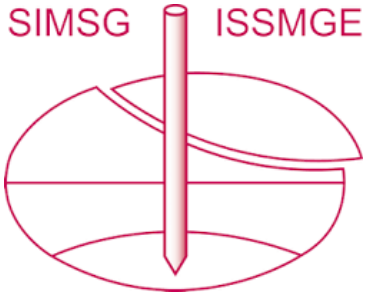
INTERNATIONAL SOCIETY FOR
SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING



This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

https://www.issmge.org/publications/online-library

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

The paper was published in the proceedings of the 6th International Conference on Geotechnical and Geophysical Site Characterization and was edited by Tamás Huszák, András Mahler and Edina Koch. The conference was originally scheduled to be held in Budapest, Hungary in 2020, but due to the COVID-19 pandemic, it was held online from September 26th to September 29th 2021.

Evaluation of the compaction effect from deep vibro compaction

Peter Nagy
Unit of Applied Mechanics, University of Innsbruck, Innsbruck, Austria, peter.nagy@uibk.ac.at

Dietmar Adam
Institute of Geotechnics, TU Wien, Vienna, Austria, dietmar.adam@tuwien.ac.at

Peter Freitag
Keller Grundbau Ges.mbH, Vienna, Austria, peter.freitag@keller.com

ABSTRACT: Deep vibro compaction was investigated in large-scale experimental field tests. Within these in-situ tests, the seismic cone penetration test was successfully applied to evaluate the shear wave velocity profile in the non-compacted and the compacted sandy gravel. On this test site complementary DPH tests were performed. Additionally, the influence of different process parameters on the compaction effect in the ground was investigated by conventional cone penetration tests performed in non-saturated uniform sand. The paper presents the concept of the research project briefly, wherein the importance of the in-situ tests is highlighted. Furthermore, test results are shown and discussed.

Keywords: deep vibro compaction; compaction effect, seismic cone penetration test; large-scale test

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 and stiffness, which in turn give rise to homogenized subsoil, reduced settlements and lower liquefaction potential of the improved soil layer.

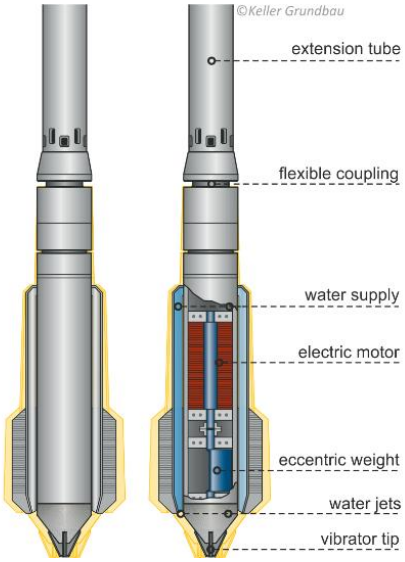


Figure 1. Deep vibrator.

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 between approximately 1.5 and 4.5 tons. Detailed information on machine and performance parameters are discussed in [1] and [2].

Deep vibro compaction is a soil improvement method with a long tradition; nevertheless, there is currently no standardized method for continuous compaction control for this ground improvement technique available.

1.2. Quality control during deep vibro compaction

There are nowadays two principal ways to estimate compaction success. On the one hand, site investigation methods such as cone penetration testing (CPTu), dynamic probing (primarily DPH) or standard penetration test (SPT) are worldwide widely used for this purpose. Other ground investigation methods like the flat dilatometer test (DMT) or the Ménard-pressuremeter (PMT) are seldom applied for compaction control. In the more recent years, the CPTu has worldwide become popular for quality control for deep compaction since it is relatively fast and cost-effective, renders a continuous profile, gives reliable and repeatable measurement and more than one measurement value [3]. Massarsch [4] estimated the changing in situ stress state due to deep vibro compaction based on CPTu results. However, in situ testing methods are often time-consuming, and can just be applied after finishing the compaction works or during an interruption of them. But the main disadvantage of these testing methods is the spot-like testing.

On the other hand, the compaction works can be controlled by monitoring process parameters recorded continuously all over the site. The most often used value is the power consumption of the vibrator engine expressed in terms of electrical current or hydraulic pressure.

However, deriving compaction performance from process parameters is often contested concerning its reliability [5].

1.3. Compaction control based on the vibrator movement

In contrast to conventional testing methods, a work- and vibrator-integrated testing tool would improve the quality of the compaction works. 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 entire compacted soil body possible.

