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Experimental and theoretical investigation of deep vibro compaction

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Abstract. Deep vibro compaction (vibroflotation) is a soil improvement technique, which was patented by the company Keller in the 1930s and since then it has been continually developed and has been successfully used worldwide for deep compac tion of granular soils. The methods for quality control of the compaction works are largely empirical in nature and therefore often unreliable. In a current research project, fundamental experimental investigations on real-time quality control for the deep vibro compaction were executed. Large-scale test measurements and numerical simulations were performed to investigate the three-dimensional vibrator movement during the compaction process. Reliable measurements with measuring instruments on the vibrator tube during the compaction process have been conducted within the current large-scale field tests. This paper presents the layout of the large-scale in-situ tests, moreover, selected test results are shown, and possible indicators of the changing soil conditions are discussed.

Keywords: Deep vibro compaction; Large-scale field tests; Real-time quality control

1 INTRODUCTION

1.1 Soil improvement by deep vibro compaction

The deep vibrator is essentially a rotating cylindrical steel tube with external diameters between 300 and 500 mm. Horizontal vibrations are induced by an eccentric weight at the bottom of the vibrator body, which rotates around its vertical axis. A flexible coupling connects the vibrator to extension tubes of the same or slightly smaller diameter, providing an extension for deep penetration into the ground up to 70 meters. The vibrator engine is mostly electricity-driven using a generator, which is generally mounted as a counterweight on the rear of the rig. Figure 1 shows the compaction process and the deep vibrator schematically. The compaction process is carried out bottom up, either by vibrating at a constant depth for a fixed time or by withdrawing the vibrator by 0.3 to 1.0 m, then lowering again by about half withdrawing depth (back-step method). Water flushing supports both the penetration of the vibrator and also the compaction process with jets of variable pressure at the nose cone. The pressure pipes and jets form an integral part of the vibrator string.

There are nowadays two principal ways to document the performance of vibro compaction. On the one hand site investigation methods such as dynamic probing are applied, on the other hand documentation is accomplished by evaluating performance factors from monitored machine parameters. Both provide advantages and disadvantages respectively. Site investigation methods generate data, which can be converted to actual stiffness using empirical formulas. The main drawback is the spot-like testing. The latter are recorded all over the site, but they are disputed regarding their applicability on compaction performance. The most often used parameter is the power consumption of the vibrator engine expressed in terms of electrical current. A more detailed description of usage the electrical current as an indicator for the compaction state can be found in Zöhrer and Wondre (2012).

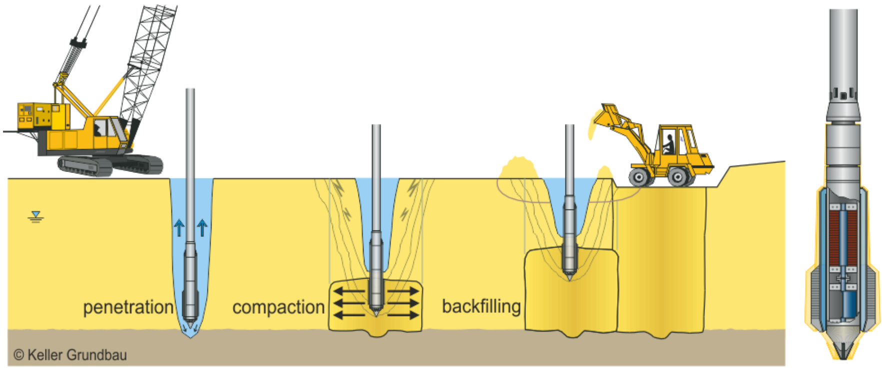

Figure 1. Compaction process during deep vibro compaction and the deep vibrator.

1.2 Vibrator movement as indicator of the compaction state

The three-dimensional movement of the deep vibrator is determined while interacting with the compacted soil. Thus, an increase of the soil stiffness during the compaction process causes changes in the vibrator movement. Therefore, the vibrator movement taking into account certain process parameters can be used for a work-integrated indication of compaction state, which could provide the machine operator with valuable information on site and would be a valuable tool for the quality assurance of the compaction works. That means the deep vibrator is not only used as compaction equipment but also serves as a measuring device at the same time. Systems for work-integrated measurement and continuous compaction control (CCC) have been developed in the last decades and are used in dynamic compaction with vibratory and oscillatory roller compactors (Adam and Pistrol, 2016).

