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Fundamentals of roller integrated compaction control for oscillatory rollers and comparison with conventional testing methods

Johannes Pistrol*, Dietmar Adam

Institute of Geotechnics, TU Wien, Karlsplatz 13/200-2, A-1040 Vienna, Austria

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ABSTRACT

Oscillatory rollers are used for compaction work in sensitive areas like inner city construction sites or near vibration-sensitive structures due to their ability to cause very low ambient vibrations. The fundamentals of oscillatory roller compaction and Continuous Compaction Control (CCC) with oscillatory rollers are discussed within the present paper. The influence of the soil stiffness on the motion behaviour of an oscillatory drum was studied to introduce a novel CCC value for oscillatory rollers based on these findings. The algorithm for the calculation of this novel CCC value for oscillatory rollers is tested on real acceleration measurements obtained from experimental field tests. Moreover, the CCC value is extensively compared to the results of dynamic load plate test by means of the Light Falling Weight Device and to the results of CCC measurements with vibratory rollers.

Introduction

Dynamic compaction methods have become the most popular technique for the compaction of soils over the recent decades. Vibro compactors are used up to great depths for the compaction of non-cohesive soils. Cohesive soils usually require the application of vibro replacement, which can also be used for compaction work in great depths. The gap between dynamic deep vibrators (vibro compaction, vibro replacement) and dynamic near-surface compactors has been closed by the rapid impact compactor [1].

Numerous structures in geotechnical engineering, such as dams and embankments for roads and railways, are built by compacting layers of granular soils. Therefore, the near-surface compaction is of great importance for the construction of these structures. Usually, dynamic rollers are used for earthworks. The drum of a dynamic roller uses rotating eccentric masses inside the drum to cause a vibration of the drum, which makes the compaction work much more efficient by transmitting dynamic forces into the soil. Various types of dynamic drum excitation have been developed during the past decades, which do not only differ in their design, but also in their operating principle. The vibrating rollers have gained the widest use in practical application, mainly because of their simpler drum excitation system and better compaction depth compared to oscillatory rollers.

Dynamic rollers improved the daily output of compaction work significantly, which increased demands for sufficient methods of quality control. Conventional spot like testing methods, e.g. the static load plate test or the dynamic load plate test [3], are not able to cover the compaction success of large areas or require a significant number of tests, which are time consuming and expensive. Therefore, numerous research projects were conducted over the past decades to develop a better understanding for the interaction between the vibrating drum of a dynamic roller and the compacted soil [2,5,7,9,15]. Based on the findings of these research works a novel method for a work- and roller-integrated Continuous Compaction Control (CCC) was developed. Various roller manufacturers adopted the idea and introduced their own CCC systems for vibrating rollers. Therefore, CCC became an accepted method for compaction control with dynamic rollers and got introduced to numerous standards and guidelines [10,14]. The cited research projects focused on the compaction with vibrating rollers, while hardly any research works (with exception of [8]) were conducted for another important group of dynamic rollers, the oscillatory rollers.

Due to the low research activities, a CCC system for oscillatory rollers has not been developed until recently, which was a drawback for the application of oscillatory rollers in earthworks. In the present paper, the development of the first functional CCC system for oscillatory rollers is shown based on the characteristic motion behaviour of an oscillatory drum.

* Corresponding author.
E-mail address: johannes.pistrol@tuwien.ac.at (J. Pistrol).

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Fundamentals of dynamic compaction with oscillatory rollers

The Swedish company Geodynamik AB developed the principle of oscillatory compaction for dynamic rollers in the early 1980s. The German company HAMM AG was the only roller manufacturer, which produced oscillatory rollers under license over two decades. However, in recent years also Bomag GmbH and Ammann Group Holding AG started with the development of oscillatory rollers.