The interaction between soil and vibrator determines the three-dimensional motion behavior of the depth vibrator. Thus, an increase in the soil stiffness during the compaction process causes changes in the vibrator movement. Therefore, the vibrator motion, evaluated together with specific process parameters, is proper for a work-integrated indication of the current compaction state. Such a system can provide the machine operator with valuable information on the site. Furthermore, it could be an appropriate tool for quality assurance.

The idea of a vibrator-integrated compaction control based on the motion behaviour of the compaction device has been followed for decades by academics and construction companies. Systems for work-integrated quality control based on the continuous measurement and evaluation of the movement behavior of a compaction device are well known in the construction industry. Continuous Compaction Control (CCC) is broadly used in dynamic compaction, both on vibratory and oscillatory rollers [6].

2. Experimental investigation of deep vibro compaction

2.1. Research aim

A pioneering basic research intended the development of the scientific basis for a system for work-integrated compaction control based on the motion behavior 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.

The outcomes of the large-scale tests and the complementary theoretical investigations on continuous monitoring and evaluation of the movement behavior, a possibility for a vibrator- and work-integrated control and quality assurance of deep vibro compaction are presented in [1] and [7] in detail.

2.2. Cone penetration test to investigate the effect of deep vibro compaction

However, the investigations on the test field were not limited to the documentation of the vibrator motion. In the scope of the experimental field tests, the cone penetration test (CPTu) and the seismic cone penetration test (SCPTu) were used on two different test sites in Austria to control the compaction effect and the influence of various process parameters on the compaction success. Additionally, the dynamic probing heavy (DPH) was applied for this purpose in sandy gravel, which is considered as a standard soil investigation tool in Austria.

Cone penetration test or dynamic probing proved – in spite of the spot-like testing – utterly valuable for control and verification of compaction effect derived from the vibrator movement. Therefore, these testing methods were used extensively during both experimental field tests. All CPTu and the SCPTu tests were performed and evaluated by the Fugro Consult Kft. Subsequently, test results from the two test sites are shown and discussed in this paper.

On the first test site, the seismic cone penetration test was successfully implemented to evaluate shear wave velocity profiles in the non-compacted and compacted sandy gravel. These investigations are shown in chapter 3.

In the second case, the effect of differences in process parameters on the distribution of compaction effect in the ground was evaluated by the cone penetration test. These tests were performed in non-saturated loose uniform sand. Chapter 4 focuses on these test results.

3. Determination of shear wave velocity profiles in sandy gravel

3.1. Assessment of soil improvement quality with the cross- and downhole technique

Geophysical ground investigation techniques for determination of dynamic soil parameters generally comprise the great advantage of allowing measurements on undisturbed ground. The ground can be investigated without changing its stress state significantly. Field tests for the determination of dynamic soil parameters are based on the principle of elastic wave propagation and therefore provide parameters that are limited in the range of very small strains.

During a seismic cone penetration test, the shear wave velocity profile of the ground is determined, based on the principle of the seismic downhole test. Hammer impact on the ground surface generates seismic waves and accelerometer installed behind the cone register the seismic body waves propagating in the underground.

According to the elasticity theory, the relationship of the shear modulus G_0, the soil density ρ, and the shear wave velocity v_s is as follows:

$$G_0 = \rho \, v_s^2 \tag{1}$$

Hence, the shear modulus can be determined using in-situ seismic methods. Since in such tests the shear wave

velocity is determined. The shear strain amplitude in such a test is usually in the range of very small strains, of the order of 10^{-6}.

This testing method is much simpler and faster and less expensive than a conventional downhole test. Since the sensors are installed above the cone, they can be penetrated easily in the ground, no borehole is necessary. During the penetration process, the standard CPTu parameters are being recorded, which provide further valuable information about the ground, in addition to the shear wave velocity profile [8].

In general, one can consider soil stiffness as a standard measure of soil improvement performance. Therefore, cross- and downhole technique can be seen as ideal tools for evaluating soil improvement performance since the measured shear wave velocity corresponds to the small strain stiffness of the soil.The strain dependency of the soil stiffness is extensively discussed in the literature [9].

Due to the relatively high costs, the cross- and downhole technique are generally rarely used for site investigations. However, in the literature, some examples of using the downhole or the crosshole technique can be found for assessment of soil improvement works. Massarsch and Broms [10] performed seismic crosshole tests in vibrocompacted sand fill to determinate the shear modulus, which was calculated from the measured shear wave velocity. In that case, the shear modulus increased significantly due to vibrocompaction. Massarsch and Eriksson [11] determined the deformation properties of dry mixed-in-place columns in the field, with seismic downhole tests, by measuring the shear wave velocity, which was related to the small-strain shear modulus of the soil. Wehr and Berg [12] performed crosshole measurements in different directions, before and after installation of “powder columns” using the vibro replacement technique. A significant increase in the shear wave velocities could be observed in all measurements. The increasing shear wave velocity corresponds to a rising soil stiffness as a result of vibro replacement.