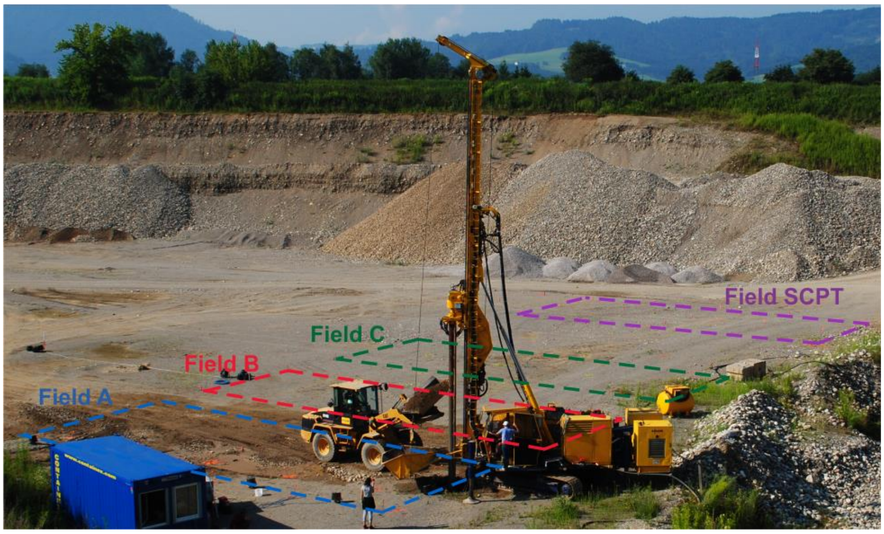

Figure 2. Test area near Fisching (Austria), divided into several subfields.

The connection between the movement of the deep vibrator and the compaction state of the soil was first analyzed by Fellin (2000a-b) by simple physical models. Model tests were performed in saturated sand by Nendza (2006). However, reliable vibrator instrumentation and a comprehensive measurement campaign could not be realized so far. A pioneering basic research project was initiated to investigate the three-dimensional dynamic movement of deep vibrators comprehensively, including large-scale experimental tests and complementary theoretical investigations based on numerical simulations. This research project is a collaborative effort between the Institute of Geotechnics at TU Vienna, Keller Grundbau GmbH, VCE Vienna Consulting Engineers ZT GmbH, and the Unit of Applied Mechanics at University of Innsbruck.

2 IN-SITU TESTS

2.1 Test area

The three-dimensional movement of the deep vibrator during the compaction process has been investigated in large-scale experiments. A test area was prepared and equipped in a gravel pit near Fisching (Austria). A detailed underground exploration program was carried out on the test area mainly by core drilling and dynamic probing. Down to the exploration depth of 20 m the subsoil was classified as well graded sandy gravel with low relative density, therefore ideally suited for deep vibro compaction.

2.2 Measuring technique

Several sensors were installed on the vibrator body to investigate the three-dimensional vibrator movement, which were exposed to very high demands during the compaction process. The installed sensors had to be protected against possible mechanical damages caused by larger soil grains, and since the compaction was carried out below ground water table against water penetration, too. They were protected against estimated temperature up to 170°C on the vibrator body. Therefore, a novel specific monitoring and data recording system was developed by the company VCE for the experimental field tests.

