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Model and field tests to optimize and control deep vibratory compaction

Marylin Hell
Keller Holding GmbH, Offenbach, Germany, marylin.hell@keller.com

Wolfgang Jimmy Wehr
University of applied sciences, Erfurt, Germany

ABSTRACT: Optimising vibratory compaction was the objective of an ongoing research project. The project was initiated with the aim of gaining a more profound understanding of the method in general. In this project, the effects of modifying the compaction method and altering the vibration frequency and the eccentric moment were evaluated. It became apparent that new variables needed to be incorporated in addition to the existing control variable, namely motor power consumption. To achieve the above objectives, a scaled model test facility was built. In a parametric study reproducible behaviour was identified and a control algorithm was developed for compaction. As part of the investigation the displacement amplitude, the phase angle and the newly introduced sensor phase angle were identified as potential control parameters. These parameters reflect the behaviour of the surrounding soil and are used to adjust the compaction frequency and compaction time automatically. The suitability of this control algorithm and the knowledge gained during the project was further investigated by comparing the data to field trials in Singapore. Recommendations for implementation were derived with the aim of optimising vibratory compaction on construction sites and making the method more efficient and sustainable.

KEYWORDS: Deep vibratory compaction; soil compaction; control; algorithm; optimization

1 INTRODUCTION

Vibratory compaction was developed in the 1930s by the Johann Keller company and has been continuously developed since then. As part of a large-scale model test facility, a detailed parameter study was carried out with the aim of identifying new control parameters and developing a control system suitable for practical application. More detailed explanations and many other details can be found in [3].

2 MODEL TEST SET UP

2.1 *Test facility*

The model test facility consists of two reinforced concrete shafts. The test container is shown in Figure 1. The gravelly sand is temporarily stored in the storage container. At the beginning of each test, the test container is filled with sand using a pump. Sensors are also installed during the flushing process. The water-saturated sand installed is a suspension with a water content w of approx. 15 % after compaction. For more detailed information on the sensors, their installation method or the sand, please refer to [3].

2.2 *Model vibrator*

The dimensions of the four-bladed vibrator were modeled on the Keller S700 vibrator on a scale of 1:3. Figure 1 shows the device after penetration to the maximum depth. Two acceleration sensors are installed on two levels in the model vibrator so that it is possible to calculate the amplitude of the vibration displacement or the movement pattern. The alignment of the sensor axes can also be seen. The point of zero vibration is located in the suspension or the flexible coupling.

The model vibrator is equipped with an eccentric mass that can be exchanged depending on the selected test setting. In this context, the phase angle (Figure 2) is an essential parameter, which is calculated by the Hall sensor in combination with a magnet and an acceleration sensor, as shown in Figure 1. The phase angle defines the angle between the direction of deflection of the vibrating body and the axis of the eccentric mass.

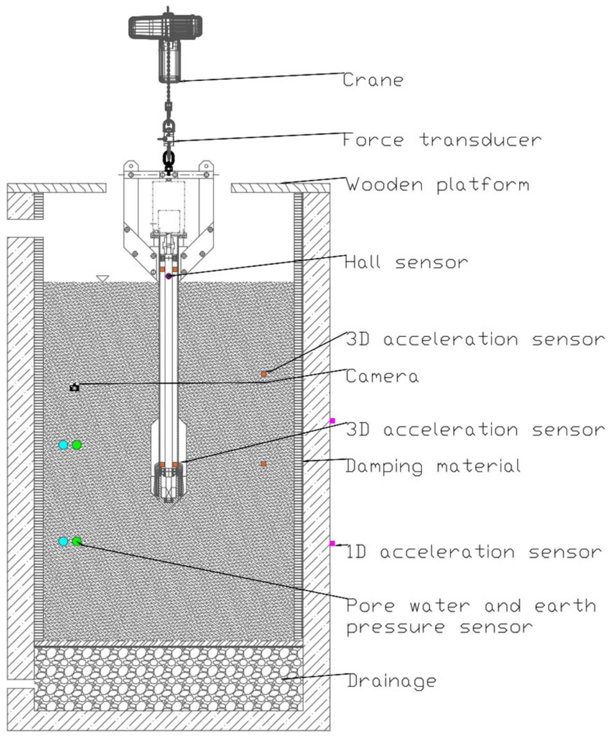

Figure 1. Test container with built-in model vibrator in the sand and built-in sensors [3]