3.2. Evaluation of shear wave velocity using the seismic cone penetration test

The large-scale compaction tests, including investigations using the seismic cone penetration test (SCPTu) technique, were carried out on a test site in a gravel pit, in Styria, Austria.

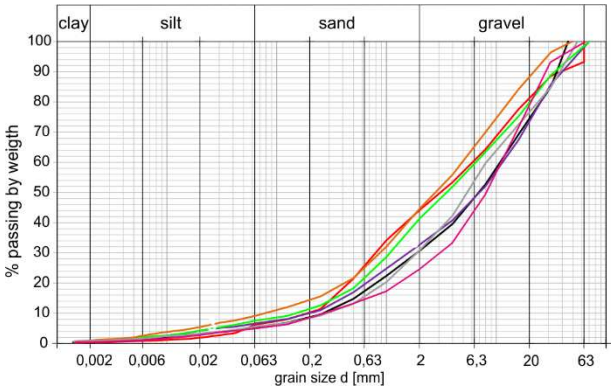


Figure 2. Grain size distribution curves of the subsoil on the test area in Styria, Austria [4].

An extensive pre-compaction ground exploration program was carried out on the test area mainly by core drilling and dynamic probing heavy (DPH). Down to the exploration depth, the subsoil was classified as well-graded sandy gravel with low relative density, therefore ideally suited for deep vibro compaction. Figure 2 shows grain size distribution curves of samples taken on the test site. The ground water level lay 2.0 meters below the ground surface.

In the scope of the experiments, the soil compaction was carried out up to a depth of 9.0 m using a deep vibrator of the company Keller. The compaction process was executed in back-step procedure, with compaction steps of between 0.4 and 0.6 meters. The experiments are discussed extensively in [4].

3.3. Execution of the SCPTu tests

In the scope of the testing program, individual vibro compaction slots were investigated, which made a straight comparison of the shear wave velocities in the non-compacted and compacted subsoil possible.

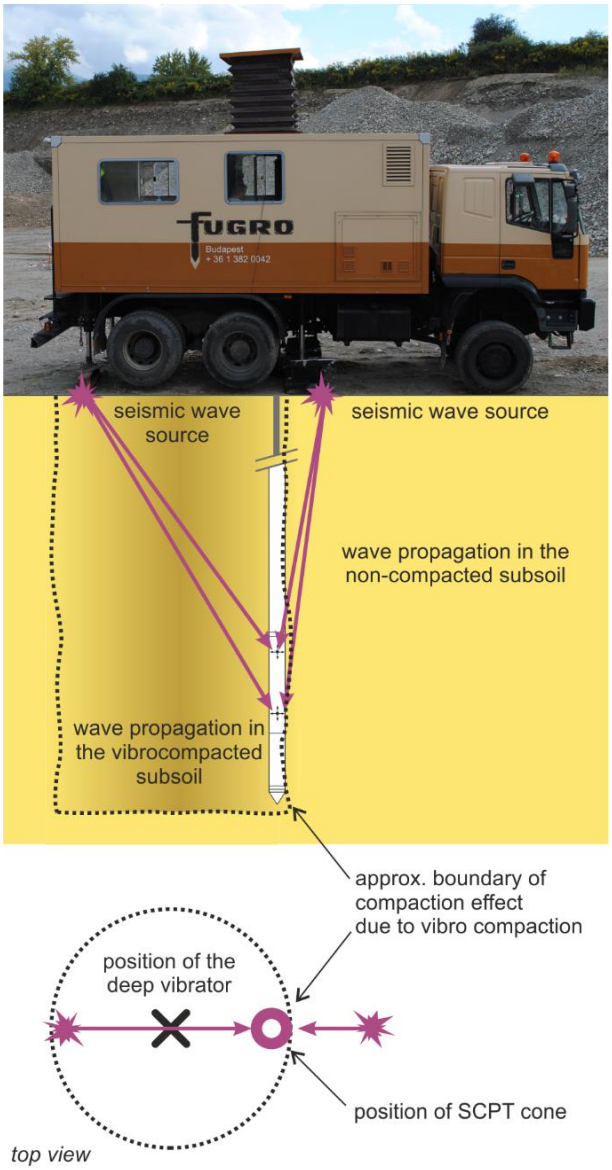


Figure 3. Seismic cone penetration test to compare shear wave velocity in non-compacted and compacted subsoil.

