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Quality control of deep vibro compaction based on the vibrator movement

Contrôle de la qualité du vibrocompactage fondé sur le mouvement du vibrateur

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ABSTRACT: The method of compacting granular soils using deep vibrators, which is also called as vibroflotation, was first developed in Germany over 80 years ago. As with all ground improvement techniques, the quality assurance and the control of the compaction works are fundamental and often-discussed issues. In a current research project, experimental and theoretical investigations on real-time quality control for deep vibro compaction are executed. The paper presents selected results of this research. Moreover, aspects of a work-integrated indication of the compaction state are discussed briefly.

RÉSUMÉ: La méthode de compactage des sols granulaires à l'aide de vibrateurs profonds, également appelée vibroflottation, a été développée pour la première fois en Allemagne il y a plus de 80 ans. Comme pour toutes les techniques d'amélioration des sols, l'assurance de la qualité et le contrôle des travaux exécutés de compactage sont des questions fondamentales souvent débattues. Dans le cadre d'un projet de recherche en cours, des études expérimentales et théoriques sur le contrôle de la qualité en temps réel pour le compactage vibrant profond ont été effectuées. Ce travail présente une sélection de résultats de cette recherche. Les aspects d'une indication de l'état de compactage intégrée à l'exécution sont également discutés en bref.

Keywords: deep vibro compaction, real-time quality control, large-scale field tests, analytical modelling

1 INTRODUCTION

1.1 Deep vibro compaction

Deep vibro compaction was developed and patented by Johann Keller GmbH in the 1930s, and since then it has been worldwide successful used for deep compaction of a wide range of granular soils. The principle of the process is based on particles being rearranged into a denser state through the horizontal vibration of the compaction device. Appropriate execution of this ground improvement technique increases soil density, friction angle and stiffness, which in turn give rise to homogenised subsoil, reduced settlements and reduced liquefaction potential.

The cylindrical depth vibrator (see Figure 1) is typically between about 3 m and 5 m long with external diameters between 240 and 500 mm and weighs approximately 1.5 – 4.5 tons. The core element of the vibrator is a rotating eccentric weight, which induces the horizontal vibrations of the vibrator body. The vibrator string is assembled with the vibrator and extension tubes to suit the improvement depth and suspended from a crane or mounted on a custom built base machine. 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 electric-driven.

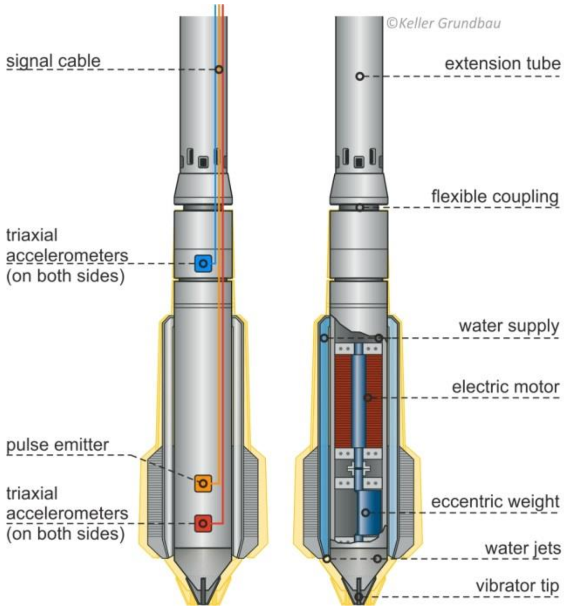

Figure 1. Deep vibrator with the measurement system used in the experimental field tests.

The compaction process is carried out bottom up after lowering the vibrator body. There are two principal ways to execute deep vibro compaction; either by vibrating at a constant depth for a fixed time or by withdrawing the vibrator, then lowering again by about the half the withdrawing depth (back-step method). In this case, the penetration process is often supported by hydraulic pull-down pressure.

1.2 Quality control of the compaction works

1.2.1 State of the art

However deep vibro compaction is a soil improvement method with a long tradition; there is currently no approved method for a reliable and continuous compaction control for this ground improvement technique available. There are nowadays two principal ways to estimate compaction success. Site investigation methods such as cone penetration testing or dynamic probing are widely used for this purpose. These techniques are often time-consuming, and one only can apply them after finishing the compaction works or during an interruption of them. Moreover, the main drawback of these testing methods is the spot-like testing. The other possibility to control the compaction works is the monitoring of process parameters recorded continuously all over the site. The most often used parameter is the power consumption of the vibrator engine expressed in terms of electrical current. Deriving compaction performance from process parameters is often contested concerning its reliability.