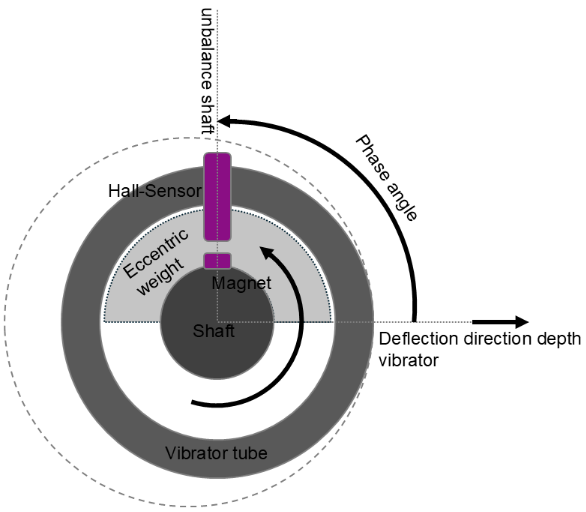

Figure 2. Phase angle of a depth vibrator [5]

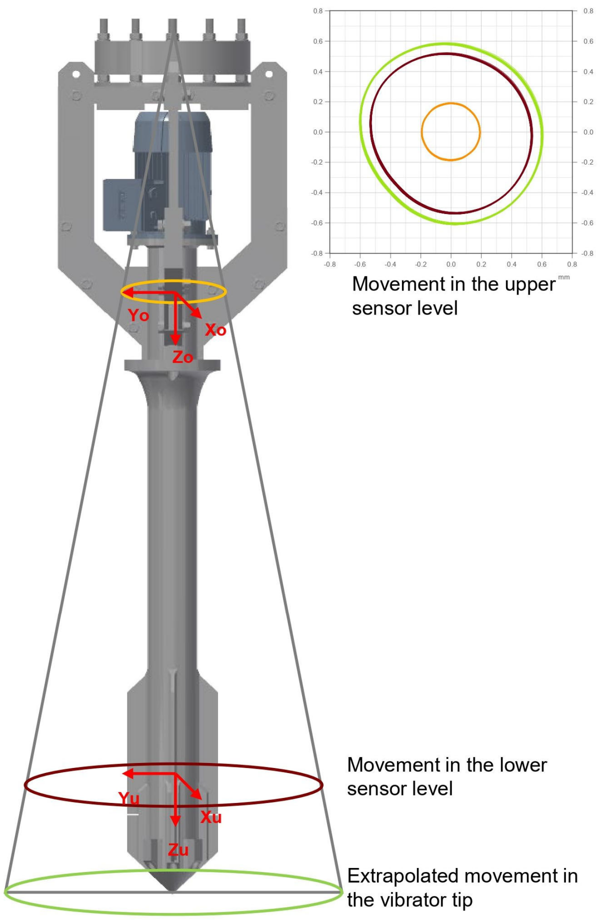

Figure 3. Comparison of the movement behavior in the air and the movement pattern over a period of t = 1 s in the top right-hand corner [3]

The sensor phase angle is an empirical variable that is calculated over a self-selected time interval analogous to the phase angle. The directions of the maximum acceleration amplitudes of the lower plane in both the x-direction and the y-direction form this angle, which indicates the compatibility of the movement for the depth vibrator. A movement behavior that is compatible with the depth vibrator is expressed by a sensor phase angle of approximately 90°. This can be seen from the movement patterns in Figure 3 for the model vibrator. Furthermore, pipes are attached to the outside of the vibrator that can be used for flushing with water or air. This makes it possible to compare the two flushing methods during penetration. Above the motor there is a variable ballasting system that can be used to imitate the different follower tubes of the large vibrators [4].

