MOTION BEHAVIOR OF DEEP VIBRATORS INVESTIGATED IN LARGE-SCALE TESTS

Peter Nagy [1], Dietmar Adam [1]

ABSTRACT:
Deep vibro compaction (vibroflotation) 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 research project, fundamental experimental investigations on real-time quality control for the deep vibro compaction were executed. Large scale tests were performed to investigate the three-dimensional vibrator motion during the compaction process. Based on the measurement data, complementary theoretical investigations were performed, and an analytical model was developed. This paper presents selected results of the large-scale tests and discusses the modelling approach briefly. Moreover, possible indicators in the measured data for the changing soil conditions are shown.

1 Introduction

The principle of the compaction process during deep vibro compaction 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 and stiffness, which in turn give rise to homogenised subsoil, reduced settlements and reduced liquefaction potential.

The deep vibrator is a steel tube with a rotating eccentric mass at the cone, which induces horizontal vibrations of the compaction device. The three-dimensional motion behavior 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. Such a system could provide the machine operator with valuable information on site during the compaction works and would be a worthwhile tool for the quality assurance of the compaction works.

Systems for work-integrated measurement and Continuous Compaction Control (CCC) have been developed in the last decades and are widely used in dynamic compaction with both vibratory and oscillatory roller compactors (Adam and Pistrol, 2016).

[1] Dipl.-Ing. Dr.techn. Peter Nagy and Univ.Prof. Dipl.-Ing. Dr.techn. Dietmar Adam, Address: TU Wien, Karlsplatz 13/220-2, 1040 Vienna, Austria, Phone No.: +43-1-58801-22115 and +43-1-58801-22100, E-mail: peter.nagy@tuwien.ac.at and dietmar.adam@tuwien.ac.at

2 Compaction control during deep vibro compaction

2.1 State of the art

There are nowadays two principal ways to estimate the success of deep vibro compaction. The first possibility is the application of well-tested in-situ site investigation methods such as dynamic probing or cone penetration testing. The other possible way is deriving performance factors indirectly, from monitored process parameters. Both disclose advantages and disadvantages respectively.

Dynamic probing and cone penetration testing are worldwide used on construction sites. These techniques generate reliable data, which can be directly used for judging the compaction success or can be converted to soil stiffness using different empirical formulas. However, these testing methods are relatively time-consuming. Their main drawback is the spot-like testing.

Process parameters are recorded all over the site, but they are often contested regarding their applicability on compaction performance. The most often used process parameter is the power consumption of the vibrator engine expressed in terms of electrical current. Server-based tools can accumulate and process the production protocols of single columns and to consolidate machine-generated data into easily understandable plans. Figure 1 shows a plot, which was generated by merging vibro compaction protocols recorded all over the construction site.

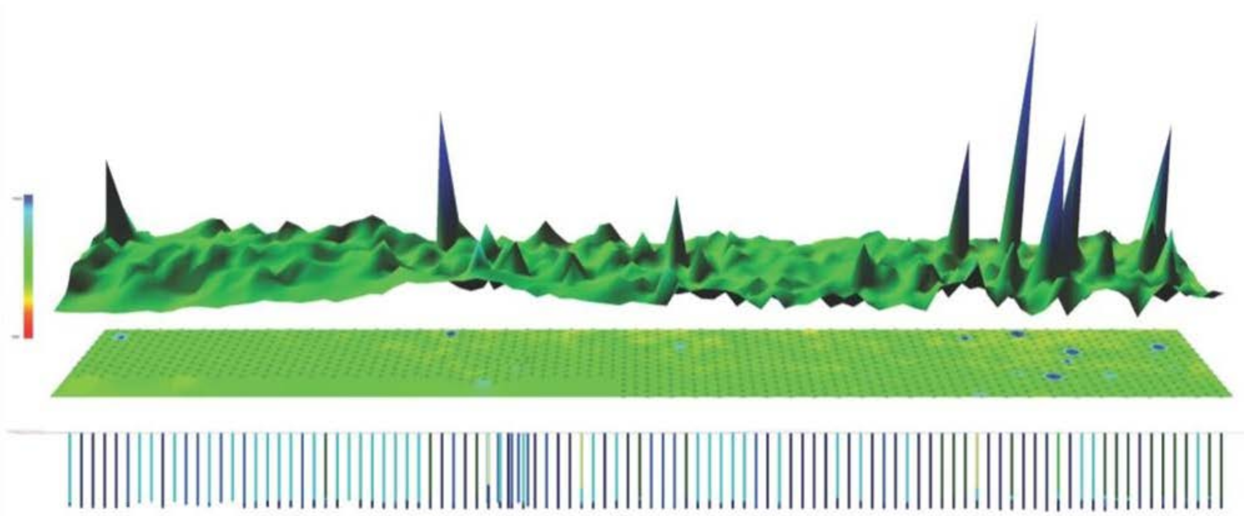

Figure 1. Visualisation of compaction results in power consumption of the vibrator engine expressed in terms of electrical current (Zöhrer and Wondre, 2012).