Tests were executed after finishing the compaction works. The standard investigation process was slightly adapted to enable the comparison of the wave propagation velocities in the natural and the treated soil. Figure 3 illustrates the testing concept schematically.

At a certain measurement depth, seismic waves were triggered on two different positions on the ground surface. The vibration sources were arranged to allow the determination of the shear wave velocity both in the non-compacted and compacted soil.

The seismic cone was penetrated in a distance of 1.5 m from the center of the respective vibro compaction slot. This distance represented the approximate radial compaction effect of the vibrator. The underground was loosened in the upper 1.5 to 2.0 meters before the SCPTu tests to minimize the danger of cone damage. During the test, the cone tip was positioned at depth intervals of 1.0 m. Vibrations were triggered on the ground surface through a horizontal hammer impact on a steel beam. Two triaxial accelerometers in the cone registered the signals of the propagating body waves. In the scope of the test program, eleven selected compaction slots were investigated in total.

3.4. Test results

Since a seismic cone with two accelerometers was used in the current field test, the shear wave velocities could be evaluated using the interval velocity method [13]. The vertical distance between the two sensors was 50 cm. The first arrival of the shear wave was determined using the cross-correlation technique.

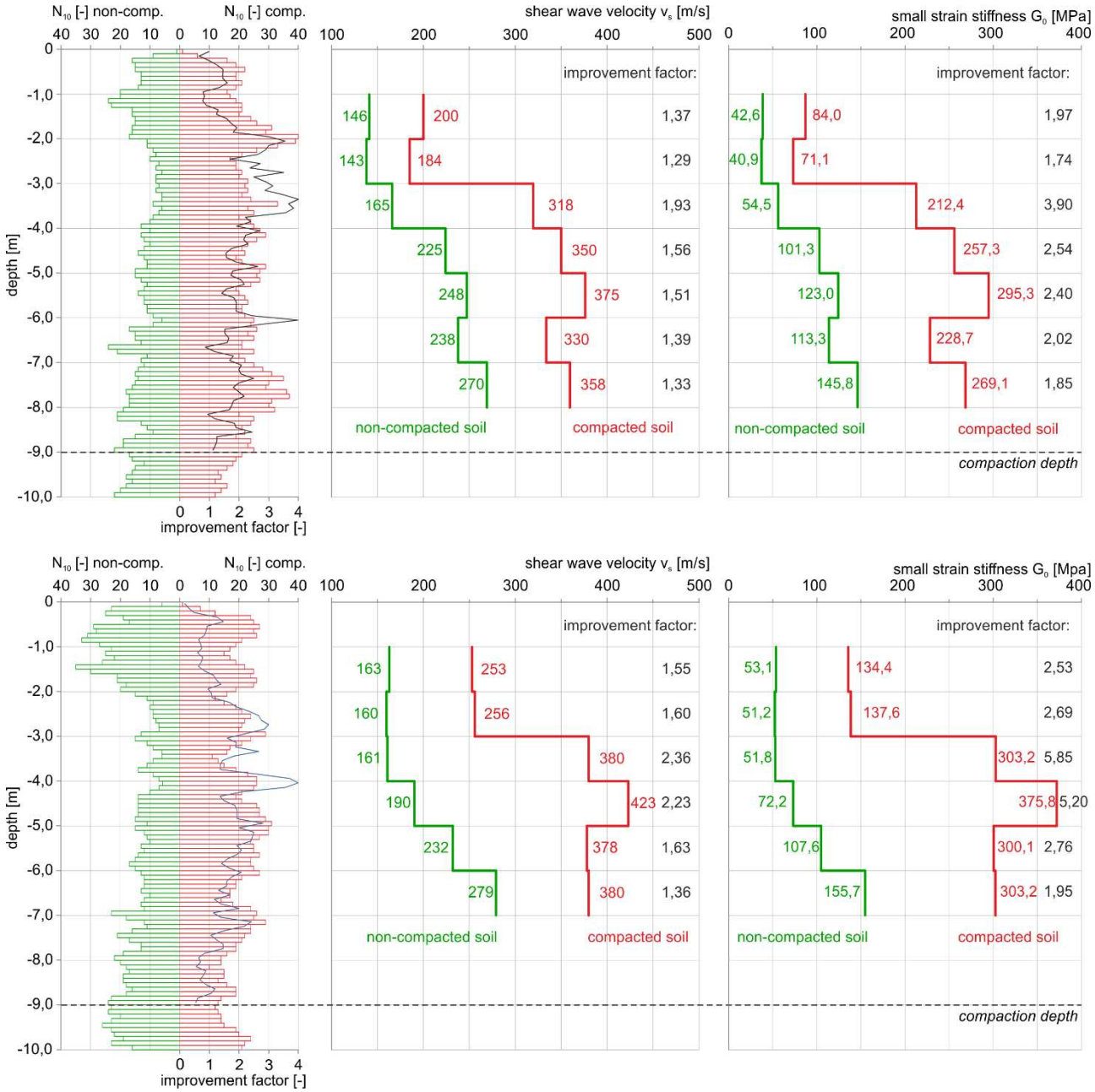


Figure 4. Shear wave velocity profiles and dynamic probing results measured in non-compacted and compacted soil, at two deep vibro compaction slots, small strain stiffness of the non-compacted and compacted soil calculated from the shear wave velocities [3]. The improvement factor is defined as the ratio of the values in the non-compacted and compacted soil.

Figure 4 shows the shear wave velocity profiles and complementary dynamic probing results (DPH) in non-compacted and compacted soil, respectively, at two selected deep vibro compaction slots. Additionally to that, the corresponding pre- and post-compaction dynamic probing results are displayed. These tests were carried out at a distance of 0.5 m from the center of the respective vibro compaction slot.