3 EXPERIMENTAL PROCEDURE

At the beginning of each test, there is a reproducible, very loose relative density. The actual test begins with the penetration of the model vibrator to the final depth. Basically, only one variable is changed at a time so that possible changes in movement and compaction behavior can be detected. The following parameters are examined as part of the parameter study: frequency, eccentric mass, compaction time, compaction method (gradual compaction, pilgrim step method or constant pulling), ballasting, type of flushing and flushing flow rate. Compaction is stopped as soon as the model vibrator has reached the sand surface.

To evaluate compaction, the surface is surveyed before and after compaction to record the existing settlements. The compaction is also checked by means of dynamic probing. The wooden platform shown in Figure 1 is used for this purpose. Fixed positions for the starting points of the dynamic probing are defined within the template, so that a basis for comparison is provided. Only the determined blow counts are used to compare the compaction, as a conversion of the blow counts can lead to false judgements [1], [2], [3].

4 EVALUATION OF MODEL TESTS

4.1 *Effect of the compaction frequency on the movement behavior*

The following section presents various parameter variations and explains their influence on the compaction. The displacement amplitude represents the envelope curve of the displacement amplitude of the lower sensor level in the y-direction. It is currently possible to adjust the compaction frequency during the process. The compaction is significantly influenced by the depth and the relative density. The frequency was varied in steps of 10 Hz in Figure 4. The x-axis displays the time and the y-axis the phase angle (orange color), the vertical load (brown color), the sensor phase angle (green color) and the maximum vibration amplitudes in y-direction (blue colors).

At a compaction frequency of 25 Hz, hardly any movement of the model vibrator can be detected, which is confirmed by a displacement amplitude of 0.05 mm and a phase angle of approx. 30°. In this frequency range, the amplitudes of the lower frequencies from 25 to 35 Hz are greater than those of the 45 Hz compaction. This observation leads to the conclusion that an adjustment of the compaction frequency in the course of compaction to the respective soil properties or depth is a sensible measure.

Compaction at a frequency of 55 Hz shows a fundamentally different behavior than at lower frequencies. The sensor phase angle with a value of just under 20° is an indication of a strong ellipsoidal movement. Apart from the very inhomogeneous compaction a strongly ellipsoidal movement behavior with a high number of dynamic probing blows is not consistently shown, as is the case with lower frequencies.

As a result, it is recommended to avoid strongly ellipsoidal movement behavior, e.g. by using high frequencies. However, the use of high displacement amplitudes, generated by higher frequencies or higher eccentric masses may lead to increased compaction [1], [6], [7].