For example, Keller's VibroScan tool uses the production data recorded by the data acquisition unit installed on the rig for automated quality control. The data taken from a network database is checked for plausibility and evaluated depending on the technique applied on the equipment and used on the construction site. In general, a combination of two- and three-dimensional plots are used to visualise the results of the evaluation process (see Figure 1). A more detailed description of the VibroScan tool can be found in Zöhrer and Wondre (2012).

2.2 Research and development

The connection between the motion behaviour of the deep vibrator and the compaction state of the soil was first analysed by Fellin (2000a) by simple physical models and numerical simulations. Based on his theoretical investigations, Fellin (2000b) executed experimental investigations in large-scale, to measure the motion behaviour of the vibrator body. Nendza (2006) performed extensive tests in saturated sand using a model vibrator. However, reliable vibrator instrumentation and a comprehensive measurement campaign could not be realized so far.

Therefore, a pioneering basic research project was initiated to investigate the three-dimensional dynamic motion of deep vibrators comprehensively, including large-scale experimental tests and complementary theoretical investigations based on analytical models and numerical simulations. 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.

3. Large scale in-situ tests

3.1 Test area

The three-dimensional motion of the deep vibrator during the compaction process has been monitored in large-scale experiments. A test area was prepared and equipped in a gravel pit near Fisching (Austria). The test site was subdivided into four subfields (see Figure 2) with different compaction patterns.

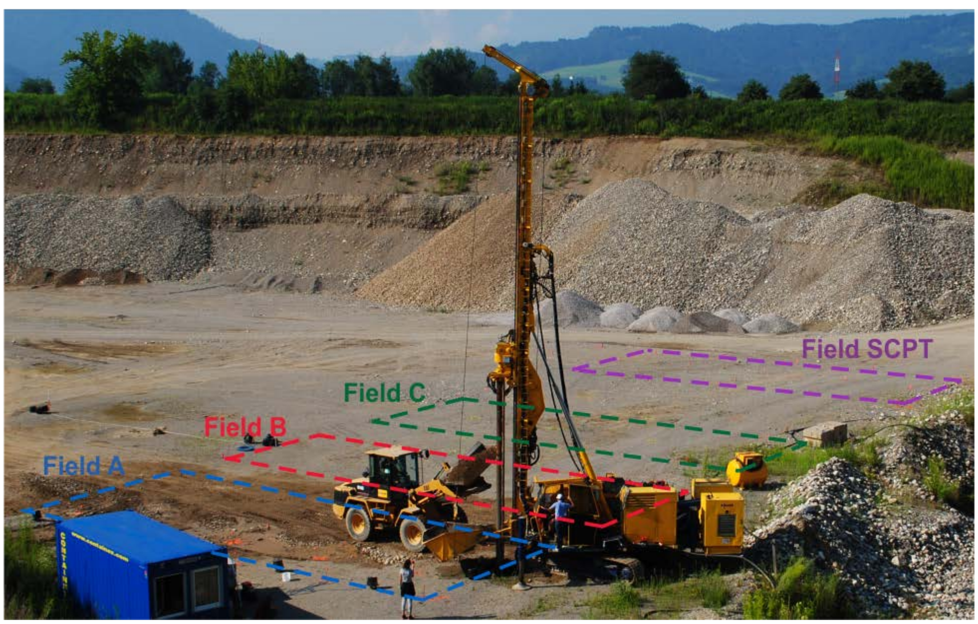

Figure 2. Large-scale in-situ tests in a gravel pit near Fisching (Austria). The test area is divided into several subfields.

A detailed underground exploration program was carried out on the test area mainly by core drilling and dynamic probing (DPH). 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. Additionally to that, within the in-situ tests, the seismic cone penetration test (SCPTu) was successfully applied to evaluate several shear wave velocity profiles in the non-compacted and compacted ground.

