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Monitoring of processes on the compaction device and in the soil during deep vibro compaction

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Abstract

Deep vibro compaction is a widely-used ground improvement technique for the treatment of mainly granular soils to a depth of up to 70 meters. During the compaction process, the vibrator body is constantly interacting with the compacted soil. The changing ground conditions influence the motion behaviour, making it possible to use the deep vibrator as a compaction device and as a measurement tool indicating the current compaction state. Within the scope of the present study, large-scale experimental field tests were realized on a construction site to better understand the soil processes during deep vibro compaction. A novel specific monitoring and data recording system was developed for the experiments. The tests were realized in homogenous reclaimed sand fill under fully saturated conditions. Within these experiments, special tests were designed and carried out to disclose the role of the mechanisms leading to the compaction effect. Pore water pressure measurements were executed using a CPTu cone, positioned close to the compaction device. This paper shows the concept and selected results of the experimental investigations. Especially the measurement system and the experiments wherein pore water pressure measurements were conducted are discussed in detail.

Keywords: Deep vibro compaction, pore water pressure, large-scale test

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. Proper execution of this ground improvement technique increases soil density and stiffness, which in turn give rise to homogenised subsoil, reduced deformations and liquefaction potential. This ground improvement technique is widely used for deep compaction of a broad range of granular soils with a relatively low level of fine content, for example, in the scope of land reclamation projects, but also loose natural sediments. Aspects of the practical application of deep vibro compaction are extensively discussed in the literature, e.g. by Kirsch and Kirsch (2013).

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 changes in the vibrator movement. Therefore, the vibrator movement, together with specific process parameters, can be used for a continuous, work-integrated indication of the compaction state. Such a system can provide the machine operator with valuable information on the site. Furthermore, it can serve as a practical tool for quality assurance purposes. Systems for work-integrated quality control based on the continuous measurement and evaluation of the movement behaviour 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 (Pistrol and Adam, 2016). 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. A selection of research works on this topic is shown in Nagy et al. (2021). A possible approach for compaction control founded on the motion behaviour based on experimental test results is presented in Nagy and Adam (2019), which can be seen as the basics for the investigations presented in this paper. The current experiments include compaction tests with an additional vibrator type in different soil conditions.

The role of different mechanisms responsible for the rearrangement of soil particles during deep vibro compaction is an extensively discussed subject. However, the literature remains inconclusive on this topic. In different scientific papers, a temporary decrease of shear strength due to excess pore pressure (soil liquefaction) or a certain level of grain acceleration (soil fluidization or vibrofluidization) are pointed out as crucial reasons for the compaction effect. An overview of research works on the role of different mechanisms leading to a compaction effect is shown in Nagy et al. (2022).

2. Experimental large-scale field tests

2.1. Concept and aim of the experiments

Figure 1 shows the basic layout of the experimental field tests and the measuring system, which was used during the tests. Due to the special requirements on the equipment, an innovative monitoring and data recording system was developed and installed on the vibrator tube and on the rig. The measuring system consisted mainly of heavy-duty triaxial accelerometers for recording the vibrator movement and a pulse emitter for determining the current position of the rotating eccentric mass. In general, the rotating eccentric mass is situated above the vibrator cone as visible in Figure 1. In the present case, accelerometers were mounted in two measuring levels, at the elastic coupling (upper level) and above the vibrator tube (lower level). All sensors were chosen or built and installed in a way that they were protected against possible mechanical and thermal impacts as well as against penetration of water.

In addition to the vibrator movement, numerous process parameters were recorded during the compaction process, such as vibrator frequency, pull-down force, vibrator depth, the power consumption of the electric motor and the flow rate of the water. Furthermore, a separate measuring system was installed on the ground surface to record the wave field triggered by the dynamic soil-machine interaction. This system consisted of highly sensitive accelerometers installed at different distances from the deep vibrator.

The recorded data was synchronized with very high precision and stored on a computer installed on the rig's cab. In addition, a wireless data recording system enabled the transmission and monitoring of the measured data on the site in real-time.