1.2.2 Compaction control based on the vibrator movement

In contrast to conventional testing methods, a work- and vibrator-integrated testing tool is required. That means the deep vibrator should serve not just as a compaction device but at the same time as a measurement tool. Deep vibro compaction is commonly executed in compaction patterns, which makes a systematic control of the compacted soil body possible.

The interaction between soil and vibrator determines the three-dimensional movement of the depth vibrator. Thus, an increase in the soil stiffness during the compaction process causes changing in the vibrator movement. Therefore, the vibrator movement together with specific process parameters can be used for a work-integrated indication of compaction state. Such a system can provide the machine operator with valuable information on the site. Furthermore, it is a valuable tool for quality assurance. The idea of a vibrator-integrated compaction control based has been followed for decades by several academics and construction companies, for instance by Morgan and Thomson (1983) or Fellin (2000). Systems for work-integrated quality control based on the continuous measurement and evaluation of the movement behaviour of a compaction device is well known in the construction industry. Continuous Compaction Control (CCC) is widely used in dynamic compaction, on vibratory and oscillatory roller compactors (Adam and Pistrol, 2016).

2 EXPERIMENTAL INVESTIGATION OF DEEP VIBRO COMPACTION

A pioneering basic research intended the development of the scientific basis for a system for work-integrated compaction control based on the motion behaviour of the vibrator body. For this purpose, fundamental experimental investigations were executed on a test field with an extensive test program. This research project is a collaborative effort between the Institute of Geotechnics at the TU Wien, the Keller Grundbau GmbH, the VCE Vienna Consulting Engineers ZT GmbH, and the Unit of Applied Mechanics at the University of Innsbruck.

Several compaction tests were performed in well-graded sandy gravel with low relative density — this type of subsoil suits ideally for soil improvement by deep vibro compaction.

2.1 Measurement system

A monitoring and data recording system was developed, which consisted mainly of heavy duty triaxial accelerometers and a pulse emitter installed on the vibrator tube. As Figure 1 shows, the accelerometers were settled in two measurement levels, at the elastic coupling (upper level) and above the vibrator tube (lower level). In addition to the vibrator motion process parameters were recorded during the compaction process, for instance, the vibrator frequency, pull-down pressure, vibrator depth and the power consumption of the electric motor. The measured data were synchronised with very high precision and were stored on a measuring computer installed behind the cab of the rig. A detailed description of the experimental field tests and the measurement system are presented in Nagy et al. (2017).

2.2 Selected results of the experimental field tests

The results of the current experimental investigations allowed identification of the movement behaviour of the vibrator body during the vibration in the air and the compaction process. Both are schematically shown in Figure 3.

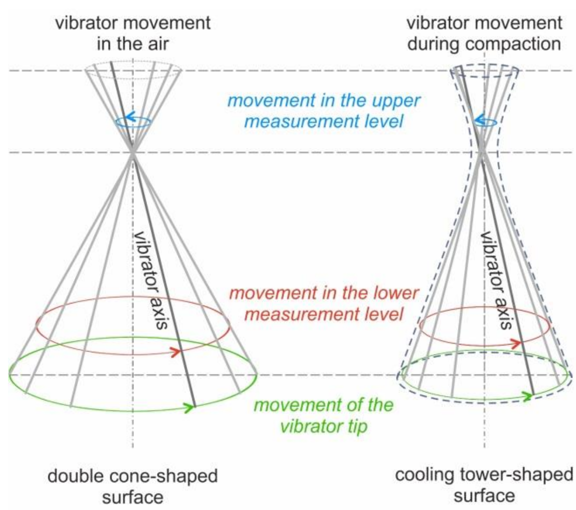

Figure 2. Movement behaviour of the vibrator body, during the vibration in the air and during the compaction process.

The movement behaviour is profoundly similar in both cases. However, the amplitudes measured during the compaction are significantly lower. A double cone-shaped surface describes the shape of the vibrator movement in the air. In contrast to that, during compaction, it can be described as a circular hyperboloid (cooling tower-shaped surface). The point with the lowest amplitude is situated in both cases in the upper third of the vibrator body.

