Work-integrated indication of compaction state from deep vibro compaction based on the vibrator movement

Indication de l'état de compactage pour le vibrocompactage basée sur le mouvement du vibreur pendant l'opération

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ABSTRACT: Deep vibro compaction (vibroflotation) is a method, which was patented by Keller in the 1930s and since then it has been successfully used worldwide for deep compaction 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 are executed. Large scale test measurements were performed to investigate the three-dimensional vibrator movement during the compaction process. Within the current large-scale field tests reliable measurements on the vibrator tube during the compaction process have been conducted for the first time worldwide. This paper presents selected results of the large-scale tests; moreover, possible indicators for the changing soil conditions are discussed.

RÉSUMÉ : Le procédé de vibrocompactage (ou vibroflottation), breveté par Keller dans les années 30, a été utilisé avec succès dans le monde entier pour le compactage de sols granulaires. Néanmoins, les méthodes de contrôle de la qualité des travaux de vibrocompactage sont en grande partie de nature empirique, et donc souvent peu fiables. Dans un projet de recherche actuel, des études expérimentales fondamentales sur le contrôle de qualité en temps réel pour le vibrocompactage ont été exécutées à grande échelle, pour étudier le mouvement vibratoire tridimensionnel pendant le processus de vibrocompactage. C'est la première fois au monde que des mesures fiables sur le tube vibreur pendant le processus de vibrocompactage ont été obtenues. Cet article présente des résultats de ces essais à grande échelle; en plus, des indicateurs possibles pour les conditions changeantes du sol y seront discutés.

KEYWORDS: deep vibro compaction, large scale field tests, real-time quality control.

1 INTRODUCTION

The three-dimensional movement of the deep vibrator is determined by the interaction between the compacted soil and the compaction device. Thus, an increase of the soil stiffness during the compaction process causes changes in the vibrator movement. Therefore, the vibrator movement together with certain process parameters can be used for a work-integrated indication of compaction state, which would provide the machine operator with valuable information on site and would be a valuable tool for the quality assurance of the compaction works.

The connection between the movement of the deep vibrator and the compaction state of the soil was first analyzed by Fellin (2000a-b) on the basis of 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 the TU Vienna, the Keller Grundbau GmbH, the VCE Vienna Consulting Engineers ZT GmbH, and the Unit of Applied Mechanics at the University of Innsbruck.

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. 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 displays the compaction process and the deep vibrator schematically.

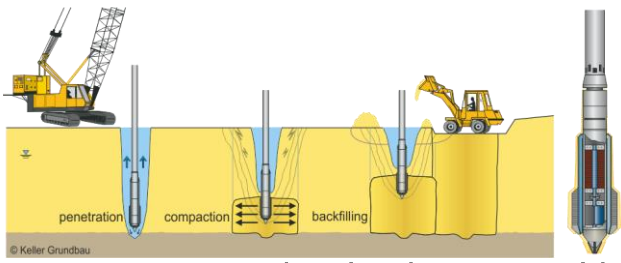

Figure 1. Compaction process during deep vibro compaction and the deep vibrator.

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 the half the withdrawing depth (back-step method).

2 COMPACTION CONTROL

2.1 *State of the art*

There are two principle ways to estimate the success of vibro compaction. In-situ using well tested site investigation methods such as dynamic probing or indirect deriving performance factors from monitored machine parameters. Both disclose advantages and disadvantages respectively. The first methods generate data, which can be converted to actual stiffness using empirical formulas. Main drawback is the spot-like testing. The latter are recorded all over the site, but they are contested in regard to their applicability on compaction performance. The most often used parameter is the power consumption of the vibrator engine expressed in terms of electrical current. There are soils (for example in northern Germany), which do not show power consumption in the vibrator although a compaction can be measured using direct methods. Nonetheless the second approach can be seen as state of the art, often in connection with random pointwise direct investigations for calibration.

2.1 *Research and development*

Current research on compaction control aims to consolidate machine generated data into easily understandable plans. Server based tools are able to accumulate and process the production protocols of columns. For example Keller's VibroScan tool uses the production data recorded by the DAQ unit of the rig for an automated quality control. The data taken from a network data base is checked for plausibility and evaluated depending on the technique applied and on the equipment used on site. A more detailed description of the tool can be found in Zöhrer and Wondre (2012). A combination of two- and three-dimensional drawings is used to visualize the results of the evaluation process (see Figure 2). Printable data using protocols are described by Zöhrer and Wondre (2012). This data can be visualized using third party software giving site managers a means for compaction control.