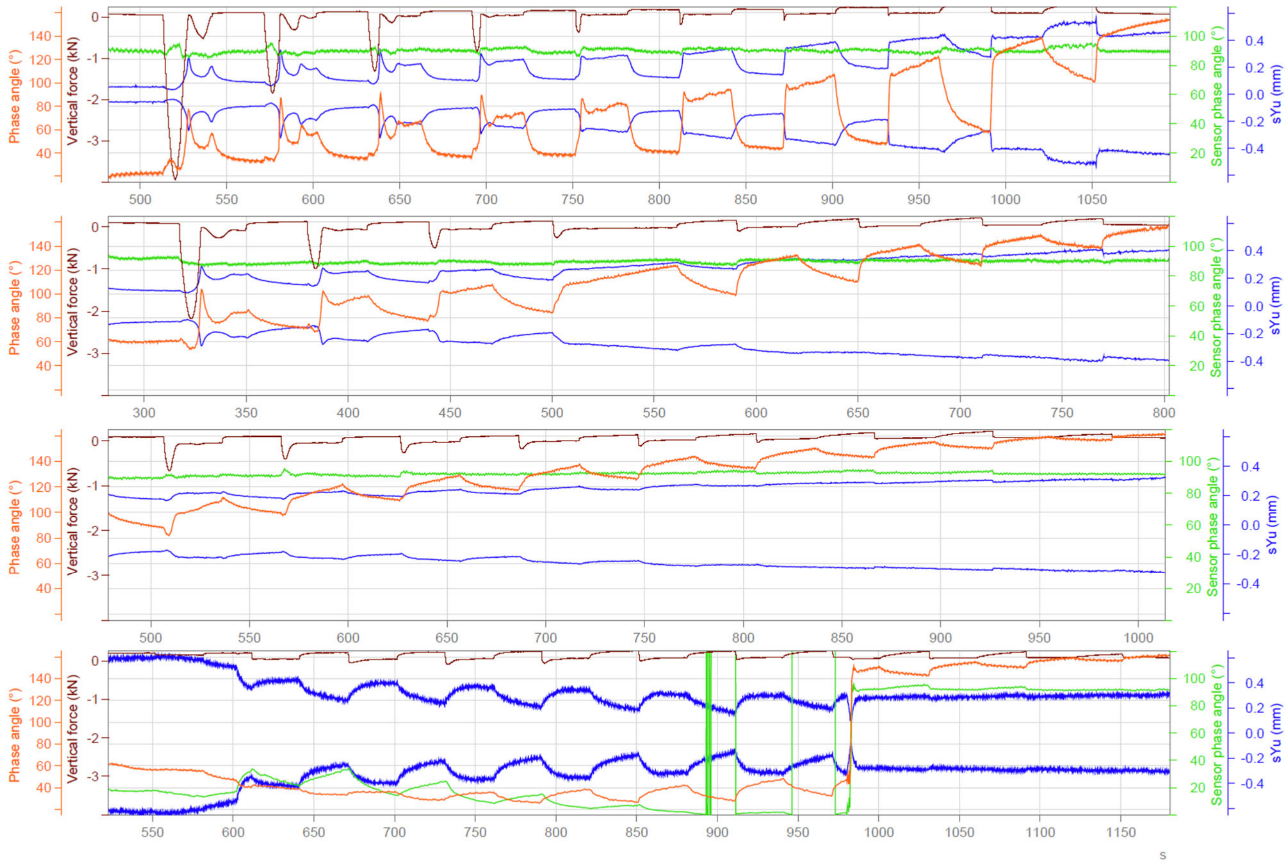

Figure 4. Comparison of the frequencies; top: 25 Hz, upper center: 35 Hz, lower center 45 Hz and bottom: 55 Hz and 30 s compaction time [3]

4.2 *Effect of the eccentric mass on the movement behavior*

Another way to adjust the displacement amplitude of the model vibrator is to change the eccentric mass in Figure 5. A 500 g mass results in a vibration displacement amplitude in the range of 0.05 - 0.2 mm, while a 1000 g or 1500 g mass generates an amplitude of between 0.1 - 0.4 mm or between 0.21 - 0.58 mm. Consequently, a doubling of the amplitude can be observed with each 500 g increase in eccentric mass. In contrast to the change in frequency, this doubling is consistent over the entire depth, while a change in frequency only shows a change in the deep soil layers and the lower frequencies have higher amplitudes at lower depths.

To enable an evaluation of the compaction, Figure 6 shows a comparison of the average total blow counts of the frequency and the eccentric mass. An increase in the number of blows with increasing frequency can be observed. At a frequency of 45 Hz, however, a change in the gradient of the number of blows can be observed. However, the high blow counts at a frequency of 55 Hz were associated with highly chaotic behavior, which impairs the service life of the vibrator and leads to considerable irregularity. A comparison of the behavior at 1,500 g eccentric mass also shows a significant increase in the number of blows with a compaction time of only 30 s.