The test results showed significantly higher shear wave velocities in the vibrocompacted soil compared to the non-compacted ground, in all measurement levels. Since the shear wave velocity relates to the soil stiffness, the raise of this parameter is caused by the increased stiffness due to deep vibro compaction. This tendency reappeared at all investigated vibro compaction slots. The shear wave velocity raised in the most measurement levels by a factor of 1.30 to 1.80. In some instances, even an increase by a factor of 2.30 could be observed.

Based on the measured shear wave velocities, the small strain stiffness of the non-compacted and compacted soil was calculated using Eq. 1 under consideration of the increasing soil density due to compaction. Figure 4 shows the results based on the measurement data. The growth in the shear wave velocity results in an increase in the small strain stiffness of the soil, in most cases by a factor between 1.70 and 3.20.

4. Evaluation of compaction effect in sand using the cone penetration test

The compaction effect decays with increasing radius from the vibrator, in such a way that the area treatment is attained by suitable grids to achieve overlapping compaction from adjacent vibrator positions [2]. The distribution of compaction effect depends on machine parameters, soil properties and specific process parameters. Essential process parameters, such as the flow rate of flushing water or the time spent at each compaction depth or the maximal allowable current, are often chosen by the site manager. Therefore, the proper execution of deep vibro compaction highly relies on the experience of the site manager.

The current investigation program focused on the effect of process parameters on compaction success. Subsequently, the outcomes from a field test are discussed, where the cone penetration test was applied to evaluate the distribution of the compaction effect in the ground.

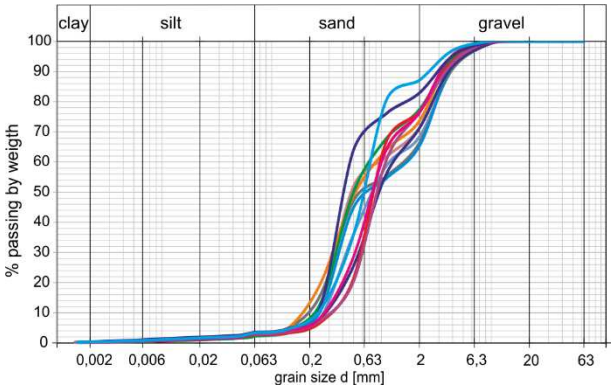


Figure 5. Grain size distribution curves of the samples taken from the embankment fill material on the test site in Lower Austria.

4.1. Ground conditions on the test site

An approximately 5.5 m high embankment was filled for the compaction tests (see Figure 6), therefore the compaction tests were executed in non-saturated soil. The relative density of the sand fill was kept as small as possible. The test site was located in Lower Austria.

During the embankment construction, the grain size distribution curves of samples taken from the fill material were determined (see Figure 5). The fill material was classified as uniform sand with a fine content lower than 5%.

4.2. Compaction tests

A deep vibrator of Keller was used during the compaction tests, which is the most powerful device available in the product range of the company.