3.2 Measuring technique

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

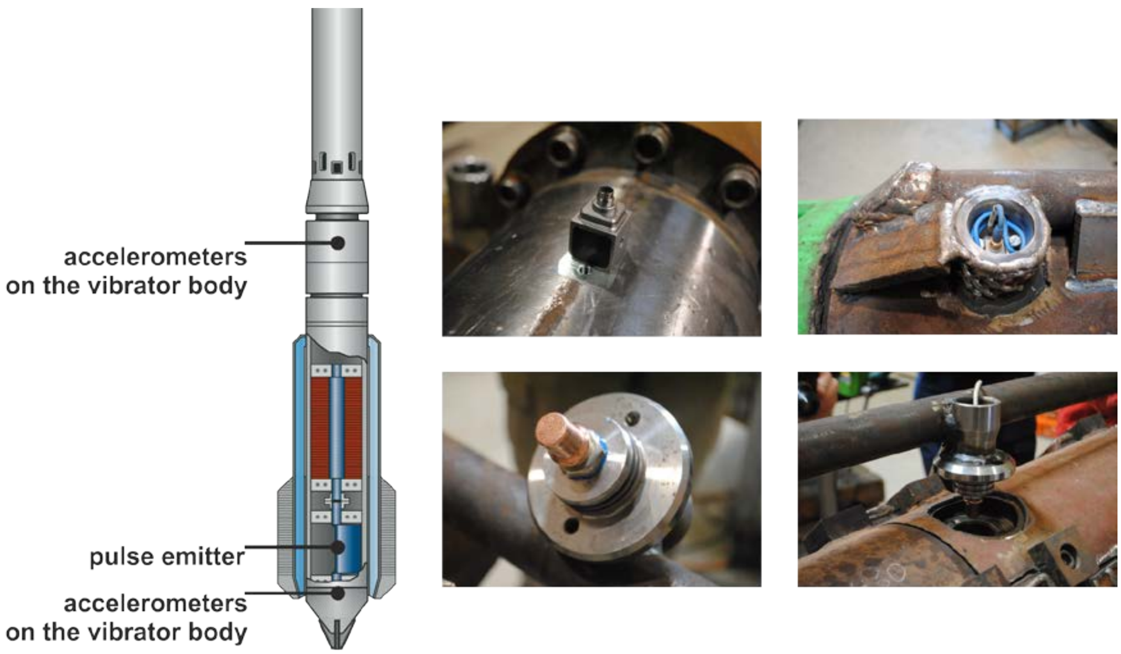

Figure 3. The position of the triaxial accelerometers and the pulse emitter on the vibrator body (left), installation of the accelerometers and the of the pulse emitter in the vibrator body (right).

Heavy duty triaxial accelerometers were installed on both sides on the vibrator tube in two measurement levels (see Figure 3) to measure the accelerations of the vibrator tube in three orthogonal directions at the vibrator tip and the coupling. Additionally, a pulse-emitter was used to determinate the current position of the rotating eccentric mass.

The triaxial accelerometers and the pulse were mounted in thick-walled steel cylinders to protect them from mechanical damages and water penetration (see Figure 3). The measured data could be synchronised with very high precision and were stored on a measuring computer installed behind the cab of the rig used during the experiments. 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 generally used for monitoring bridges and other structures.

4. Selected results of the experimental field tests

4.1 Vibrator motion during vibro compaction in standard operation mode

Figure 4 shows selected process parameters and the vibrator motion during an experiment in standard operation mode of the deep vibrator. In the first step, the vibrator tube was penetrated into the subsoil until it reached the predetermined soil improvement depth. Following that, the compaction process was executed bottom-up in back-step procedure by withdrawing a lowering of the vibrator tube sequentially.

In the current case, a pull-down force supported the penetration of the vibrator cone both during the lowering process and during the single compaction steps. During the experimental field tests, the pull-down force was recorded in terms of a hydraulic pressure, which is denoted in Figure 4 as pull-down pressure. In the current case the machine operator governed the compaction process, while he chose the process parameters based on his experience.