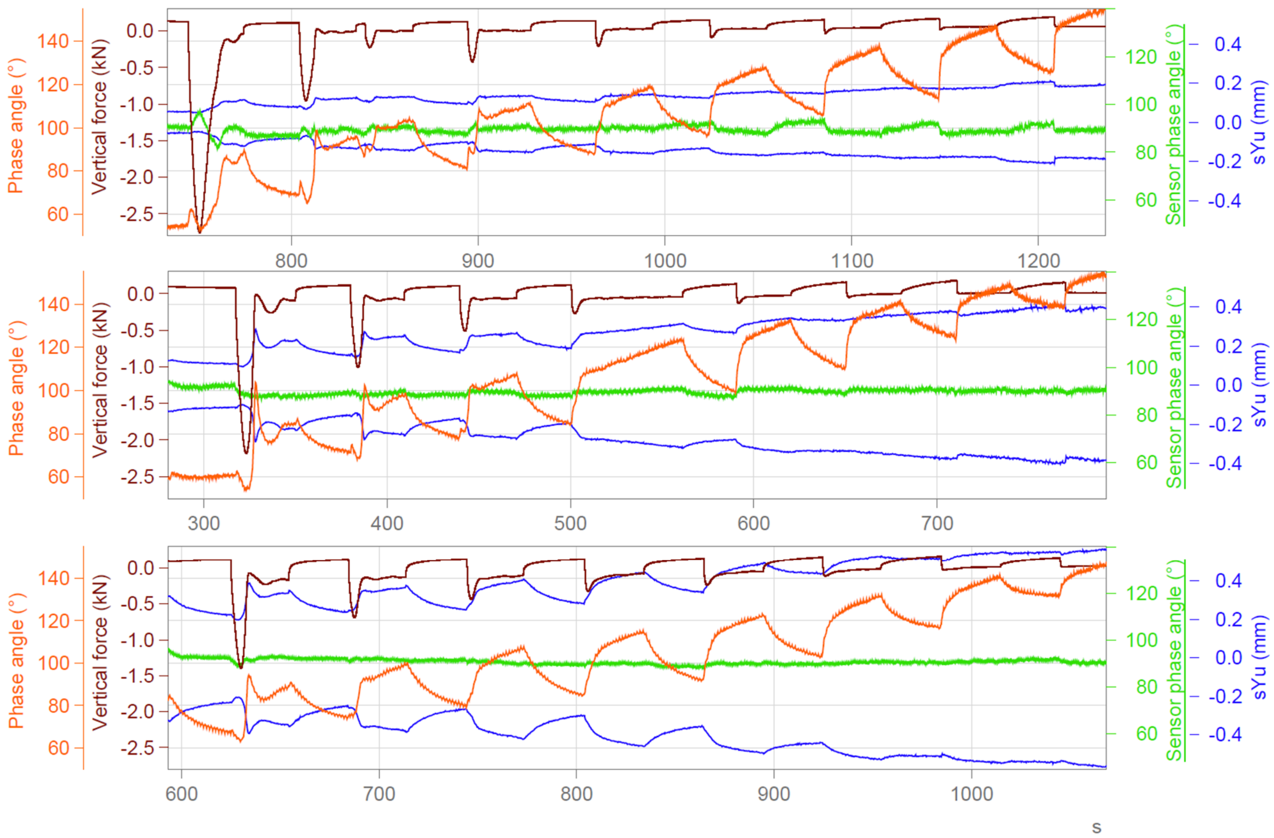

Figure 5. Comparison of the eccentric weights; top: 500 g, center: 1000 g and bottom: 1500 g at 35 Hz and 30 s compaction time [3]

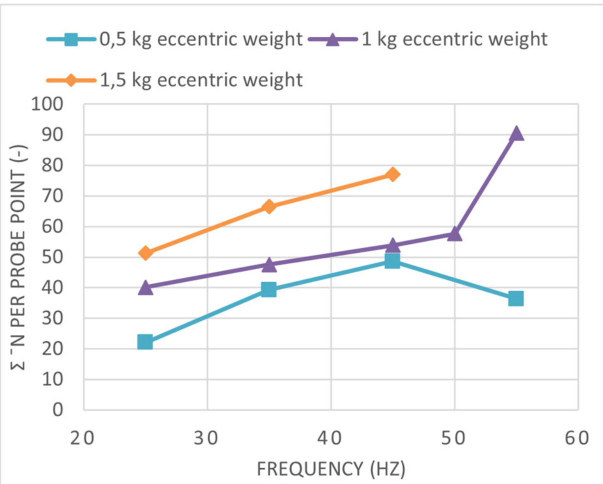

Figure 6. Comparison of the average total blow count as a function of the compaction frequency and eccentric mass [3]