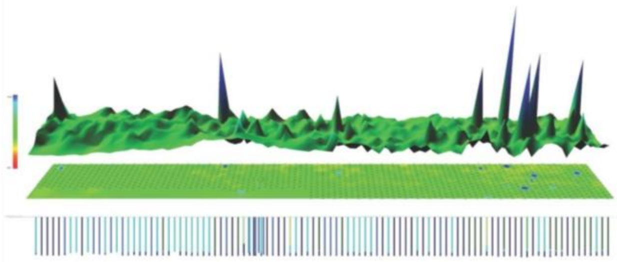

Figure 2. Visualization of compaction results, expressed as ampere factor

The drawings are used by the site managers to get a good overview of the overall conditions of the site and to be able to react quickly, if deviations to the expected conditions are detected. This of course can be seen more as a quality control than a direct compaction control. As stated before, direct methods should be used to calibrate the monitored data.

Another approach is to try to reduce the necessity of compaction control by upgrading the control units of the rigs. Automated systems are able to work using prescribed constraints such as step lengths or duration.

The aim of ongoing research on this topic is to break down the construction process into production steps or sub-processes which can be implemented in assistance systems similar to those found in modern cars. For example, such a system could position a rig automatically on the right point. At the moment sub-processes directly related to compaction are hard to identify because this requires a fundamental understanding of the underlying processes going on in the subsoil during the compaction process. At the moment this knowledge is mainly based on experience, therefor scientific field tests using precise measurement techniques have to be done.

3 IN-SITU TESTS

3.1 *Test area*

Figure 4. Test area near Fisching (Austria), divided into several subfields.

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).

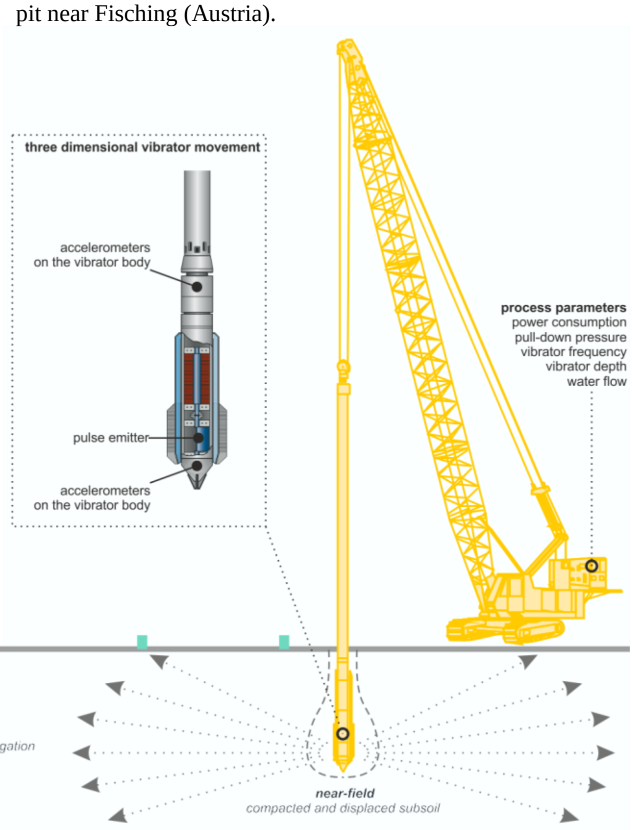

Figure 3. Basic layout of the experimental field tests

3.1.1 *Underground conditions*

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 (see Figure 5), therefore ideally suited for deep vibro compaction.

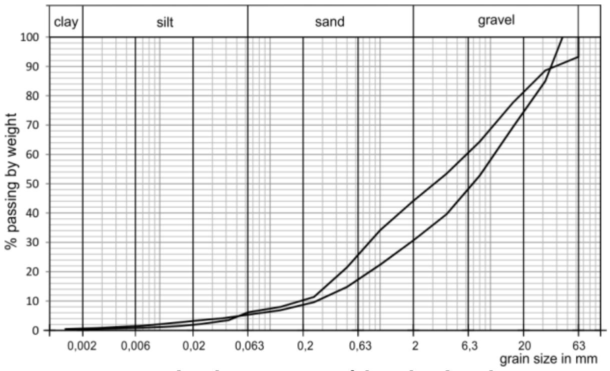

Figure 5. Grain size distribution curves of the subsoil on the test area.

3.2 *Measuring technique*

To investigate the three-dimensional vibrator movement several sensors were installed on the vibrator body, which were exposed to very high demands during the compaction process. The installed sensors had to be protected against possible mechanical damages caused by bigger 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 for the experimental field tests.

