitude and centrifugal force.

Based on initial field trials, the following conclusion was drawn: "*The results of these tests indicated that very excellent densities were obtained to depths of at least one and one-half times the width of the surface plate.*" The sharpness of the resonance peak is somewhat masked by the fact that displacement varies with dynamic force, dynamic force varies with frequency and soil non-linearity reduces the amplitude at resonance. The resonance frequency becomes clearly visible when the displacement

amplitude is divided by the centrifugal force, which increases with frequency (Fig. 1b). The effectiveness of the system was verified by field density tests before and after compaction. It was concluded that by the resonance compaction method: “The density in the field was actually approximately 100% of the value obtainable in the laboratory at the same moisture.” It was concluded that at the system resonance frequency (vibrator-plate-soil) displacements are at a maximum, resulting in optimal compaction effect.
Nelissen et al. (1983) described the application of vibratory plate compaction under water. The main objective of the system was to achieve maximum compaction when operating at large water depth, using a perforated compaction plate. The operating frequency of the vibrator was adjusted to achieve optimal transfer of the dynamic force to the ground surface, avoiding “disconnection of the plate” which resulted in uncontrollable movement.

2 RESONANCE COMPACTION

Resonance deep compaction using vertically oscillating probes was introduced by Massarsch (1991). The objective of the system was to insert the compaction probe at a high frequency and thereafter, to adjust the vibration frequency to the system frequency of the vibrator-probe-soil system. The resonance frequency is usually significantly lower than the frequency used for sheet pile installation. Another advantage of the resonance compaction system is that all phases of the compaction process are monitored and can be optimized.

2.1 Dynamic tuning of the system

An important aspect of the vibratory plate compaction system is the optimal tuning of the static mas-vibrator/plate-soil system, assuring smooth performance and avoiding unnecessary wear of the compaction equipment. The optimization of the system is carried out using theoretical models, as shown in Fig. 2.

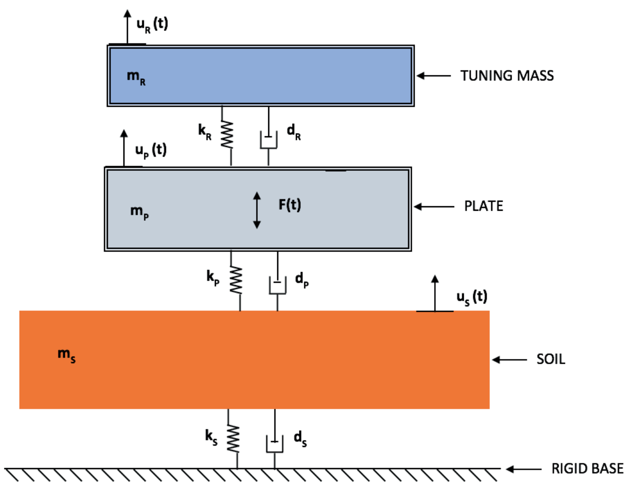

Figure 2. Theoretical model for optimization of vibratory plate compaction system.

The dynamic properties of the soil are important when designing the optimal compaction equipment. However, by continuously adjusting the excitation frequency of the vibratory plate and at the same time measuring the displacement amplitude, resonance amplification can be achieved without prior knowledge of the resonance frequency (“resonance compaction”). The advantages of resonance compaction are increased amplitude and contact force, in spite of lower centrifugal force and less energy consumption. This facilitates compaction at a lower frequency which causes the plate to move in phase with the soil, while higher frequencies cause the plate and the soil moving out of phase, resulting in a significant portion of the compaction energy being transformed to friction. Fig. 3 shows results from model tests using a compaction plate, 84 mm in diameter, to compact sand at various frequencies (Wersäll et al., 2015). The settlement below the plate, closely related to soil compaction, shows a maximum around the resonance frequency, approximately 40 Hz. At higher frequencies, the compaction effect again increases due to a high centrifugal force. Under field conditions, however, high frequencies cause double-jump and chaotic movement of the plate which is not suitable for compaction. The most effective compaction frequency is thus at resonance.