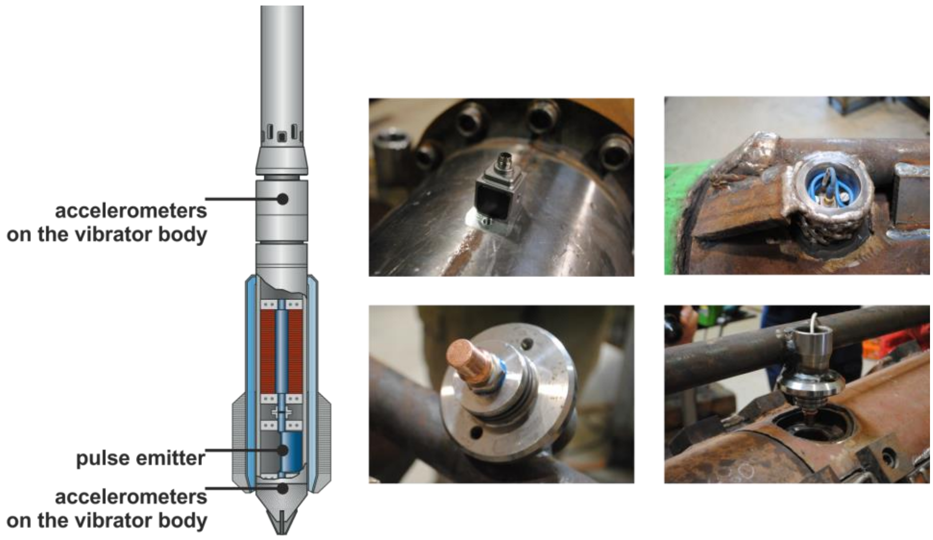

Figure 3. The position of the triaxial accelerometers and the pulse emitter on the vibrator body (left), installation of the accelerometers and the of the pulse emitter in the vibrator body (right).

Heavy duty triaxial accelerometers were installed (see Figure 3) to measure the accelerations of the vibrator tube in three orthogonal directions at the vibrator tip and the coupling. The triaxial accelerometers were mounted in thick-walled steel cylinders to protect them from mechanical damages and water penetration. The measured data could be synchronized with very high precision and were stored on a measuring computer installed behind the cab of the rig. Using the Brimos wireless data recording system the measured data could be transmitted and observed on the test area in real time. The Brimos wireless system developed by company VCE is usually used in particular for monitoring bridges and other structures.

3 SELECTED RESULTS OF THE EXPERIMENTAL FIELD TESTS

An extensive test program could be implemented within the scope of the experimental investigations. Some of the vibro compaction spots were carried out without any specifications concerning the process parameters at the discretion of a skilled machine operator in standard operation mode. Selected vibro compaction spots were treated with predetermined non-standard process parameters, wherein a variation of different compaction parameters was achieved in the highest possible range. Subsequently, selected results of the experimental field tests are presented.

3.1 New insights into the movement behaviour of deep vibrators

The detailed study of the vibrator movement reflected new substantial insights into the movement behaviour of the deep vibrator. According to previous assumptions (see Figure 4 left) the envelope of the vibrator movement was cone-shaped, the vibrator amplitude was zero at the flexible coupling, and it reached its maximum at the nose cone. In contrast to that, measurements in the experimental field tests showed different behaviour. The shape of the vibrator movement can be described as a circular hyperboloid (cooling tower-shaped surface) with lowest amplitudes in the upper third of the vibrator body and not at the flexible coupling (see Figure 4 right).