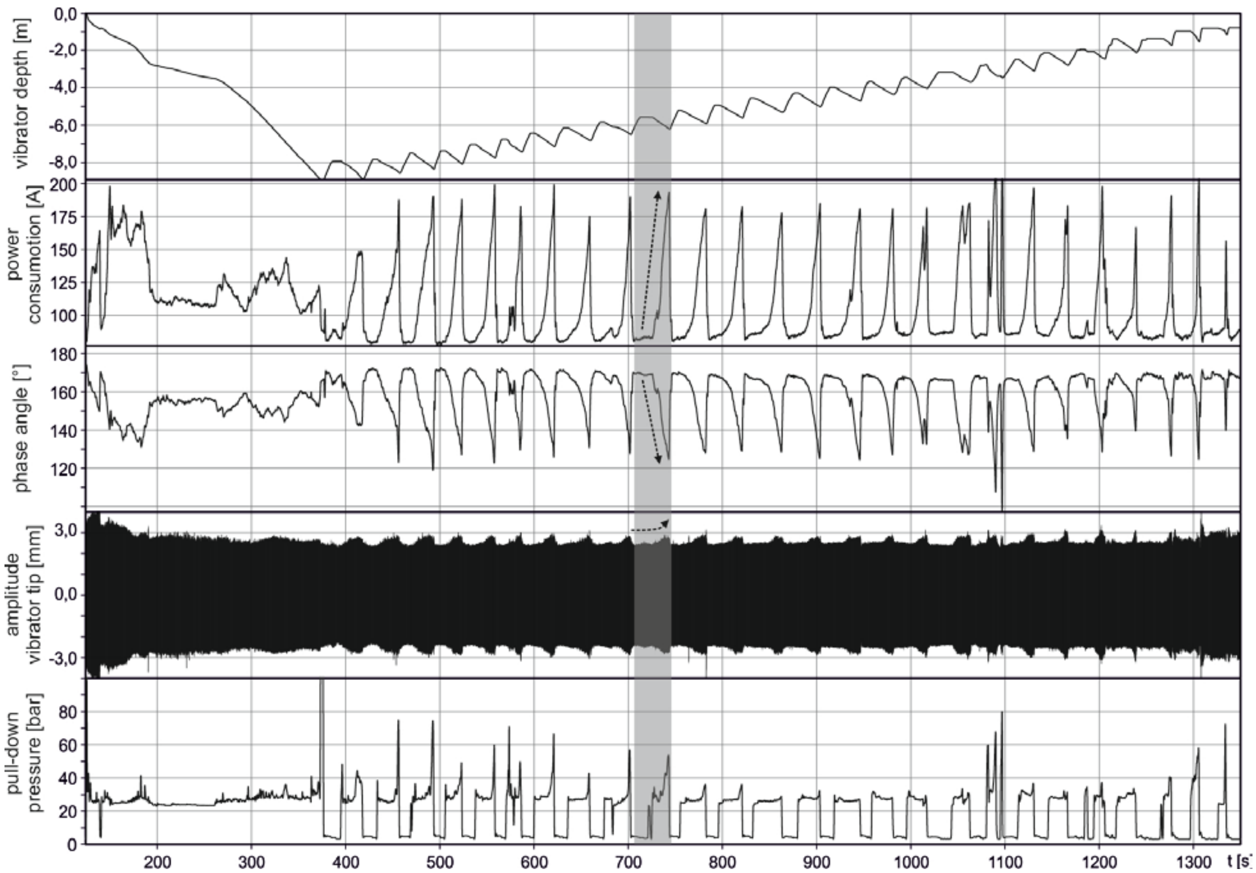

Figure 4. Time history of the vibrator depth, current power consumption of the electric engine, amplitude of the vibrator tip, phase angle and pull-down pressure during deep vibro compaction in standard operation mode (Nagy et al. 2017).

The motion behaviour of the vibrator is shown in Figure 4 both during lowering and during the compaction process. Additionally, the time history of the vibrator depth and current power consumption of the electric engine are shown. The power consumption of the electric engine in terms of the electric current and the vibrator depth together with the amount of backfill material are the most established parameter used by Keller (and by other companies) for quality assurance of the compaction works.

In the current study the vibrator motion is characterised by two parameters; by the amplitude of the vibrator tip and the phase angle. The phase angle was defined as the current angle between the position of the rotating eccentric mass and the direction of the vibrator movement. This parameter can be determined based on the measured accelerometer data and the pulse emitter signal.

As the time history of the vibrator depth shows, the compaction device was penetrated into the subsoil to the predetermined compaction depth of 9.0 m. The compaction process began at about 370 s. It 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 from the water jets at the cone nose (bottom jets) and nearby constant vibrator frequency of 50 Hz.

In Figure 4 a compaction step is highlighted exemplarily. During the lowering process, the soil was compacted and displaced laterally and downwards due to vibration and penetration of the vibrator cone. While the vibrator body is moving downwards, the power consumption of the vibrator engine increases with increasing resistance of the soil. During withdrawing drops the power consumption again quickly. During the penetration process, one can observe significant changes in the three-dimensional vibrator motion, indicated by the increasing amplitude of the vibrator tip and decreasing phase angle. Since this motion pattern recurs during all compaction steps, a clear reproducibility in the vibrator motion is visible during the whole experiment shown in Figure 4.

4.2. Influence of the contact stress between vibrator cone and soil on the motion behaviour

The contact stress between vibrator cone and soil is an essential influence factor on the motion behaviour, and therefore it was investigated extensively in the scope of the current experimental field tests. Figure 5 shows the motion behaviour of the compaction device during a selected compaction step in this experiment.

The compaction process was executed in this case also in back-step procedure, but in contrast to the experiment shown in Figure 4, the single compaction steps were not broken off at an optimal compaction depth. The vibrator depth was decreased on purpose, even after the possible compaction effect was reached. In Figure 5, slightly increasing vibrator amplitude and a significantly decreasing phase angle are visible at the beginning of the lowering process, with decreasing vibrator depth. The changing vibrator motion is more significant at high contact stress between vibrator cone and soil at the end of the compaction step. After reaching the depth of about -6.6 m further compaction and therefore a further penetration into the subsoil were hardly possible. Due to this reason, the stress at the contact surface between soil and vibrator cone increased significantly, which is indicated by the rapidly upwards trending pull-down pressure.