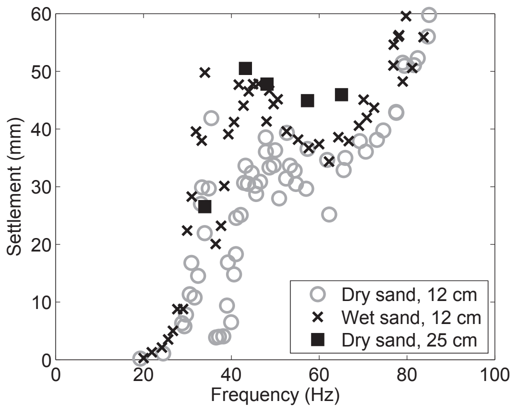

Figure 3. Frequency-dependent settlement/compaction in model tests, from Wersäll et al. (2015).

3 APPLICATION OF RESONANCE PLATE COMPACTION

The following gives an example of the practical application of the resonance compaction plate system on a natural sand deposit. The site conditions were investigated using cone penetration tests (CPT). The subsoil down to 8 m depth consisted of very dense sand with occasional layers of silt. The average cone stress down to 4 m depth varied between 10 and 30 MPa. The compaction unit used for the trials consisted of a vibrator Dieseko PVE 38M, provided with static weights, attached to a compaction plate of size 2.6 m x 2.6 m. The technical specifications of the compaction unit are given in Table 1.

Table 1. Specifications of Compaction Equipment PVE 38M with compaction plate.

Eccentric moment	38	kgm
Max. frequency	1 700	rpm
Max. frequency	28	Hz
Centrifugal force	1 200	kN
Total mass	45 570	kg
Total dynamic mass	12 600	kg
Static mass	25 800	kg
Maximum pressure	35	MPa
Nominal displacement amplitude	6	mm

A monitoring and process control system (MPCS) was used to optimize and document the compaction process. The following parameters were measured: a) acceleration of vibrator; b) depth of plate; c) hydraulic pressure and d) time. From these measurements, the following parameters were derived: 1) displacement amplitude; 2) frequency; 3) plate penetration 4) plate penetration rate. During compaction, the frequency was adjusted to close to the resonance frequency of the system. Fig. 4 shows the compaction plate and measured parameters during one compaction test. Since the soil below the plate was initially very dense, the resulting compaction is moderate, but the monitoring illustrate how frequency can be adjusted to obtain resonance by observing the displacement amplitude. At the highest frequency, the dynamic displacement amplitude decreases, indicating that the resonance frequency was exceeded. Towards end of compaction, the frequency is lowered and the amplitude increases again as the frequency pass through resonance.

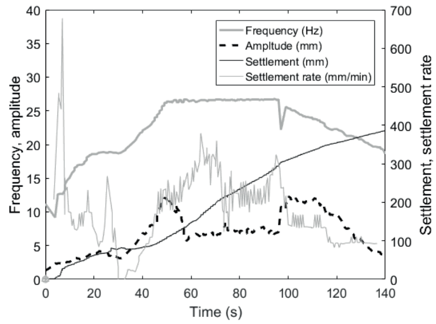

Figure 4. The vibrator and results from one compaction test.

4 CONCLUSIONS

The resonance plate compaction system has evolved during more than 50 years. However, resonance compaction has been made practically applicable only recently, thanks to the availability of powerful vibrators and development of advanced monitoring and control systems. By continuously monitoring and adjusting dynamic parameters, resonance amplification can be utilized throughout the compaction process. This generally implies a lowering of the compaction frequency, which decreases energy consumption and wear of equipment and at the same time increases the compaction effect. The efficiency of resonance compaction has previously been shown in model tests and its practical use was, for the first time, demonstrated in this study by full scale tests using a powerful vibratory compaction plate.

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