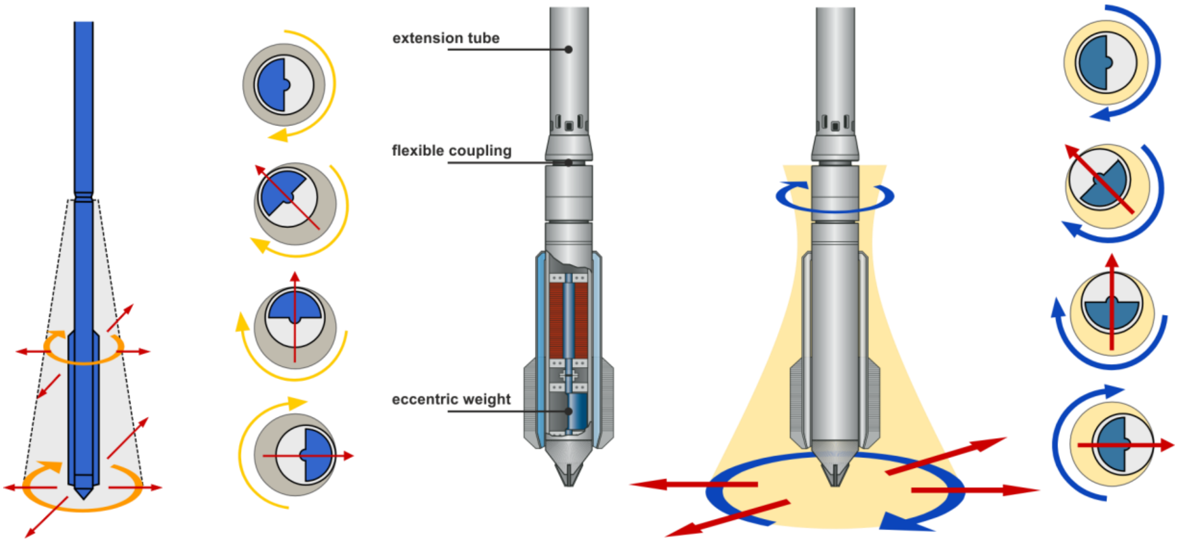

Figure 4. Vibrator movement according to the previous assumptions (left) (Kirsch and Kirsch, 2010), vibrator movement based on measurement data (right)

A more important issue than the shape of the vibrator movement is its changing, due to the changing compaction state of the adjacent soil body. Subsequently, the first fundamental findings of the dependency of the vibrator movement on the changing compaction state of the soil are presented briefly based on measurement data from a compaction spot, which was carried out in standard operation mode.

3.2 Vibrator movement during vibro compaction in standard operation mode

Figure 5 shows selected process parameters and the vibrator movement during the lowering and the compaction process. The time history of the vibrator depth and current power consumption of the electric engine are the most established parameters used by Keller (and by other companies) together with the amount of backfill material for quality assurance of the compaction works. The vibrator movement is characterized by two parameters; the amplitude of the vibrator tip and the phase angle. The phase angle is defined as the current angle between the position of the rotating eccentric mass and the direction of the vibrator movement.