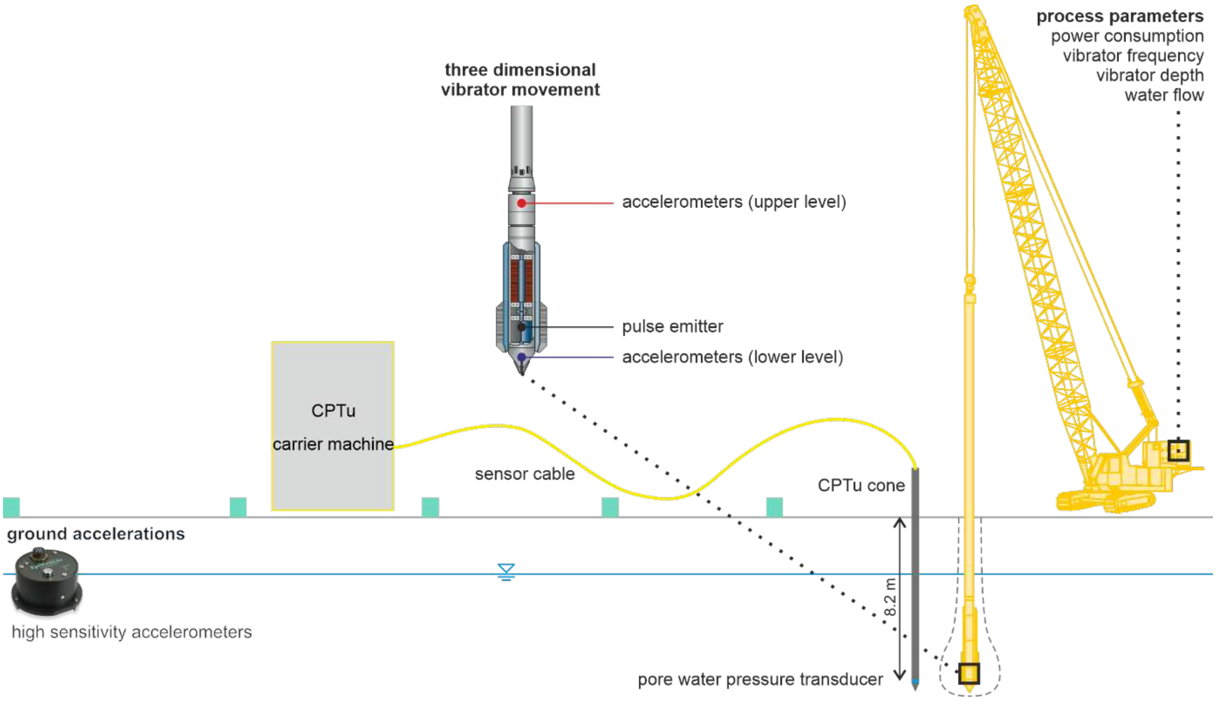

Figure 1: Concept of the large-scale experimental field tests including pore water pressure measurements.

Pore water pressure measurements were executed during the vibrocompaction process using a CPTu cone positioned close to the compaction device within the scope of selected compaction tests. Figure 1 also displays the basic layout of the experimental field tests, including the measurement of pore water pressure during deep vibro compaction.

A CPTu cone was used with a pore water pressure transducer installed behind the cone. First, the CPTu cone has penetrated the subsoil and was positioned at a depth of 8.2 m below the ground surface. The soil was fully saturated at this depth. The CPTu cone was positioned at a distance of 2.0 m from the vibrocompaction points investigated in these experiments. Therefore, the CPTu cone was far enough to prevent possible mechanical damages resulting from the compaction process, but at the same time close enough to register the pore water pressure in the influenced zone due to the vibrocompaction process.

2.2 Underground conditions on the test site

The experiments were executed in a homogenous sand fill, partly above and partly below the groundwater level. Figure 2 shows the results of CPTu tests, which were performed on the site. The result of a single test on the left-hand side, the mean value and the envelope of about 20 tests on the right-hand side are displayed. The cone was penetrated through the sand fill, with a thickness of about 11 meters, where a soil layer consisting of predominantly soft marine clays was reached. This soil layer deviates distinctive regarding its soil mechanical properties from the sand fill above.