3.2.1 *Vibrator movement*

Heavy duty triaxial accelerometers were installed (see Figure 3 and 6) 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 against mechanical damages and water penetration.

Figure 6. Triaxial accelerometer on the vibrator body (left), sensor installation in steel cylinders (right).

Additionally, a special self-developed pulse emitter was used to determine the phase angle between the current position of the rotating eccentric mass and the vibrator movement. The vibrator movement can be characterized completely by means of the accelerometer measurements and of the phase angle.

In addition to the vibrator movement numerous process parameters were recorded during the compaction process (see Figure 3).

3.2.2 *Ground accelerations*

Numerous tri-axial accelerometers (see Figure 7) were positioned on the ground surface in the close surroundings of the current compaction point and up to a distance of 120 m to measure the vibration emission of deep vibro compaction.

The measured data were 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 used especially for monitoring bridges and other structures.

Figure 7. High sensitivity accelerometers on the ground surface to record ground accelerations.

4 SELECTED RESULTS OF THE EXPERIMENTAL FIELD TESTS

A very extensive test program could be implemented within the scope of the experimental investigations. A part of the vibro compaction points was compacted without any specifications with respect to the process parameters at the discretion of a skilled machine operator in standard operation mode. Selected vibro compaction points were processed with predetermined non-standard process parameters, wherein a variation of different compaction parameters was obtained in the highest possible range. Subsequently, selected results of the experimental field tests are presented.

4.1 *Compaction in standard operation mode*

Figure 8 shows selected process parameters and the vibrator movement during the compaction process at constant vibrator frequency of 50 Hz. The time history of the vibrator depth and current power consumption of the electric engine are parameters used by Keller together with the amount of backfill material for quality assurance of the compaction works.

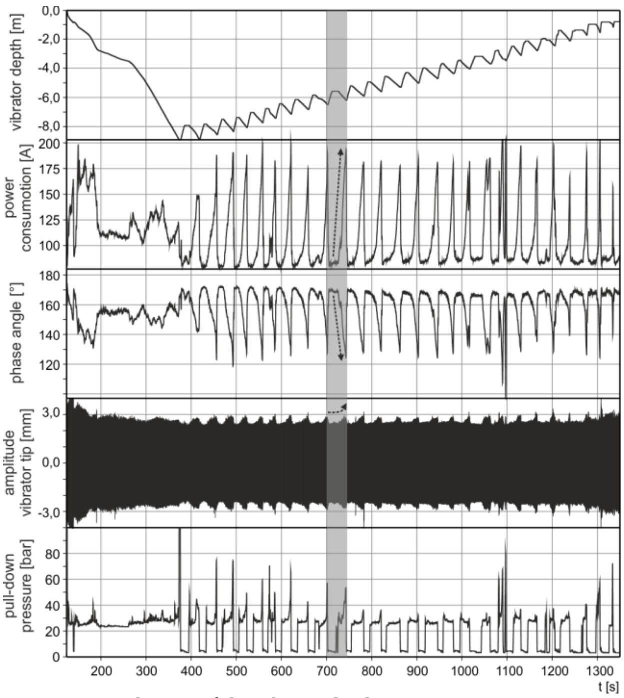

Figure 8. Time history of the vibrator depth, current power consumption of the electric engine, amplitude of the vibrator tip, phase angle, pull-down pressure during deep vibro compaction in standard operation mode.

The vibrator was lowered to the depth of 9.0 m, the compaction was performed bottom up sequentially using the back-step procedure by withdrawing the deep vibrator by 0.9 m and lowering again about by 0.5 to 0.6 m. During the lowering process the soil was compacted and displaced laterally and downwards due to vibration and penetration of the vibrator cone. In Figure 8 such a pilgrim step is highlighted exemplarily. During the lowering process the power consumption of the vibrator 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 9 shows the horizontal movement of the vibrator tip at the beginning and at the end of the lowering process during the highlighted pilgrim 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.

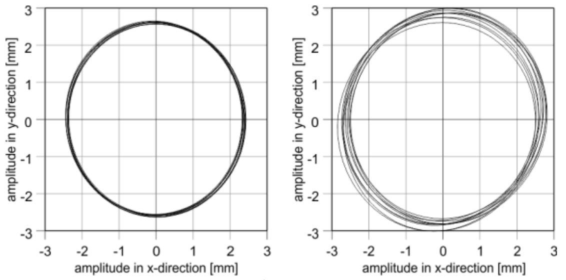

Figure 9. Horizontal movement of the vibrator tip at the beginning (left) and at the end (right) of the lowering process during the highlighted pilgrim step.