The dominant direction of compaction of oscillatory rollers results in a lower compaction depth compared to vibratory rollers of same size and weight. This has to be taken into consideration on site by reducing the thickness of the filled layers. Asphalt construction – which uses significantly smaller layer thicknesses compared to earthworks – is an ideal field of application for oscillatory rollers. Furthermore, oscillatory rollers enable the making of very homogenous and smooth surfaces, which is a crucial advantage in asphalt construction. Another advantage of oscillatory rollers, which makes their application in earthworks a considerable option to vibratory rollers, is given by the significantly reduced ambient vibrations caused by oscillatory rollers [11]. Therefore, oscillatory rollers can also be used in sensitive areas, such as inner-city construction sites or on and near bridges.

Principle of oscillatory rollers

The drum of an oscillatory roller has two eccentric masses; their shafts are mounted eccentrically but point symmetrically to the drum axis. Two identical eccentric masses with the same eccentricity are mounted with a shift of 180° to each other and rotate in the same direction (see Fig. 1). The horizontal and vertical forces cancel each other out resulting in a sinusoidal moment around the drum axis that causes a torsional motion in terms of a fast forward-backward-rotation. The described rotation is superposed with the translational motion of the roller.

The friction between the drum and the surface of the compacted soil, the dead weight of the drum and roller, and the oscillatory motion cause a transmission of mainly tangential forces into the soil. The soil is primarily compacted by shear stresses.

Modes of operation

In contrast to vibratory rollers, no uplift of the drum from the ground (caused by excitation) can be observed from oscillatory rollers. However, different modes of operation can be identified by analysing the differential displacements and velocities in the contact area between drum and soil [8]. The modes of operation of an oscillatory roller depend on soil stiffness, amplitude of excitation, excitation frequency, and roller speed similar to the vibratory roller; additionally, the friction properties between drum and soil significantly influence the operation behaviour. The illustration of the modes of operation for oscillatory rollers is provided in Fig. 2 based on [8].

If the static friction force between drum and soil is not exceeded at any time, the mode of operation is “Stick“; the soil beneath the roller is able to follow the motion of the drum and no relative displacements between drum and soil occur. This mode of operation is only of minor relevance for on-site compaction work. A small amount of dynamic slip – caused by the motor drive of the roller – can always be observed even without any oscillation.

The oscillatory motion is superposed with the translational motion of the roller. This can cause a one-sided exceedance of the static friction force and a slipping phase with corresponding displacements and, thus, relative velocities in the contact area between drum and soil occurs for each period of excitation. This so called “One-sided Slip” can already be observed at a very low soil stiffness. The slipping phase of one period of excitation increases with increasing soil stiffness.

The mode of operation “Asymmetric Slip” can be observed with increasing soil stiffness. It is the typical mode of operation for oscillatory roller compaction. Slipping phases occur in case of “Asymmetric Slip”. However, they appear twice for each period of excitation since the static friction force is also exceeded during the forward rotation of the drum. The slipping phase during the backward rotation of the oscillatory motion is usually longer compared to the slipping phase caused by the superposition of forward rotation and travelling motion. Therefore, the described behaviour is called asymmetric. The duration of the slipping phases increases with increasing soil stiffness. An excessive amount of slip can indicate that no further compaction is possible and can cause an undesired significant wear of the drum.

A double periodic exceedance of the static friction force in each period of excitation might occur as well; the corresponding mode of operation is called “Symmetric Slip”. The phases during the forward rotation and the backward rotation comprise the same length in contrast to the behaviour observed with “Asymmetric Slip”. This mode of operation has a limited relevance for practical applications since it has been observed only at standing rollers with activated oscillatory excitation. However, “Symmetric Slip” can be approached for very low travelling speeds.