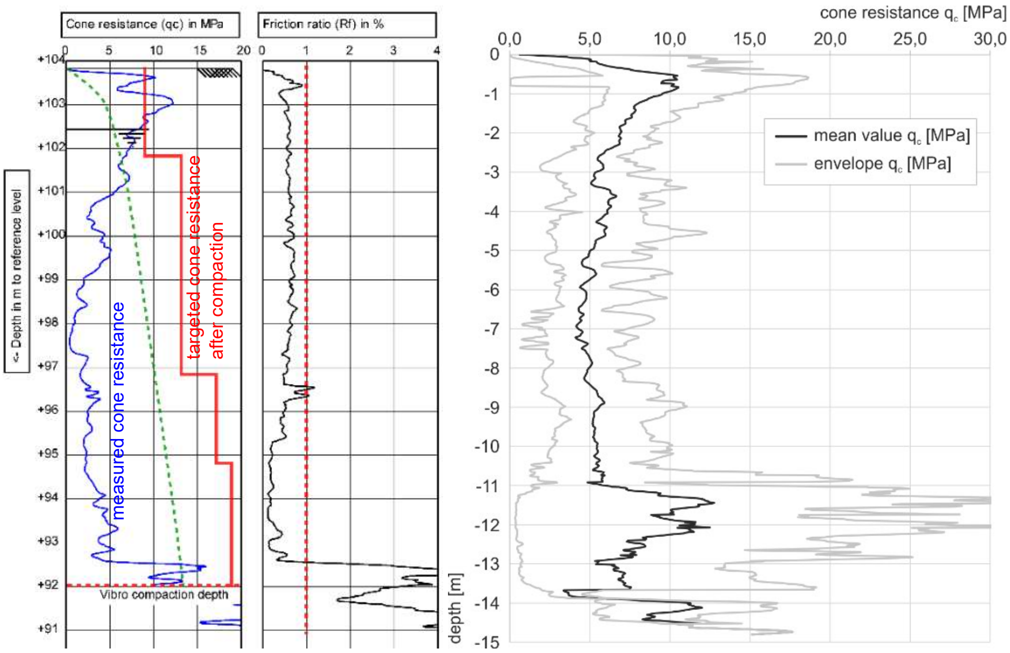

Figure 2: Results of pre-compaction CPTu tests. Single test (left), average and the mean value of about 20 tests (right)

3. Selected results of the experimental field tests

3.1 Shape of the vibrator motion

After penetrating the depth vibrator to the predefined depth, the compaction process is generally carried out bottom-up, either by vibrating at a constant depth for a fixed time or using the back-step method. While using the current deep vibrator, different amplitudes and frequencies are applied during the penetration and compaction processes. Higher frequency and a lower amplitude help to reach the intended depth as fast as possible during penetration. In contrast to that, while compaction, the vibrator frequency is decreased, and the maximal amplitude is increased to achieve a higher range of influence around the compaction device. In the case of the deep vibrator used in the current experiments, the amplitude during compaction is more than twice as high as during the penetration. Different amplitudes can be set by activating different eccentric weights, while the frequency can be controlled easily by adjusting the current frequency.

The monitoring system used in the large-scale experimental field tests allowed an exact characterisation of the motion behaviour of the deep vibrator. In the following, the shape of the vibrator motion is shown both during the penetration and the compaction process at three different depth levels, respectively. Accelerometers were positioned at two levels, at the vibrator cone (lower level) and below the elastic coupling (upper level). The amplitudes were calculated from the registered accelerometer signals by double numerical integration. The motion is illustrated with blue and red colours at the lower and the upper level, respectively.

In Figure 3a, the motion behaviour is shown during the vibration in the air. As expected, the vibrator tip describes a perfect circular shape. Equal amplitudes can be seen in the x- and the y-direction. In Figure 3b, the motion is displayed in a stage where the vibrator was penetrated just partly into the soil. Therefore, the influence of the surrounding soil on the vibrator motion is more significant at the lower measurement level. During the movement shown in Figure 3c, the whole vibrator body was situated below the ground surface. During the vibration in the soil, generally smaller amplitudes were measured than in the air. During the vibration in the underground, the amplitudes in the x- and y-direction are not equal anymore; the ones in the x-direction tend to be smaller. This fact results from the significant influence of the vibrator wings on the vibrator motion, which are oriented in the y-direction for this particular layout of the depth vibrator.