The changing vibrator movement and the connection between the discussed process parameters and the vibrator movement indicate that the rising contact pressure between soil and vibrator cone has a significant impact on the vibrator movement and generally influences the compaction process.

4.2 *Test with non-standard process parameters*

Based on the findings contact conditions between vibrator and soil have been investigated extensively within the scope of tests with non-standard process parameters. Figure 10 shows results of a test for deeper investigation of the contact conditions.

During this test the deep vibrator was lowered into an already compacted area. The vibrator engine was stopped at a certain depth and the vibrator frequency was gradually increased within 4 minutes to 60 Hz, was kept nearly constant and was reduced again to 0 Hz within 4 minutes. During this process, the pull down pressure was increased manually and reduced again at time intervals as regular as possible. Due to the high resistance of the already compacted soil a significantly higher pull-down pressure was applied than during the standard compaction process. As the highlighted range of the test data shows there is a clearly noticeable connection between pull-down pressure and the vibrator movement, which is the most evident in the higher frequency range. At relatively low pull down pressure the deep vibrator shows almost free vibrations in the subsoil. Owing to the increasing pull-down pressure the deep vibrator moves downwards and penetrates into the already compacted soil. The rapidly increasing pull down pressure is an indicator of high resistance against the penetration of the compaction device and it means high contact pressure between the soil and the vibrator cone. With increasing contact pressure, at first, the amplitude of the vibrator tip increases significantly. Then, after reaching a local maximum it declines again rapidly. Meanwhile the phase angle is decreasing simultaneously. At high contact pressure the compaction device gets more and more trapped due to the strong coupling with the surrounding soil. At low vibrator frequency no reliable evaluation of the phase angle is possible.

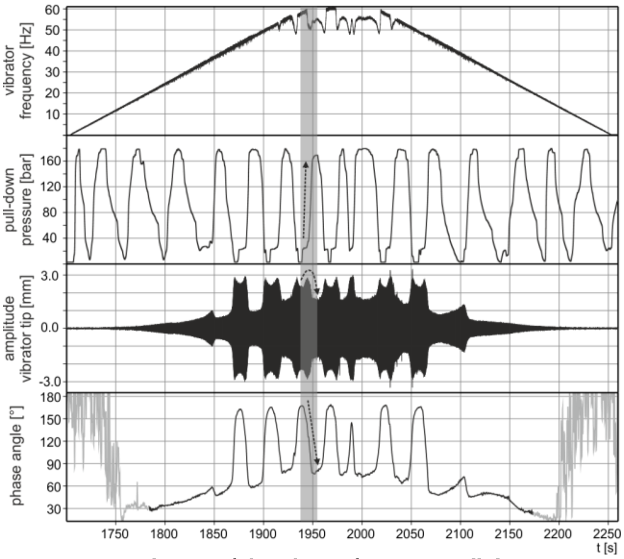

Figure 10. Time history of the vibrator frequency, pull down pressure, amplitude of the vibrator tip and phase angle, during a test with non-standard process parameters.

The outcomes of the discussed test confirm that the changing compaction state of the soil has a decisive influence on the vibrator movement.

5 CONCLUSION

The presented study demonstrates selected results of fundamental experimental investigations of deep vibro compaction. The outcomes of the large-scale tests provide new insights into the highly complex soil-vibrator interaction system. The outcomes of the experimental investigations disclosed numerous previously less known mechanisms of the vibrator-soil system with high precision.

The measurement results show generally high reproducibility of the vibrator movement and essential process parameters. Consequently, there is a high potential for the development of a real-time, work-integrated quality control system based on the three-dimensional vibrator movement and on particular process parameters.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

Fellin W. 2000a. *Deep vibration compaction as plastodynamic problem* (in German). Doctoral thesis. University of Innsbruck, Austria.

Fellin W. 2000b. Quality control in deep vibrocompaction. *Compaction of Soils, Granulates and Powders*, 133-144.

Kirsch K. and Kirsch F. 2010. *Ground Improvement by Deep Vibratory Methods.* Spon Press, New York.

Nendza M. 2006. *Untersuchungen zu den Mechanismen der dynamischen Bodenverdichtung bei Anwendung des Rütteldruckverfahrens.* (in German) Doctoral thesis. Technische Universität Carolo-Wilhelmina zu Braunschweig, Germany.

Zöhrer A. and Wondre J. 2012 Neue Entwicklungen und Anwendungen von Vibroscan. (in German) *2. Symposium Baugrundverbesserung in der Geotechnik*, 193-208.