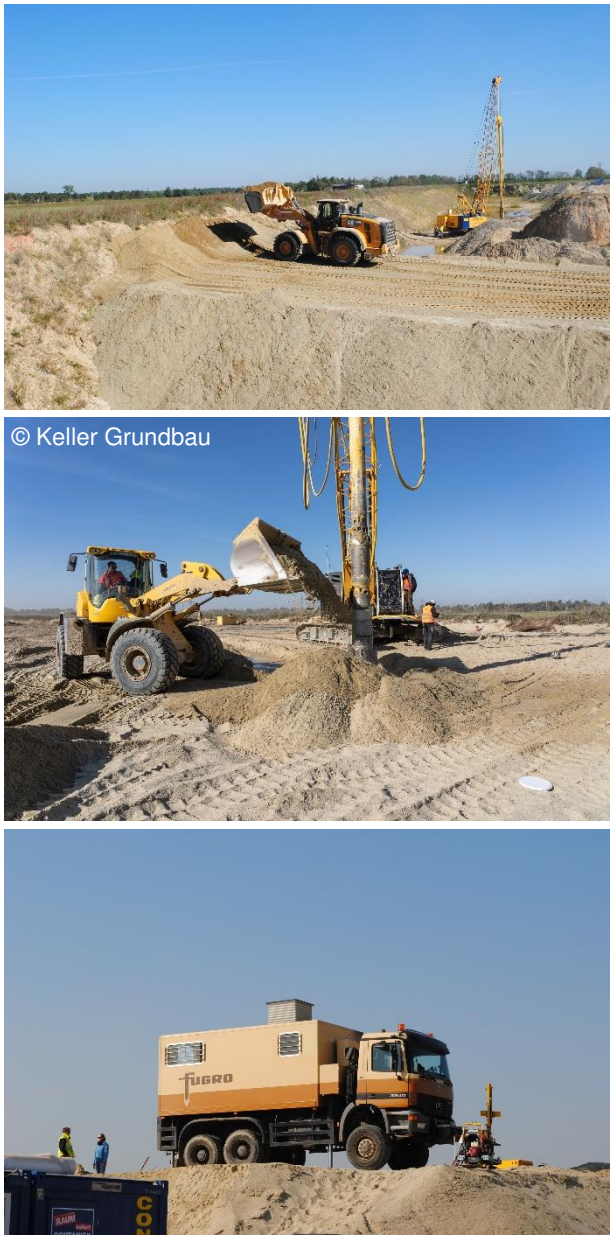


Figure 6. Embankment filling (top), deep vibro compaction (middle) and cone penetration testing in sand fill to determinate the distribution of compaction effect in the ground (bottom).

Thus, the test embankment height was only 5.5 m, the vibrator was penetrated during the experiments up to a maximum depth of 7.0 m into the natural ground, beneath the embankment base.

This sediment layer consisted of sandy gravel. The cone penetration tests were performed directly in the center of the vibro compaction slot and in distances of 1.0 m 2.0 m and 4.0 m from the center respectively. This investigation aimed at the evaluation of the influence of different process parameters on the distribution of compaction effect in the ground. All cone penetration tests were performed a few days after finishing the vibro compaction works.

4.3. Test results

Figure 7 shows a comparison of the cone resistance q_c measured in the center and in different distances from the center, at three different compaction slots. Additionally to that, two pre-treatment cone penetration results are displayed in each chart, which were executed after finishing the embankment fill. In each of these compaction tests, deep vibro compaction was performed by choosing different process parameters.

There are two principal ways of executing deep vibro compaction. The compaction process is carried out in both cases bottom-up either by sequentially withdrawing the compaction device and vibrating at constant depth or by withdrawing the vibrator, then lowering again into the subsoil by about the half the withdrawing depth (back-step or pilgrim-step method).

There is a definite increase in the cone resistance recognisable compared to the pre-treatment results in all three experiments. However, the first two experiments (see Figure 7a and Figure 7b) show generally significantly higher values than the third one. In the upper 2.5 to 3.0 m, the cone resistance is increasing with increasing depth. However, in the near-surface area – especially in the upper 1.0 m below the ground surface – almost no compaction effect could be gained, which corresponded to the overall on-site experiences.

In the center of the compacted area, there is almost no difference in the cone resistance between sequentially vibrating at a constant depth (see Figure 7a) and back-step method (see Figure 7b) visible. In the latter case, the compaction steps of 0.50 m are recognisable as local peaks in the cone resistance. However, in a 1.0 m distance from the center, at the depth between about 1.0 and 3.0 m, the application of the back-step procedure led to a slightly higher compaction effect. In 2.0 m distance, in both cases, there is a marginal compaction effect visible. In 4.0 m distance, there is no difference between the pre- and post-treatment diagrams noticeable. It can be concluded, that sequentially vibrating at constant depth or back-step method did not result in significantly different compaction result in this type of soil using the deep vibrator.