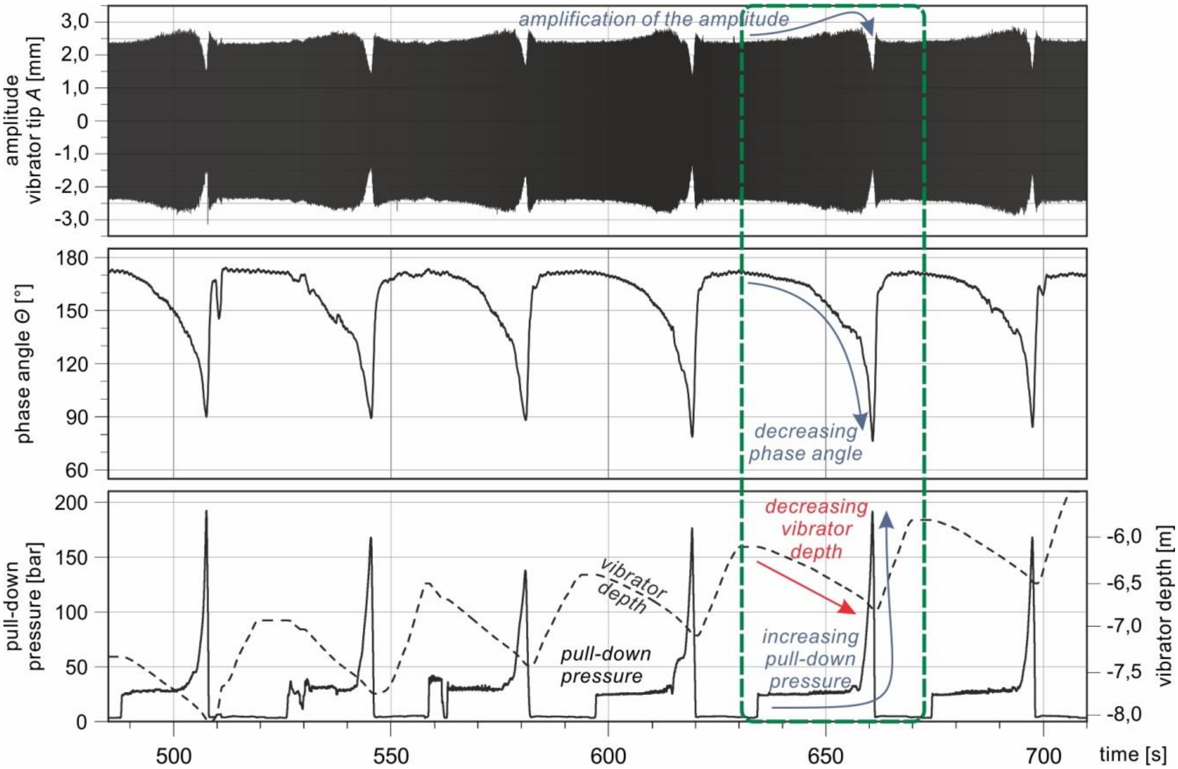

Figure 3. Time history of the amplitude of the vibrator tip, phase angle, vibrator depth and pull-down pressure during deep vibro compaction in back-step procedure.

The movement behaviour of the vibrator body is characterised by the amplitude of the vibrator tip and the phase angle. The phase angle represents the current angle between the position of the rotating eccentric mass and the direction of the movement of the vibrator body. Figure 4 shows the time history of the amplitude of the vibrator tip, phase angle, vibrator depth and pull-down pressure. As the time history of the vibrator depth shows, the compaction was performed in back-step procedure by withdrawing the vibrator, then lowering again into the subsoil. The hydraulic pull-down pressure supported the lowering process. The compaction process was executed below the groundwater table at a constant flow rate of jetted water. Due to the high permeability of the sandy gravely soil, water did not influence the investigations significantly.

The compaction process can be subdivided into individual compaction steps. During the lowering process, the soil was compacted and displaced laterally and downwards due to vibration and penetration of the vibrator cone. A significant change in the vibrator movement can be seen during each compaction step, both in the time history of the amplitude of the vibrator tip and of the phase angle. The phase angle shows a significant decrease with decreasing vibrator depth. In the amplitude of the vibrator tip is a significant decrease visible after an amplification. This movement behaviour is visible during all compaction steps in Figure 3.