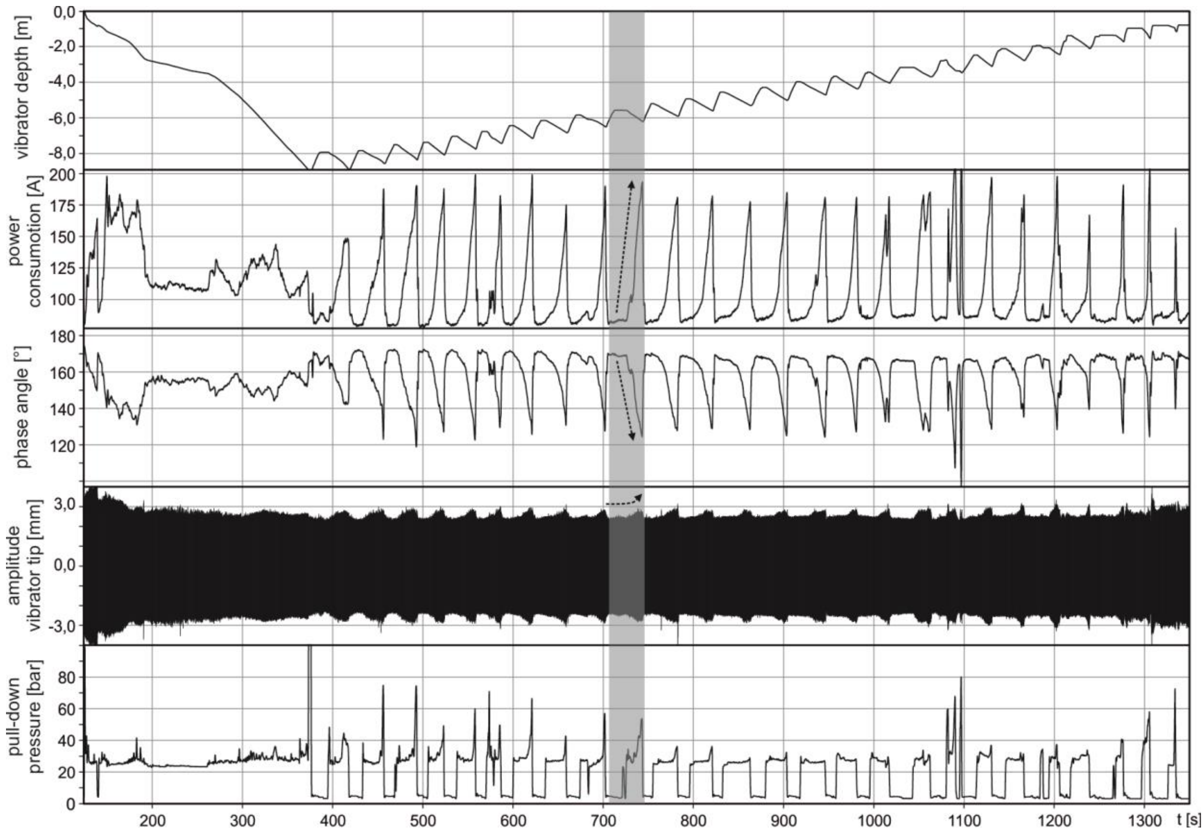

Figure 5. Time history of the vibrator depth, current power consumption of the electric engine, amplitude of the vibrator tip, phase angle and pull-down pressure during deep vibro compaction in standard operation mode (Nagy et al. 2017).

The vibrator was lowered to the intended compaction depth of 9.0 m, and the compaction was performed bottom-up sequentially using the back-step procedure by withdrawing the deep vibrator for about 0.9 m and lowering it again about for 0.5 to 0.6 m. Both the lowering and the compaction process were carried out at constant water flow pressure from the water jets at the cone nose and constant vibrator frequency of 50 Hz.

During the lowering process the soil was compacted and displaced laterally and downwards due to vibration and penetration of the vibrator cone. In Figure 5 such a compaction step is highlighted exemplarily. During the lowering process the power consumption of the vibrator motor increases with increasing resistance of the soil while during withdrawing it drops again quickly. During increase of the power consumption significant changes in the three-dimensional vibrator movement can be observed (increasing amplitude of the vibrator tip and decreasing phase angle). Figure 6 shows the horizontal movement of the vibrator tip at the beginning and the end of the lowering process during the highlighted compaction step. In both cases the vibrator tip describes almost a perfect circular shape; however, at the end of the lowering process the amplitude of the vibrator tip is higher than at the beginning, and the movement becomes more irregular.

Since all process parameters are kept constant during the compaction process the changes in the vibrator movement can only be caused by the changing compaction state of the influenced soil body. Thus, the outcomes of the discussed test confirm that the changing compaction state of the soil has a decisive influence on the vibrator movement.

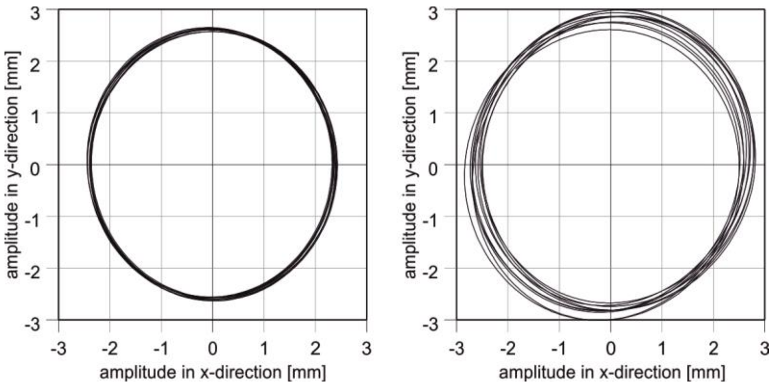

Figure 6. Horizontal movement of the vibrator tip at the beginning (left) and at the end (right) of the lowering process during the highlighted compaction step (Nagy et al. 2017).

4 CONCLUSION

The presented study demonstrates selected results of fundamental experimental investigations of deep vibro compaction. The outcomes of large-scale tests provide new insights into the highly complex soil-vibrator interaction system. The outcomes of the experimental investigation disclosed numerous previously less known mechanisms of the vibrator-soil system with high precision.
The measurement results show a clear connection between the vibrator movement and the current compaction state of the soil and a high reproducibility of the vibrator movement and essential process parameters especially the power consumption of the vibrator motor. Consequently, there is a high potential for the development of a system for *Vibrator integrated Compaction Control (VCC)*.

5 ACKNOWLEDGEMENTS

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