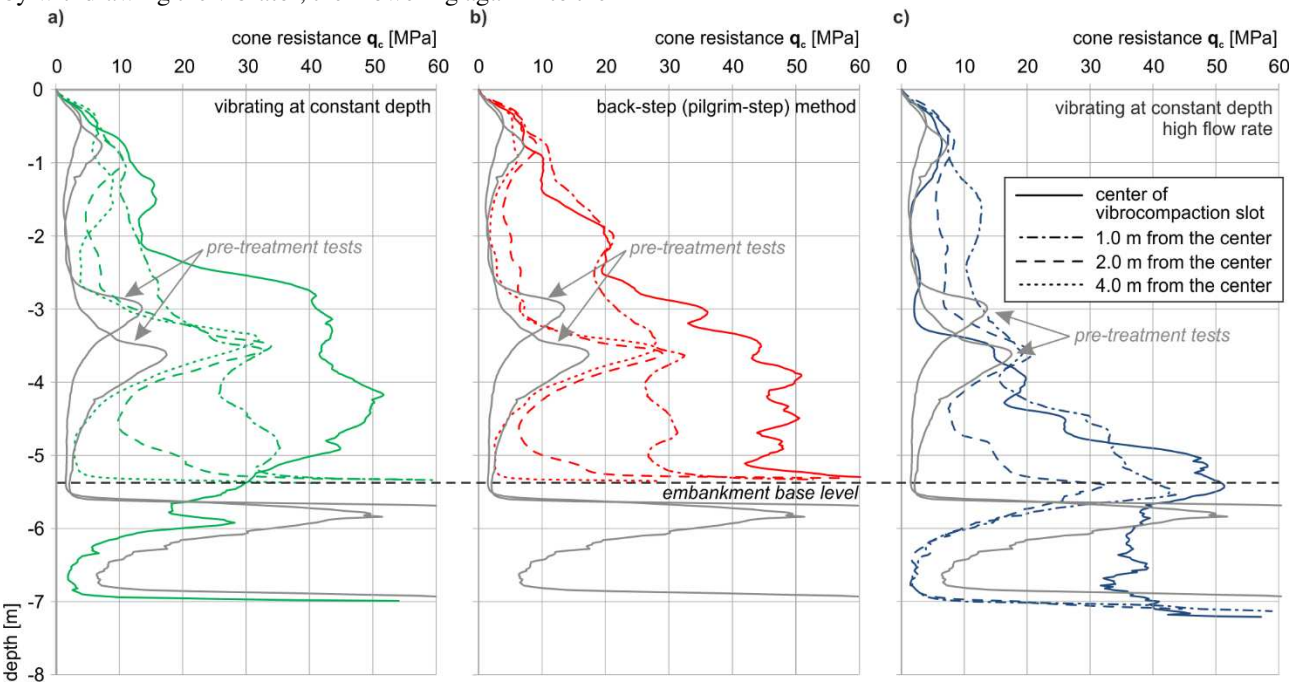


Figure 7. Pre-treatment test results (grey) in the test embankment and post-compaction cone resistance in the center and in different distances from the center of three vibro compaction slots processed with different process parameters (green, red and blue).

As Figure 7b shows, the cone resistance is not necessarily the highest immediately at the deep vibrator. This outcome correlates with the numerical results of Henke et al. [14]. Similar behavior can be observed in Figure 7c. The cone resistance measured in 1.0 m distance is higher than in the center. Consequently, the extensively higher flow rate of jetted water resulted in poor compaction effect directly at the centre of the vibro compaction slot. Especially in the upper 3.5 m, the cone resistance is even lower than measured in the pre-treatment tests. Similar to the first and second experiment, in the 2.0 m distance, there is a slight increase in comparison to the pre-treatment diagrams recognisable. It should be noted that due to experimental purposes, the flow rate at the bottom jet was set extensively higher than during standard site operations.

5. Conclusions

This paper presents the results of cone penetration tests and seismic cone penetration tests in combination with DPH tests for evaluation of the compaction effect from deep vibro compaction.

The seismic cone penetration test showed a definite increase in the shear wave velocity after application of deep vibro compaction in sandy gravel, which is an evidence for a significantly higher soil stiffness of the vibrocompacted soil. The measurement results using the cone penetration test indicated a marginal difference between vibrating at a constant depth and back-step method regarding the soil improvement quality in uniform non-saturated sand. Especially the flow rate at the bottom jet proved as a sensitive process parameter.