Since all process parameters were kept constant during the compaction process, the changes in the movement behaviour can only be caused by the changing compaction state of the soil. Thus, the outcomes of the discussed test confirm that the changing compaction state of the soil has a decisive influence on the vibrator movement. Furthermore, there is a clear periodicity and a high reproducibility visible in the motion behaviour of the deep vibrator, which is an essential requirement for work-integrated compaction control. The movement behaviour of the vibrator is discussed in Nagy et al. (2017) further. However, alone the movement behaviour is not enough to devise reliable statements about the current compaction state of the soil. For this purpose, an analytical modelling of the soil-vibrator system is necessary.

3 ANALYTICAL MODELLING

3.1 The analytical model of the soil-vibrator system

Based on the measurement data, complementary theoretical investigations were performed. A simplified analytical model was developed, which is shown in Figure 4. The essential model parameters are shown in the figure. Thereby denotes m_u the mass, e the eccentricity, ω the angular velocity of the rotating eccentric weight, M_B the additional soil mass, which is coupled with the mass of the vibrator body M_R. The soil-machine interaction is modelled by two orthogonal arranged Kelvin–Voigt elements, represented by an elastic spring k^* and a viscous damper c^* connected in parallel.

3.2 The indication of soil stiffness using the analytical model

In general, soil stiffness is considered as a standard measure of soil improvement performance. The spring stiffness in the current analytical model can be seen as a possible indicator of the soil stiffness since in the present analytical approach this parameter is related to the stiffness of the soil. However, the spring stiffness does not directly correspond to the soil stiffness. In the present modelling approach, it represents a state-dependent reaction of the compacted soil. Therefore, the spring stiffness is denoted in the current case as state-dependent stiffness indicator, and it is denoted with the symbol k^*.

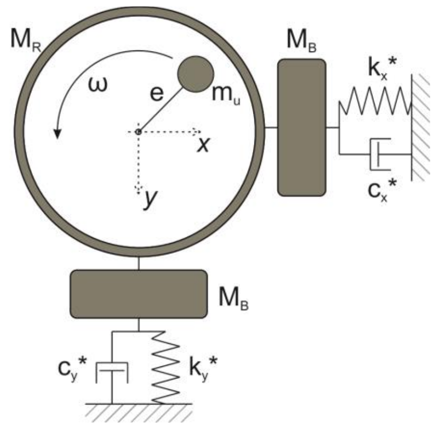

Figure 4. The analytical model of the soil vibrator system (Nagy, 2018).

The state-dependent stiffness indicator k^* was calculated from the vibrator movement using the analytical model shown in Figure 4. For the current parameter identification are the amplitude of the vibrator tip A and the phase angle Θ the most essential input parameters. As discussed above, these parameters are used for characterising the dynamic movement behaviour of the vibrator body. Since in back-step procedure compaction effect is only achieved during the lowering of the vibrator, the state dependent stiffness indicator was only calculated when the vibrator penetrates into the subsoil.

3.3 Identification of major processes in the soil during the compaction process

Figure 5 shows the movement behaviour of the deep vibrator during a single compaction step; the amplitude of the vibrator tip A and the phase angle Θ. Additionally, to these parameters, the calculated state- dependent stiffness indicator k^* and the vibrator depth and the pull-down pressure are shown. With decreasing vibrator depth a significant increase in the state-dependent stiffness indicator k^* can be seen. Since this parameter is related to the stiffness of the soil, it indicates an increasing soil stiffness due to soil compaction by the deep vibrator. A significant change in the gradient of the increasing state-dependent stiffness indicator k^* recognisable, which is marked with a purple circle in Figure 5.

This point is of high importance because it divides two major processes in the soil, which are responsible for its rising stiffness during the single compaction steps.

Due to the penetration and vibration of the vibrator cone, the subsoil is being compacted and displaced. The soil shows contractant behaviour, while the soil stiffness increases primarily due to the decreasing void ratio. Since the vibrator is continuously in interaction with the compacted soil, its movement behaviour is changing due to the increasing soil stiffness.

The void ratio cannot be reduced with the applied compaction device below a certain level. Therefore, the compaction effect is limited. During the compaction step shown in Figure 5, the vibrator depth was decreased purposely, even after the possible compaction effect was reached. Due to this reason, the already compacted soil shows dilatant behaviour. Since there is no increase in the soil volume is possible, effective soil stress rises rapidly. The stress at the contact surface between soil and vibrator cone increases too, which is indicated by the significantly upwards trending pull-down pressure. Because of the increasing effective stress in the soil, its stiffness increases rapidly too, which influences the vibrator movement. Consequentially the increasing soil stress shows up in the rapidly rising state-dependent stiffness indicator.