The local maximum of the vibrator amplitude is located at time point t_2 and marked with a vertical blue line. This specific point is denoted as the point of resonance. After reaching its local maximum, the vibrator amplitude decreased significantly, while the phase angle also decreased further on. One can observe the local minimum of both the vibrator amplitude and the phase angle at the peak value of the pull-down pressure at time point t_3. The contact stress between vibrator cone and soil and therefore the stress in the influenced soil body reaches its highest value during the compaction step at this time point. Consequentially, the effect of the increasing soil stress shows up clearly in the rapidly changing motion behaviour of the deep vibrator.

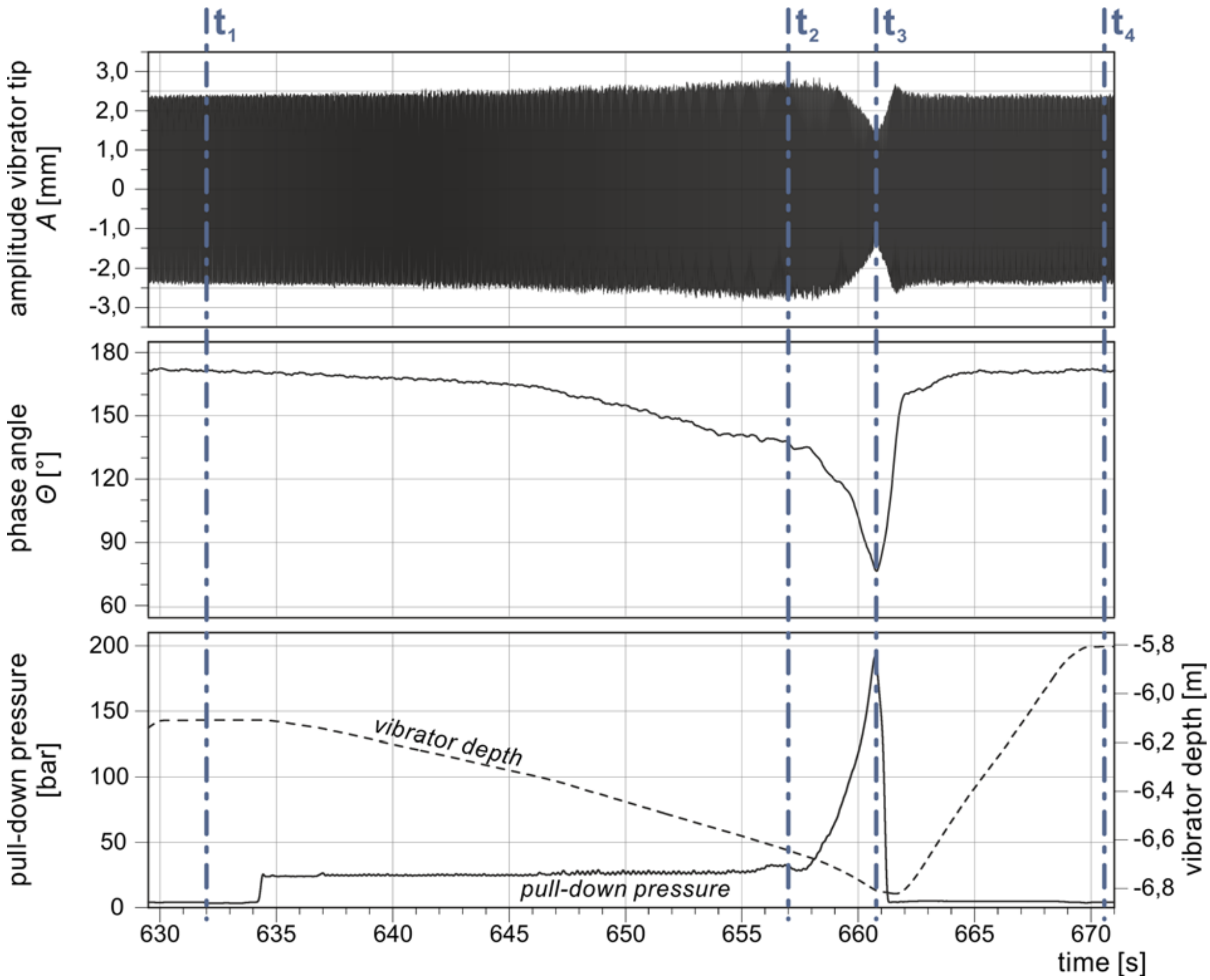

Figure 5. Time history of the vibrator depth, current power consumption of the electric engine, amplitude of the vibrator tip, phase angle and pull-down pressure at high contact stress between vibrator cone and soil (Nagy, 2018).