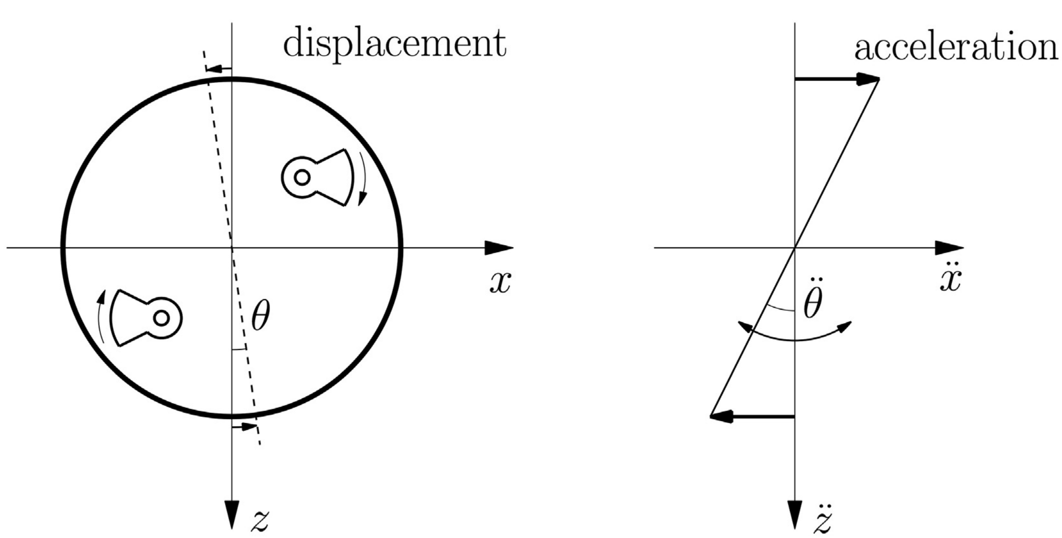


Fig. 1. Drum excitation of an oscillatory roller [2].

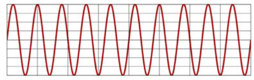
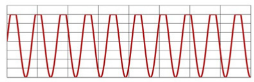
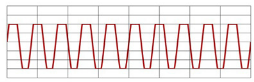
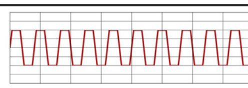
interaction drum-soil	mode of operation	horizontal acceleration in the bearing	app. of CCC	roller speed	soil stiffness	excitation amplitude	excitation frequency
continuous contact	Stick		yes	slow	low (Stick)	small (Stick)	low (Stick)
periodic loss of contact	One-sided Slip		yes				
	Asymmetric Slip		yes		high (Slip)	large (Slip)	high (Slip)
	Symmetric Slip		yes	fast			

Fig. 2. Modes of operation of an oscillatory roller [12].

Fundamentals of Continuous Compaction Control

In contrast to spot like testing methods Continuous Compaction Control (CCC) is a roller and work integrated method for the identification of soil stiffness. The roller is not only used as compaction equipment but also serves as a measuring device at the same time.

The basic principle of a CCC system is to detect the soil stiffness by evaluating the motion behaviour of the drum. The parameters governing the motion behaviour of the drum influence the values of CCC systems as well. Therefore, the first requirement for a CCC system is to keep the roller properties, such as speed, excitation frequency and excitation amplitude, constant during CCC measurements. The second requirement for a CCC system is a continuous recording of the motion behaviour of the drum. This requirement can be fulfilled by measuring the accelerations, velocities, or displacements of the drum. Usually the accelerations are measured in the bearing of the drum in vertical and in some cases also in horizontal or inclined directions (Fig. 3).

Moreover, a CCC system consists of a processing unit, which calculates the corresponding CCC value from the analysed acceleration signal for defined periods (e.g. one CCC value for the time of two periods of excitation). The processing unit also memorizes the CCC values. A display unit is provided for handling the system and to show the calculated CCC to the roller operator values online.

Early CCC systems used sensors for distance and/or speed measurements to assign the CCC values to a certain position on the construction site. Modern CCC systems use GPS for an exact positioning of the roller and, thus, the CCC values.

CCC values cannot be considered as physical soil parameters since they not only depend on soil conditions but also on machine parameters (size, weight, eccentric masses, etc.) and process parameters (excitation frequency and amplitude, etc.). However, CCC values are relative values proportional to the soil stiffness.