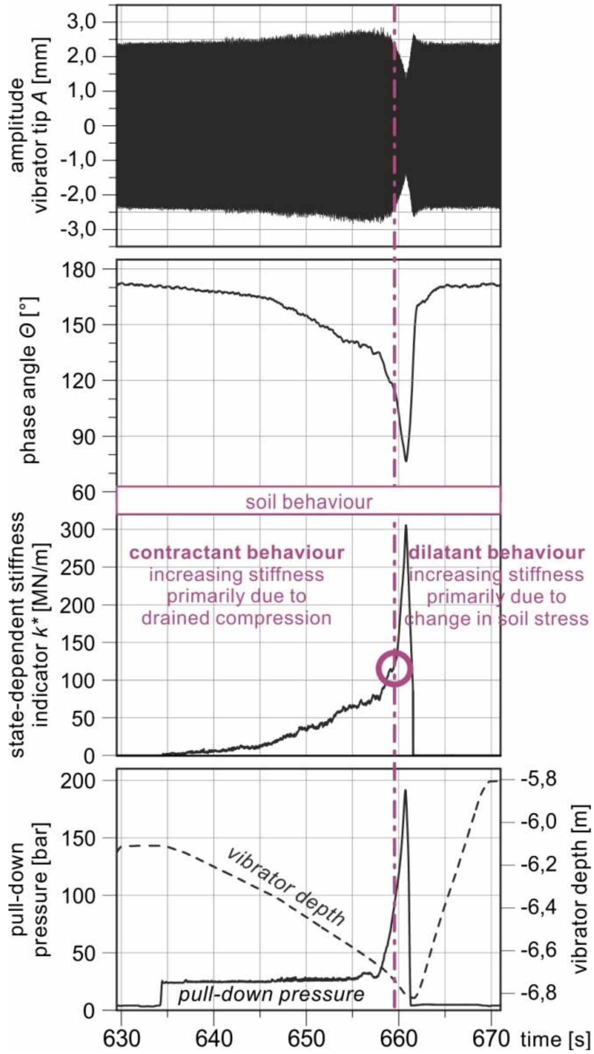

Figure 5. Time history of the amplitude of the vibrator tip, phase angle, state-dependent stiffness indicator, vibrator depth and pull-down pressure during a selected compaction step with the distinction between contractant and dilatant soil behaviour.

3.4 Compaction control based on the results of the analytical modelling

Figure 6 shows the movement behaviour of the deep vibrator, the state-dependent stiffness indicator k^*, the pull-down pressure and the vibrator depth for several compaction steps during deep vibro compaction in back-step procedure. Similar to the movement behaviour, a high reproducibility in the calculated state-dependent stiffness indicator is recognisable. A well definable transition zone between contractant and dilatant behaviour is identifiable by tagging the point in the time history of the state dependent stiffness indicator at its changing gradient. This level of the state-dependent stiffness indicator is of high importance for the compaction control.