Figure 6 shows the horizontal movement of the vibrator tip at four different time points during the compaction step shown in Figure 5:

- at the beginning of the lowering process at time point t_1 (Figure 6a)
- at the local maximum of the amplitude at time point t_2, which is denoted as the point of resonance (Figure 6b),
- at the end of the lowering process at the local minimum of the amplitude at time point t_3 (Figure 6c) and
- at the end of the withdrawing process at constant vibrator depth at time point t_4 (Figure 6d)

In all four cases the vibrator tip describes almost a perfect circular shape. Nearly the same amplitudes were measured both in the x- and the y-direction. However, the amplitudes in the x-direction are tending to be slightly smaller due to vibrator wings oriented in the y-direction. At the point of resonance, the amplitude of the vibrator tip is higher than in the other cases. Moreover, the motion becomes here more irregular than at the beginning of the compaction step and at the end of the withdrawing process, the shape of the circles is slightly deformed.

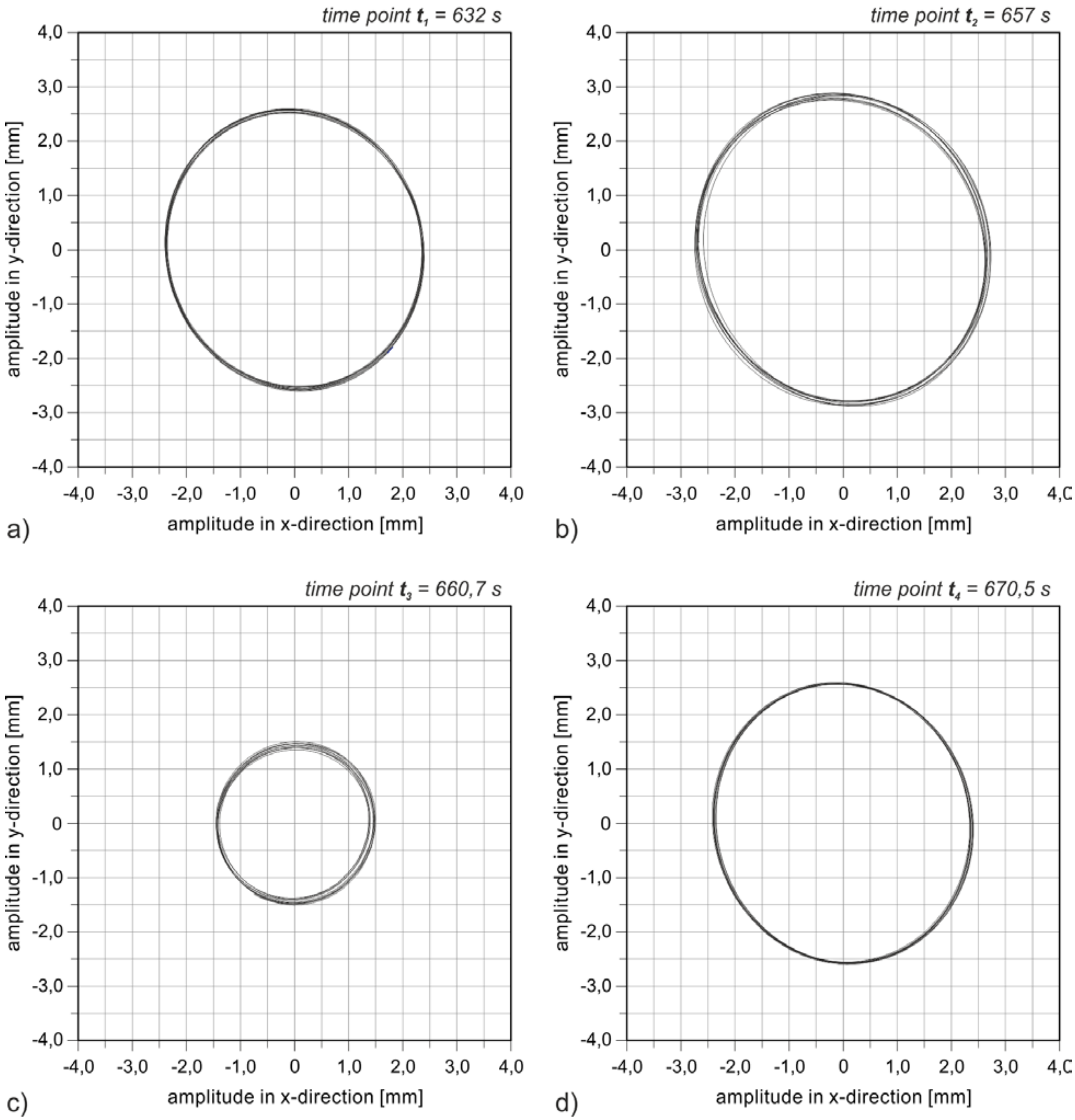

Figure 6. Horizontal movement of the vibrator tip at the beginning (left) and the end (right) of the lowering process during the compaction step shown in Figure 5 (Nagy, 2018).

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.

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 (2018) in detail.

However, the movement behaviour alone is not sufficient to ascertain reliable statements about the current compaction state of the soil. For this purpose, an analytical modelling of the soil-vibrator system was developed.