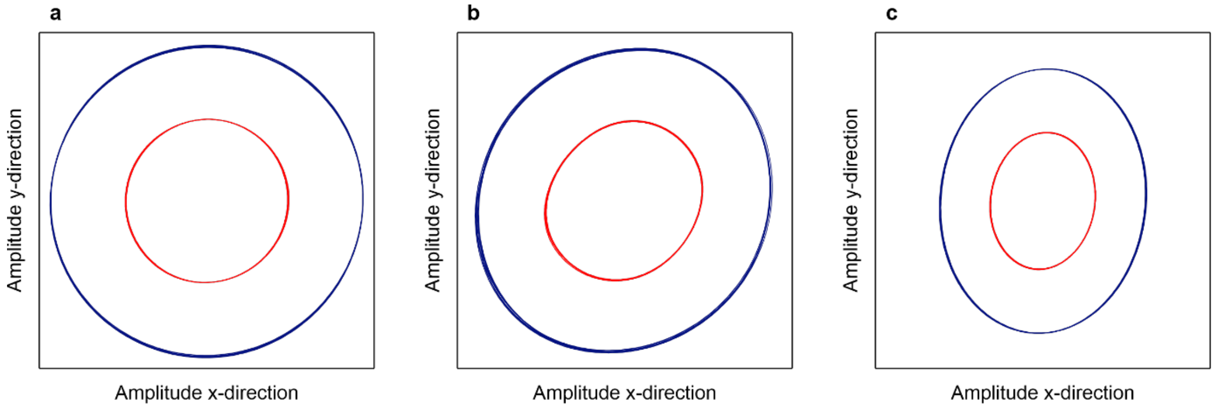

Figure 3: Shape of the vibrator motion at the lower (blue) and the upper (red) measurement level at three different depths during the penetration process.

Figure 4 shows the motion behaviour in four stages during the compaction process, executed bottom-up by gradually withdrawing the vibrator. The movement displayed in Figure 4a was recorded while the vibrator was located in the soil, the one in Figure 4b during near-surface compaction, and the one in Figure 4c during the vibration in the air. Generally, a similar shape of the movement can be seen during compaction, like during the penetration process. The amplitudes are higher due to the excitation with larger eccentric weights. However, the amplitudes are not equal in the x- and the y-direction and movement shows an opposing pattern because of the counter-rotating eccentric weights. After reaching the ground surface, the wings have no further influence on the motion; it returns to its perfectly cylindrical shape while vibrating in the air.

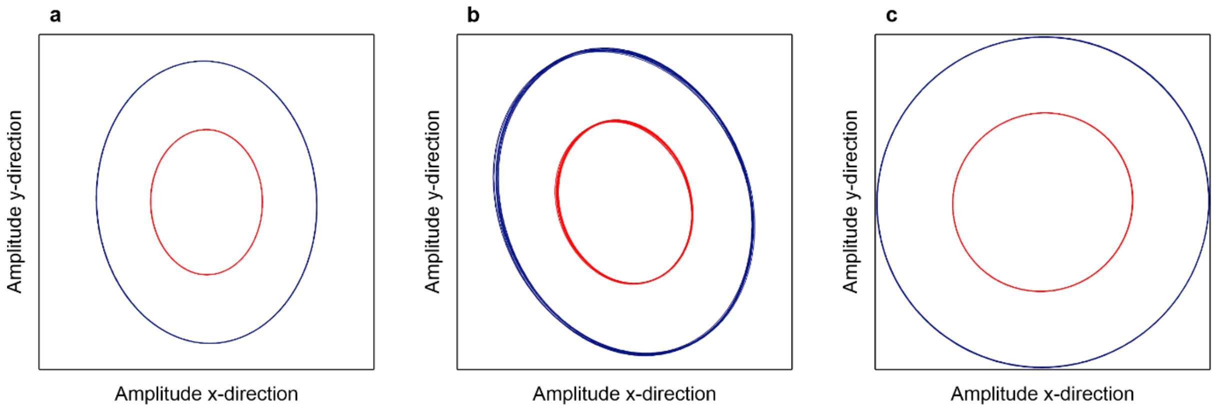

Figure 4: Shape of the vibrator motion at the lower (blue) and the upper (red) measurement level at three different depths during the compaction process.

The measured data shows an evident influence of the surrounding soil on the motion behaviour of the vibrator both during penetration and compaction. Continuous interaction between vibrator and soil can be assumed; the recorded movement indicates no temporary loss of contact.