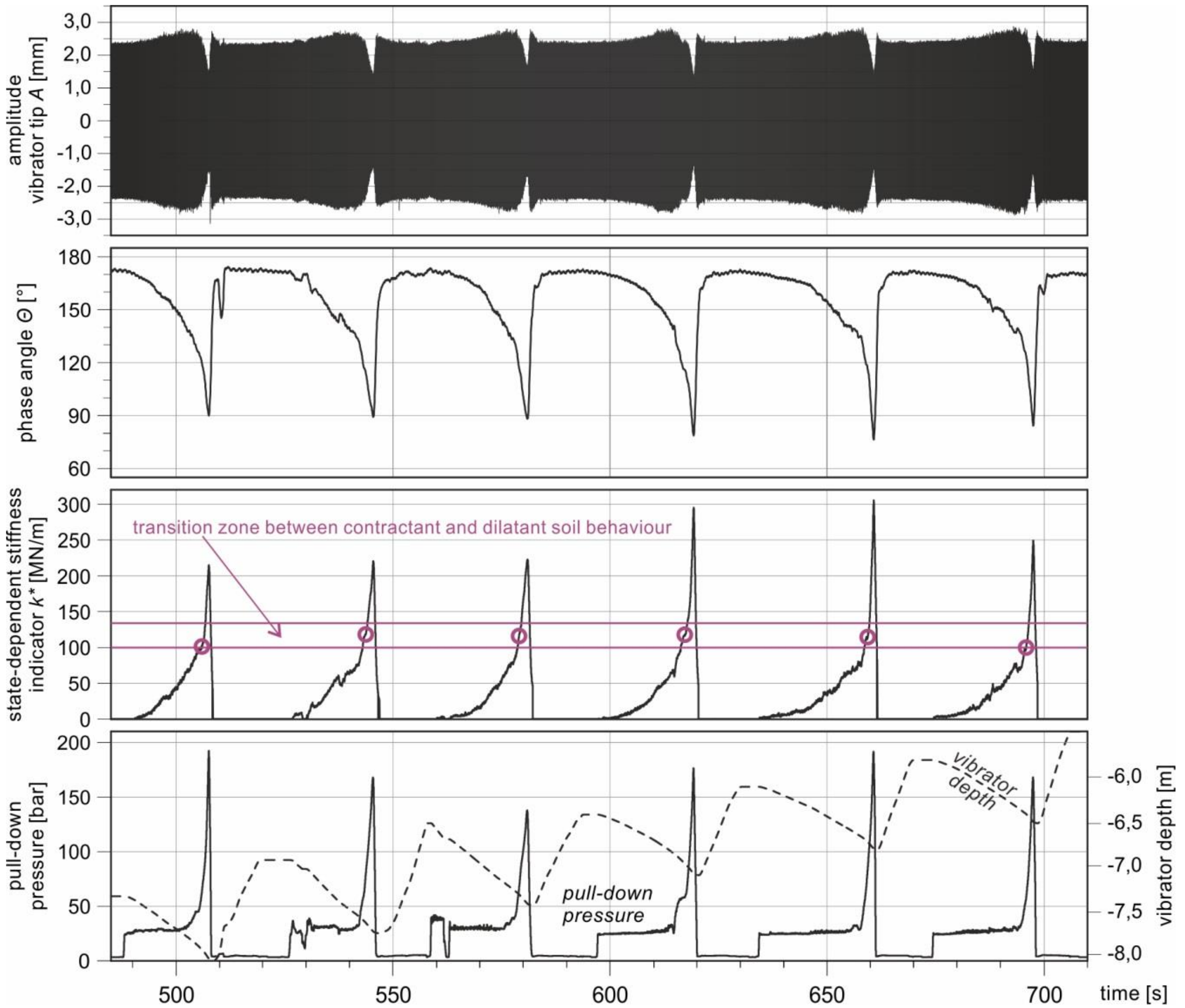

Figure 6. Time history of the amplitude of the vibrator tip, phase angle, state-dependent stiffness indicator vibrator depth, pull-down pressure during a selected compaction step.

Until the increasing state-dependent stiffness indicator does not reach the transition zone during the single compaction steps, the soil shows contractant behaviour. That means, further reduction of the void ratio and therefore additional compaction effect is possible. It is strongly recommendable to break up the single compaction steps before the transition zone is passed over. At values of the state-dependent stiffness indicator above the transition zone, dilatant soil behaviour is dominant. Thus, further penetration of the vibrator causes an increase in the soil stiffness due to the increased effective soil stress. The soil stiffness caused by the high effective stress is solely temporary, and therefore it is not related to a higher compaction effect.

That means, during dilatant soil behaviour no additional soil compaction by the deep vibrator is possible.

The increase in the soil stiffness due to deep vibro compaction was investigated using seismic cone penetration tests (SCPTu). The outcomes of these tests are presented in Nagy et al. (2018).

4 CONCLUSIONS

The outcomes of the current large-scale tests and the complementary theoretical investigations provide new insights into the highly complex soil-vibrator interaction system. The present analytical modelling of the soil-vibrator system allows an indication of increasing soil stiffness during the single compaction steps. Moreover, it made the identification of essential physical processes in the compacted soil body possible. In this way, compaction success could be quantified in the form of a parameter called state-dependent stiffness indicator, which can be derived directly from the vibrator motion. Further analysis of the state dependent stiffness indicator together with specific process parameters allowed the distinction between contractant and dilatant behaviour of the compacted soil. The transition zone between the two types of soil behaviour is related to the compaction effect, which is possible in the subsoil with this type of deep vibrator.

Based on this idea, by continuous monitoring and evaluation of the movement behaviour, a vibrator- and work-integrated control and quality assurance of deep vibro compaction is possible. Consequently, there is a high potential for the development of a system for Vibrator integrated Compaction Control (VCC).

5 ACKNOWLEDGEMENTS

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