5 The analytical model of the soil-vibrator system

Based on the measurement data, complementary theoretical investigations were performed, and an analytical model of the soil-vibrator system was developed. Figure 7 shows a comparison of the measured motion behaviour with the theoretical solution for the forced vibration of a single degree of freedom system. Machines with a rotating eccentric mass can be modelled in many cases using a single degree of freedom system with rotating-mass-type excitation.

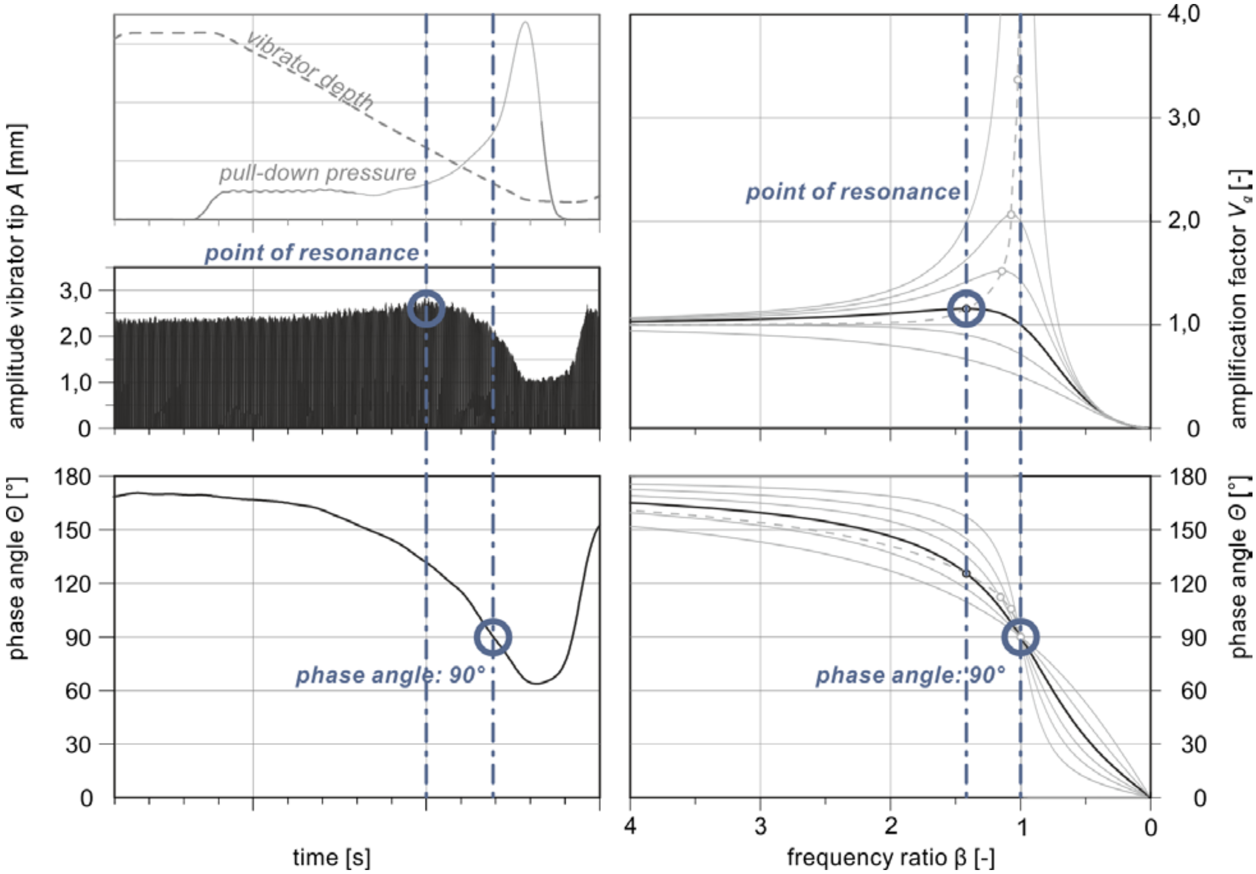

Figure 7. Comparison of the measured motion behaviour with the forced vibration of a single degree of freedom system (Nagy, 2018).

A clear agreement between the measured motion behaviour and the theoretical solution can be seen on the basis of the data shown in Figure 8. Amplification in the amplitude at a reducing phase angle is visible in both cases. At the point of resonance, the measured phase angle is in accordance with the theoretical solution significantly higher than 90°. Therefore, the local maximum in the vibrator amplitude and the reducing phase angle can be explained as a resonance of a single degree of freedom system with rotating-mass-type excitation. Due to the agreement between the measured data and the theoretical solution, this modelling approach can be used for the soil-vibrator system.

The simplified analytical model used in the current theoretical investigations can be seen in Figure 8. The essential model parameters are shown in the figure. Thereby m_u denotes the mass, e the eccentricity, ω the angular velocity of the rotating eccentric weight, and 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. In the present modelling approach it is assumed that the deep vibrator is embedded in the soil to be compacted on all sides during the entire compaction process.