Increasing the frequency makes sense up to a certain point. However, there is no need to maximize or increase the frequency in order to achieve effective compaction. In addition to the frequency, the eccentric mass can also be adjusted to the surrounding soil. The combination of a depth vibrator with an adjustable eccentric mass and intelligent control of the frequency and time enables high amplitudes without placing excessive strain on the deep vibrator.

4.3 *Effect of the compaction time on the movement behavior*

The comparison of the previously short compaction time of 30 seconds did not reveal any constancy of the phase angle or the oscillation amplitude. Longer compaction times of 60, 120 and 360 s are shown in Figure 7. However, a compaction time of 360 s appears to be clearly too long in practical construction applications. A compaction time of 120 s shows that the decrease in gradient in the last 20 s is only 0.06°/s. It can therefore be deduced that compaction is almost complete after a time of 120 s.

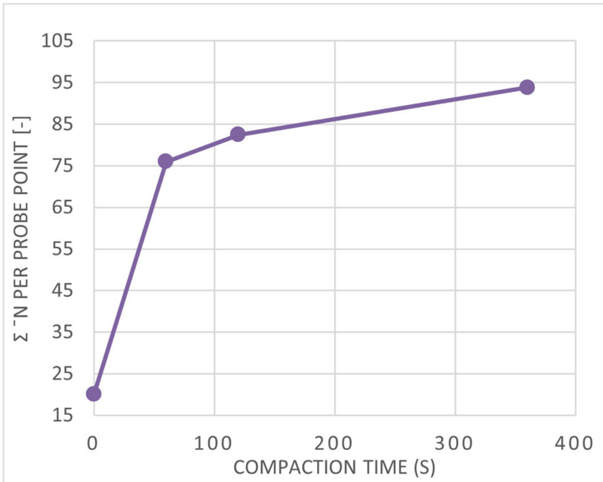

Figure 7. Average total blow count per probe point depending on compaction time [3]

A comparison of the total number of blows in Figure 7 shows a similar picture to that already described, in that there is initially a significant increase in the number of blows. However, a decrease can be observed with increasing duration of compaction.

4.4 *Influence of water and air flushing*

To achieve the final depth with a conventional depth vibrator, either air or water flushing is used in practical applications. A combination of both flushing methods is also possible. Once the final depth has been reached, compaction usually takes place in stages.

With regard to the type of flushing, it can be concluded that the penetration process was quickest when air flushing was used. With water flushing, the penetration speed was slower in every test. If only the vibration displacement amplitude is considered, this is always the highest during air flushing. During compaction, the use of air flushing for penetration shows its disadvantage. In every test, the compaction was significantly worse than during penetration with water. Although the high displacement amplitude still existed due to the high compressibility of the air, the phase angle was always lower and the movement was partially ellipsoidal, which was indicated by the sensor phase angle. Based on the results of the research project, it is not advisable to use air flushing for vibratory compaction on construction sites. However, the penetration rate can also be increased with water flushing by means of regulation.

5 VIBRO COMPACTION CONTROL

A control algorithm was developed based on a comprehensive evaluation of all tests in the parameter study. The frequency is the primary control variable in this context, as the eccentric mass can only be adjusted in a limited number of steps during compaction.