National and international standards and contractual provisions usually refer to conventional compaction parameters like the static and/or dynamic deformation modulus. Therefore, the CCC systems have to be calibrated with the static or the dynamic deformation modulus of load plate tests by finding a correlation between CCC values and conventional compaction parameters to fulfil the requirements of

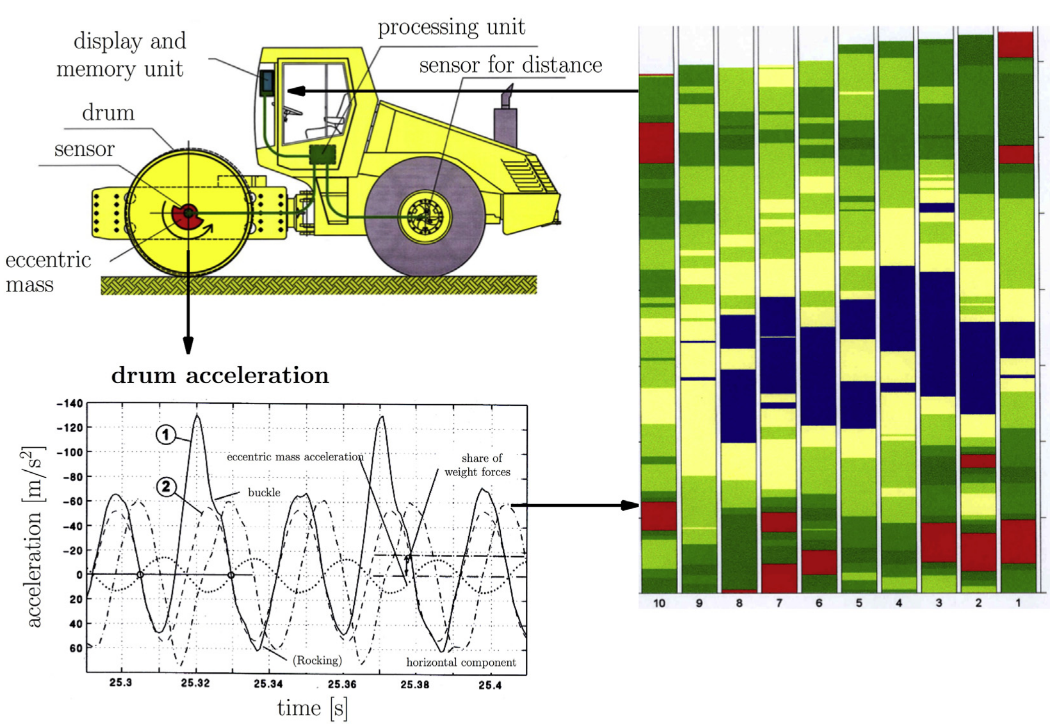


Fig. 3. Components of a CCC system (top), measured drum acceleration (bottom) and visualization of the compaction process and CCC-value (right), based on [2].

standards and contractual provisions [10,14]. A calibrated CCC system can then also be used for acceptance testing.

History of CCC with oscillatory rollers

While various CCC systems for vibratory rollers are available, only one CCC system for oscillatory rollers has been developed in the past: the Oszillometer® of the Swedish company Geodynamik AB [4]. The competing manufacturers in vibratory roller compaction encouraged the development of innovative measurement systems and compaction technologies. On the contrary, HAMM has been the only manufacturer of oscillatory rollers over years. It turned out that the Oszillometer® was not capable of providing a reliable determination of the soil stiffness comparable to the results of CCC systems for vibratory rollers. The system never went into production and no working CCC system existed for oscillatory rollers until recently.