The seismic cone penetration is a proper method to prove the success of deep vibro compaction, in terms of the shear wave velocity and the small strain stiffness of the soil. In the case of the cone penetration test, the experimental results confirm the overall on-site experiences. This ground investigation technique is excellently suitable to measure compaction effect from deep vibro compaction. Even the effect of different process parameters on the distribution of the compaction effect can be detected using this technique.

Acknowledgement

The financial support kindly offered by the Austrian Research Promotion Agency and the Austrian Society for Geomechanics made this research possible and is gratefully acknowledged. Special thanks are expressed to Fugro Consult Kft. and Ferenc Scheuring for their support of this research project and performing the investigations on both test sites.

References

[1] Nagy, P. "Deep Vibro Compaction – Compaction Control Based on the Vibrator Movement" (in German), Doctoral thesis, TU Wien, 2018. Available at: https://publik.tuwien.ac.at/files/publik_273866.pdf

[2] Kirsch, K., Kirsch, F. "Ground Improvement by Deep Vibratory Methods", Spon Press, New York, 2010. https://doi.org/10.1201/9781315372341

[3] Robertson, P.K. „Suggested QC criteria for deep compaction using the CPT", In: Lehane, B.-M., Acosta-Martínez, H. E., Kelly, R. (eds.) Geotechnical and Geophysical Site Characterisation 5, Gold Coast, Queensland, Australia, September 5–9, 2016, pp. 711-715.

[4] Massarsch, K.R., Fellenius, B.H. "Vibratory compaction of coarse-grained soils" Canadian Geotechnical Journal 39(3), pp. 695–709, 2002. https://www.nrcresearchpress.com/doi/pdf/10.1139/t02-006

[5] Zöhrer A. and Wondre J. „Neue Entwicklungen und Anwendungen von Vibroscan". (in German) In: Adam, D., Herrmann, R.A. (eds), Proceedings of the 2. Symposium Baugrundverbesserung in der Geotechnik, September 13-14, 2012, Vienna, pp. 193-208.

[6] Adam, D., Pistrol, J. „Dynamic roller compaction for earthworks and roller-integrated continuous compaction control: State of the art overview and recent developments" In: Manassero, M., Dominijanni, A., Foti, S., Musso, G. (eds.) Proceedings, Conferenze di Geotecnica di Torino, XXIV Ciclio. Torino, Italy, February 25–26, 2016, pp. 1-41.

[7] Nagy, P., Adam, D. "Quality control of deep vibro compaction based on the vibrator movement" Proceedings of the XVII European Conference on Soil Mechanics and Geotechnical Engineering, Reykjavik, Island, September 1–6, 2019.

[8] Campanella, R., Robertson, P. K. "A Seismic Cone Penetrometer to measure engineering properties of soil", In: Society of Exploration Geophysicists, SEG Annual Meeting, Atlanta, Georgia, December 2-6, 1984, pp. 138–141. https://doi.org/10.1190/1.1894361

[9] Benz, T. „Small-strain stiffness of soils and its numerical consequences" Doctoral thesis, Fakultät für Bau- und Umweltingenieurwissenschaften der Universität Stuttgart, 2007.

[10] Massarsch, K.R., Broms, B.B. „Soil compaction by VibroWing method". In: 8th European Conference on Soil Mechanics and Foundation Engineering. Helsinki, Finland 1983, pp. 275–278.

[11] Massarsch, K. R. and Eriksson, H. „Deformation Properties of Dry Mixed-in-place Columns from Seismic Field Tests." Port and Airport Research Institute, Tokyo Workshop 2002 on Deep Mixing, 2002, pp. 58–74.

[12] W.J. Wehr und J. Berg. „Compaction control of a soil improvement with powder columns" In: Kolymbas, D., Fellin, W. (eds.) International Workshop on Compaction of Soils, Granulates and Powders, Innsbruck, Austria, February 28–29, 2000, pp. 91–102.

[13] Kim, D.-S., Bang, E.-S., Kim, W.-C. „Evaluation of various downhole data reduction methods for obtaining reliable vs profiles" Geotechnical Testing Journal 27(6), pp. 585–597 2004. https://doi.org/10.1520/GTJ11811

[14] Henke, S., Hamann, T., Grabe, J. "Coupled Eulerian-Lagrangian simulation of the deep vibration compaction process as a plasto-dynamic problem", In: 8th International Conference on Structural Dynamics, Leuven, Belgium, 4-6 July 2011, pp. 482-489.