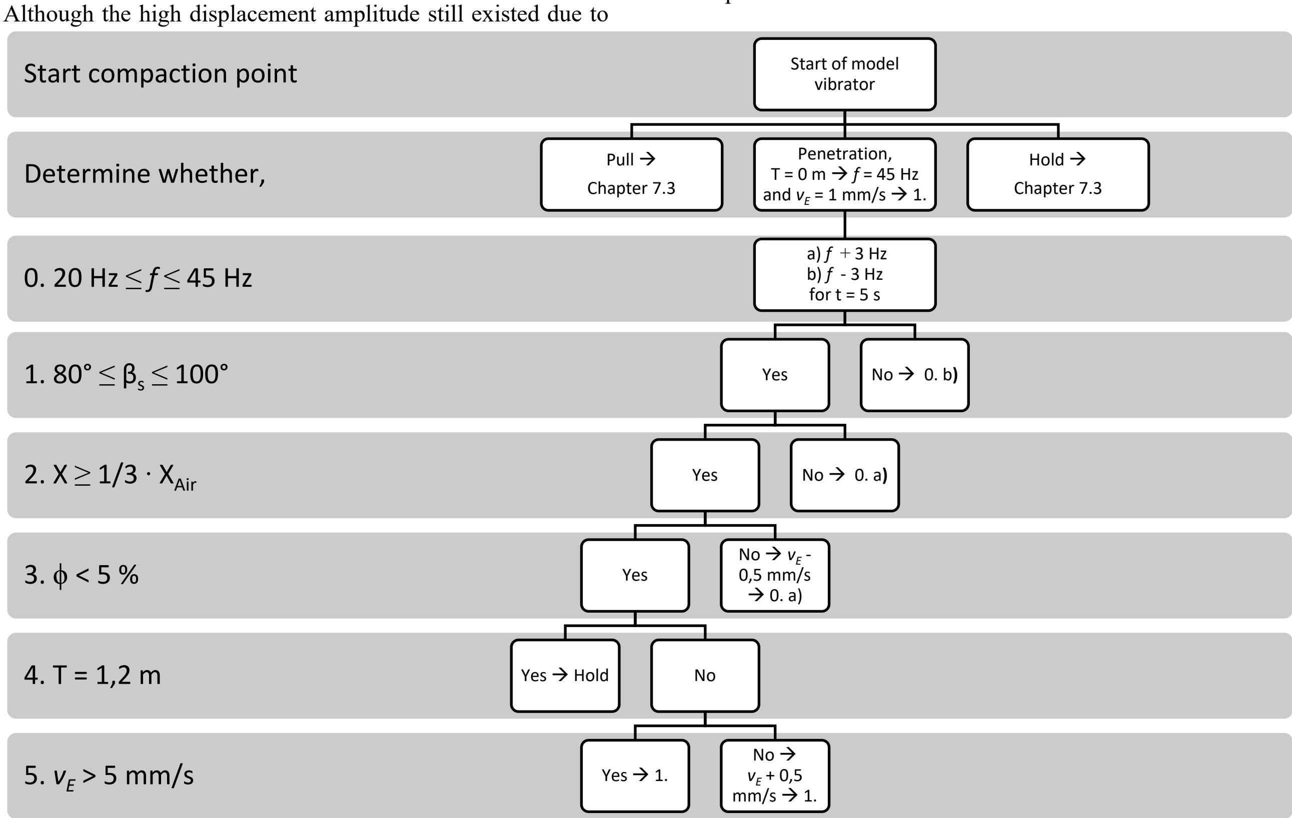

Figure 8. Control algorithm for the vibro compaction process

The algorithm presented is shown as a flow chart in Figure 8.

0.: the compaction process is initiated by defining a start frequency *f* for the first compaction step which lies between the frequency limits of the vibrator.

1.: the algorithm then checks whether the vibration displacement amplitude X corresponds to a minimum of 25 % of that in the air [1]. If the amplitude is too small, there is no compaction.

2.: a further check is carried out to determine whether the sensor phase angle β_s corresponds to a movement behavior that is compatible with the deep vibrator. The minimum β_{min} (80°) and maximum β_{max} limit value (100°) are used for this purpose.