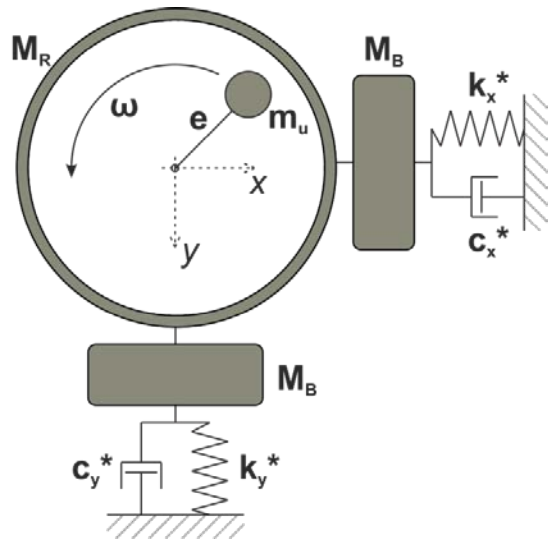

Figure 8. The analytical model of the soil-vibrator system.

The following equations of motion describe the motion behaviour of the system shown in Figure 8:

$$
\begin{aligned}
(M_R + M_B)\,\ddot{x} + c_x^*\,\dot{x} + k_x^*\,x &= m_u e \omega^2 \cos(\omega t) \\
(M_R + M_B)\,\ddot{y} + c_y^*\,\dot{y} + k_y^*\,y &= m_u e \omega^2 \sin(\omega t)
\end{aligned}
\qquad \text{Eq. 1}
$$

In general, soil stiffness is considered as a standard measure of soil improvement performance. Therefore, especially the spring stiffness can be seen as a possible indicator for the current compaction state of the soil.

Despite its simplicity, the current analytical model is able to represent the essential processes in the soil-vibrator system. The most important one is the increasing soil stiffness as a result of deep vibro compaction. Using the current analytical model the connection between the changing vibrator movement and the increasing soil stiffness can be clarified, which represents an essential finding for the development of a vibrator- and work-integrated compaction control system for the investigated deep vibro compaction (vibroflotation) technique.

6 Conclusion

This paper presents a basic research project initiated to investigate the three-dimensional dynamic motion of deep vibrators applied for deep vibro compaction (vibroflotation). Selected results of fundamental large-scale experimental investigations are shown and discussed in detail. The outcomes of the large-scale tests provide new insights into the highly complex soil-vibrator interaction system. Numerous, previously less-known mechanisms in the vibrator-soil system and essential influence factors on the vibrator motion could be clarified with high precision. In this paper, especially the influence of the contact stress between vibrator cone and soil is pointed out.

The analytical modelling makes the consideration of the significant processes in the soil-vibrator system possible. Therefore, the development of a suitable analytical model is essential for a vibrator- and work-integrated compaction control system during deep vibro compaction. A high agreement between the measurement data and the theoretical solution for forced vibration of a single degree of freedom system could be found. This key finding made the use of this simple analytical approach in the scope of the further theoretical investigations possible.

Acknowledgement

The financial support kindly granted by the Austrian Research Promotion Agency and the Austrian Society for Geomechanics made this research possible and is therefore gratefully acknowledged.

References

Adam, D., Pistrol, J. 2016. Dynamic roller compaction for earthworks and roller-integrated continuous compaction control: State of the art overview and recent developments. *Proceedings, Conferenze di Geotecnica di Torino, XXIV Ciclio*. (Eds: Manassero, M., Dominijanni, A., Foti, S., Musso, G.) 1-41. Torino, Italy.

Fellin, W. 2000. *Deep Vibro Compaction as Plastodynamic Problem* (in German). Doctoral thesis, University of Innsbruck, Austria.

Nagy, P., Adam, D., Kopf, F. Freitag, P. 2017. Work-integrated indication of compaction state from deep vibro compaction based on the vibrator movement. *Proceedings, 19th International Conference on Soil Mechanics and Geotechnical Engineering.* (Eds: Lee, L., Lee, J., Kim, H., Kim, D.). 2603-2606. Seoul, Republic of Korea.

Nagy, P., Adam, D., Kopf, F. Freitag, P. 2017. Experimental and theoretical investigation of deep vibro compaction. *Proceedings, XVI Danube - European Conference on Geotechnical Engineering*. (Eds: Jovanovski, M., Jankulovski, N., Moslavac, D., Papic, J.). WILEY Ernst & Sohn, Volume 2 (2018), 725 – 730. Skopje, Macedonia.

Nagy, P. 2018. *Deep Vibro Compaction – Compaction Control Based on the Vibrator Movement* (in German). Doctoral thesis, TU Wien, Vienna, Austria.

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