3.2 Measurement of pore water pressure during deep vibro compaction

In the case of the deep vibrator used in the current experimental field tests, the compaction process is supported by water supply. Therefore, water jets located at the vibrator cone are essential elements of the compaction device. These are denoted as bottom jets. Figure 5 shows the time history of the vibrator depth, flow rate of the water at the bottom jet, and the pore water pressure measured with the CPTu cone during an experiment to investigate the development of pore water pressure during deep vibro compaction. In the current case, the vibrator engine was not running during the whole test. The time intervals are marked in the figure when the rotating eccentric mass induced horizontal vibrations. The water flow rate at the bottom jet is displayed as the ratio of the current to the highest possible flow rate. The results of the experiments to monitor pore water pressure during the compaction process are discussed in more detail in Nagy et al. (2022).

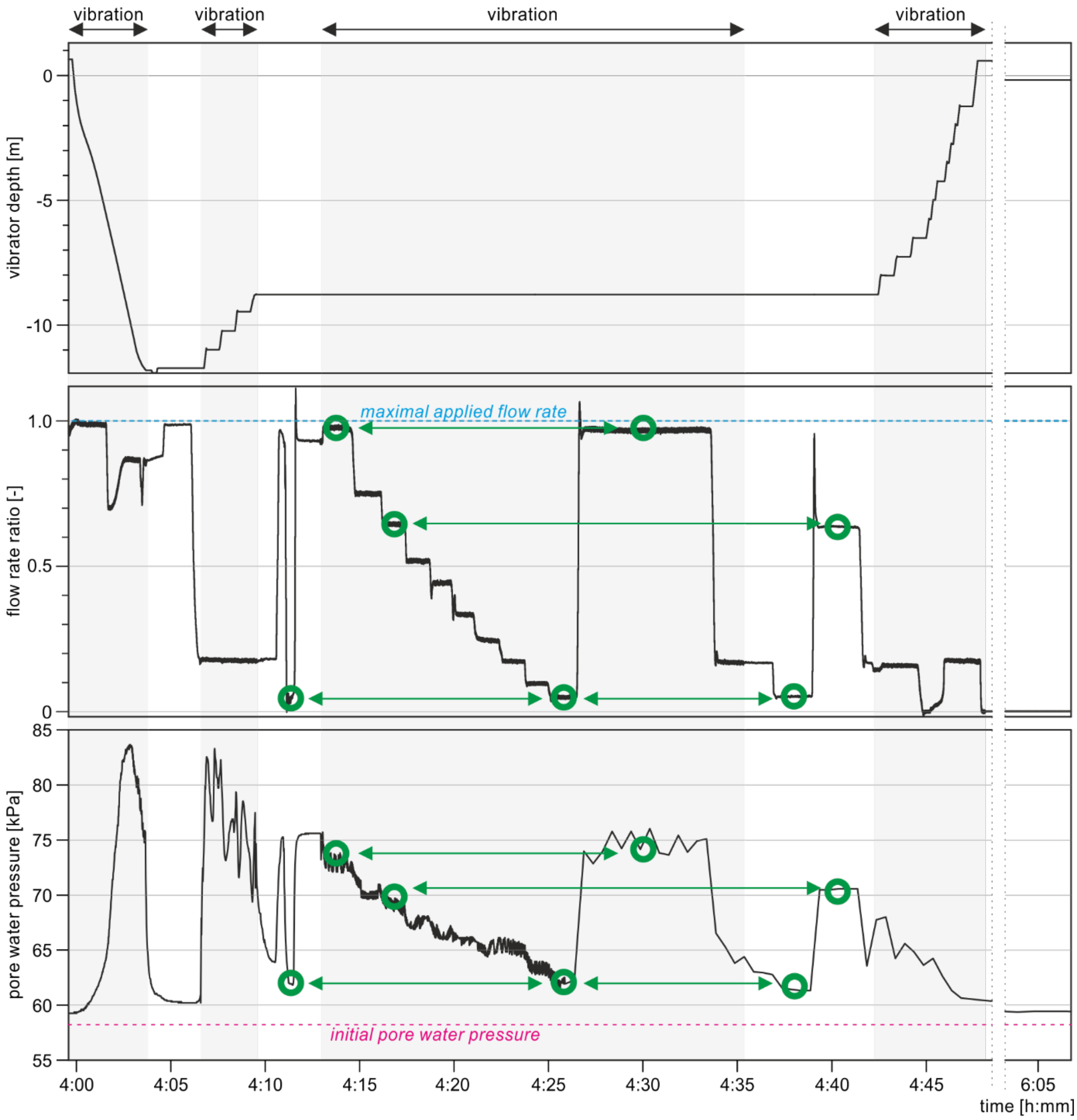

Figure 5: Vibrator depth, flow rate of the water at the bottom jet, pore water pressure measured with the CPTu cone (Nagy et al., 2022).