3.: a check is then carried out to determine whether the phase angle φ corresponds to a minimum value φ_{min}. This ensures that the movement is of sufficient size and that there is contact with the surrounding soil. If this is not the case, the frequency must be increased. The phase angle is better suited as a control criterion than the vibration amplitude, as this is in the range of 100 to 175° in both the real size and the model device, while the displacement amplitude is subject to strong fluctuations depending on the vibrator soil system.

4.: if the phase angle corresponds to a minimum value, a check is made to ensure that the maximum value φ_{max} is not exceeded. This ensures that the frequency is reduced in soil layers at lower depths, thus guaranteeing a maximum displacement amplitude with adequate soil contact.

5.: in the final step of the algorithm, the termination criteria are checked: on the one hand, a maximum time of 120 s and, on the other, the change in the phase angle. If the angle reaches approximately a constant value, this indicates that compaction is complete at the current depth. As a result, the vibrator can be moved to the next stage.

6 FIELD TESTS IN SINGAPORE

Field tests were carried out as part of a major construction site in Changi in 2019 to identify the optimum parameter settings for the control system. The soil consisted of a 12 m thick sand fill with an average grain diameter of 0.2 mm to 0.63 mm and a fines content of less than 5 %. The water table was 4m below ground level. Cone penetration tests (CPT) prior to compaction revealed cone resistances between 3 MPa and 9 MPa.

Compaction was carried out as standard with the Keller S700 depth vibrator, a frequency of 25 Hz and an amplitude in the air of 35 mm. The field tests started with a triangular grid and 3 m spacing between the compaction points.

Under the water level, after varying the frequency between 18-25 Hz, a maximum of the average CPT cone resistance in the centroid of the triangular grid of 25 MPa was obtained. It is noteworthy that this occurred at a frequency of 18 Hz, i.e. not at the highest frequency. As with the model tests, it was shown that frequency optimization is more important than maximization.

A variation of the eccentric mass towards a small amplitude of 15 mm and a high frequency of 38 Hz only resulted in CPT cone resistances of 20 MPa. This combination is therefore not recommended underwater and confirms that sand can be compacted best with low frequencies and high amplitudes.

In addition to the frequency and the eccentric mass, the flow rate of water flushing is also important. An increase in the flow rate leads to an increase in the vibration amplitude, which enables faster penetration. In addition, the vibrator does not overheat above the groundwater [3].

7 CONCLUSIONS

Various comparative tests were carried out as part of a parameter study of vibratory compaction. The comparison of different frequencies shows that both the displacement amplitude and the phase angle increase with increasing frequency. However, an increase in frequency is limited by the compatibility of the deep vibrator. At a frequency of approx. 50 Hz in the model tests, however, the movement becomes highly ellipsoidal and compaction is inhomogeneous. For this reason, the sensor phase angle was introduced, which is determined from the acceleration signals.

The eccentric mass has a further influence on the displacement amplitude. An increase in mass by 500 g resulted in a doubling of the displacement amplitude. The behavior described could be observed during the entire compaction. In contrast to the frequency increase, this was only generated at greater depths while the frequency remained constant. Consequently, the eccentric mass has a more significant influence on the displacement amplitude than the frequency and thus on the compaction.

It should also be noted that, in addition to the frequency and the eccentric mass, the compaction time also has a decisive influence on the result. If the time is too short, the compaction potential will not be fully utilized. It is not possible to determine a constant displacement amplitude curve or a constant phase angle, which are indicators for the completion of a compaction step. In this context, the phase angle proves to be more suitable.

A comparison of water and air flushing showed that although the penetration of the vibrator is slower with water flushing, the compaction of the sand is significantly better. Therefore, it is recommended not to use air flushing during vibratory compaction.

Based on the findings, a control algorithm with several easy to determine parameters was developed which adapts the frequency to the surrounding soil conditions. It is recommended not to use complicated spring and damping constants as additional parameters.

The findings were confirmed in field tests in Singapore in a more variable soil than in the model tests.

The process can thus be made more efficient and resource-saving.

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