During the experiment, the compaction device penetrated the subsoil until the vibrator cone reached the depth of about 12 m below the ground surface. Indeed, during penetration pore water pressure transducer indicated a slightly rising pressure almost immediately, even when the vibrator cone was located in the upper, unsaturated layer of the soil. The pressure increased, especially after reaching a depth of about 5 meters, rapidly further and peaked at about 83.5 kPa when the vibrator cone was passing by the pore water pressure transducer. Subsequently, the pore water pressure started to decrease. It stabilised at about 60.5 kPa after turning off the vibrator engine. However, the pore water pressure rose again abruptly due to restarting the engine at the beginning of the compaction process. In this experiment, the compaction process was interrupted intentionally at 8.2 m depth, where the CPTu cone was located. At this depth, the water flow rate at the bottom jet was varied. It was increased to the highest flow rate and reduced again to zero. During this process, the vibrator engine was turned off. Despite that, changes in the pore water pressure could be observed, depending on the current flow rate. At the highest possible flow rate, a pore water pressure of about 75.0 kPa was measured. By decreasing the flow rate, the water pressure dropped to about 62.0 kPa and rose again by increasing the flow rate. Following that, the vibrator engine was started while the highest possible flow rate was set. However, there was no increase in the pore water pressure measured; it even reduced slightly. While the bottom jet's flow rate decreased gradually, the pore water pressure also reduced continuously.

The pore water pressure rose again by increasing the water flow rate at the bottom jet in the following part of the experiment. While the flow rate was kept constant, the water pressure remained steady. It should be noted that the sampling rate of the measuring computer in the carrier machine was reduced automatically at about the point (in time) 4:26. At the end of the experiment, at a depth of 8.2 m, the vibrator engine was turned off again, but the water flow rate variation was continued. Thereby an accompanying reaction in the measured pore water pressure could be observed.

An evident linkage can be observed between the water's flow rate at the bottom jet and the measured pore water pressure. Different points of time during the experiment with the same flow rate are marked in Figure 5. The corresponding pore water pressures are highlighted, too. It is visible that the pore water pressure is essentially the same at the same flow rate at the bottom jet. The higher the flow rate, the higher the measured pore water pressure. It is also interesting to note that the pore water pressure seems not to be depending on the vibration of the compaction device. The reason for the increased water pressure is instead a local elevation of the water level around the deep vibrator.

The compaction test was completed at about the point 4:46. Nevertheless, the pore water measurements continued to investigate the consolidation process in the influenced soil. During this time interval, no compaction works were executed. The measures were intercepted when no more changes in the water pressure were observed, and therefore, the consolidation process could be seen as finished. The water pressure stabilized within about an hour, at roughly 59 kPa, barely higher than the initial value. Consequently, the measurement data indicates a rapid consolidation after finishing the compaction.

4. Conclusions

This paper demonstrates selected results of experimental investigations of deep vibro compaction using a measurement system, which allowed process-integrated monitoring of the vibrator motion. The motion behaviour of the deep vibrator could be characterised at a very detailed level. In this way, the measured data provides an outstanding basis for the following data evaluation and theoretical investigations, including analytical and numerical modelling.

Furthermore, the outcomes of the current experiments allowed to understand the processes during the compaction process better. In the scope of experimental large-scale field tests, pore water pressure measurements were realised during deep vibro compaction close to the compaction device. The current measurements were executed to analyse the possible liquefaction of the compacted soil. Significant changes in the pore water pressure could be observed during the experiments carried out on the test site. However, the pore water pressure variation was caused primarily by the variable flow rate at the bottom jet of the deep vibrator. Thereby, the vibrations of the compaction device played a subordinary role rather. Diminishing shear strength of the soil is a crucial characteristic of soil liquefaction. Such behaviour cannot be observed in the current experimental data. In summary, it can be stated that soil liquefaction is not a sufficient explanation for the temporary reduction of shear strength, which results in a compaction effect by deep vibro compaction.

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