Challenges of CCC with oscillatory rollers

According to the basic principle of CCC the drum-soil interaction is used for determining the compaction success and the soil stiffness respectively. The soil stiffness has a significant impact on the motion behaviour of a vibrating drum causing the modes of operation defined in [2]. Own investigations showed a significantly smaller impact of the soil stiffness on the motion behaviour of an oscillatory drum. The oscillatory drum performs the fast forward-backward-rotation generated by the dynamically excitation and is far less influenced by the soil conditions compared to a vibratory drum.

These facts result in two challenges and requirements for CCC systems of oscillatory rollers: Firstly, the measuring equipment for the recording of the motion behaviour of the drum has to provide data in a high quality to identify even small changes in the motion behaviour. The second requirement addresses the production of the oscillatory drum and the prevention of imbalances.

If a “perfect” oscillatory drum is uplifted, it shows a pure forward-backward-rotation without any translational motion; the dynamic centre of rotation equals the geometrical centre of the drum. Static or dynamic imbalances cause undesired motions additional to the desired forward-backward-rotation resulting in horizontal and vertical accelerations in the bearing of the oscillatory drum. These additional accelerations might be misinterpreted when calculating CCC values based on acceleration measurements.

An imbalanced drum causes motion patterns that repeat with every full rotation of the drum. This behaviour is called periodicity of a drum. Usually this periodicity of a drum can also be observed in CCC values and it reduces their quality and significance. There are various reasons for an imbalanced drum, which have to be considered in order to reduce them to a minimum. Kopf [8] first identified and distinguished various causes for an imbalanced drum. Usually a combination of multiple causes results in periodic imbalances of an oscillatory drum.

Experimental investigations on the motion behaviour of oscillatory rollers

A comprehensive research project on oscillatory rollers was launched by the German roller manufacturer HAMM AG in 2011 in cooperation with the Institute of Geotechnics at TU Wien. The aim of the project was the development of a better understanding for the motion behaviour of an oscillatory drum and its impact on the compacted soil as well as the development of a CCC system for oscillatory rollers. Within this project, large-scale in situ tests were performed with a tandem roller in a gravel pit near Vienna Airport.

The test layout of the experimental field tests is depicted in Fig. 4. Further information about the experimental field tests, including the compaction device HAMM HD^{+} 90 VO and the measuring equipment, can be found in [12,13].

Soil accelerations

The soil accelerations were measured in a depth of 0.4 m and 0.7 m below ground level under the loading of an oscillatory drum. In the results of the soil acceleration measurements a characteristic behaviour of the vertical accelerations ($\ddot{z}$) was observed. While the horizontal accelerations ($\ddot{x}$, in direction of roller travel) show the excitation frequency and a more or less constant amplitude a continuous phase change can be observed in the vertical accelerations (see Fig. 5). The measured signals indicate the formation of a secondary vibration as the oscillatory drum approaches the sensor. The secondary vibration increases until the frequency of vertical accelerations becomes twice the frequency of the horizontal accelerations and the excitation frequency respectively. The secondary vibration decreases and disappears after the drum pass and the vertical and horizontal accelerations show the same dominant frequency again, however, with a reversed phase of the vertical accelerations. This characteristic formation of vertical soil accelerations is based on the motion of an oscillatory drum in its settlement trough. One forward-backward-rotation (= one period of excitation) corresponds to one period of horizontal motion and acceleration. Simultaneously, the drum is forced to perform two cycles of motion in vertical direction caused by the boundaries of the settlement trough; the bow wave in front of the drum and the rear wave behind the drum (see Fig. 6). Hence, the signal of vertical soil accelerations shows a frequency double to the frequency of the horizontal accelerations and the excitation frequency, respectively.

Motion behaviour of oscillatory drums

The interaction of oscillatory drum and soil does not only cause accelerations in the soil, but also has an influence on the motion behaviour of the drum itself. The interaction results in a distortion of the signal and a formation of a secondary vibration with double frequency in the vertical accelerations measured in the bearing of the drum.

The characteristics of the measured accelerations in the bearing of the oscillatory drum are discussed in [13]. For a better understanding of the present paper it is highlighted, that the chronologically connected pairs of accelerations of the drum center ($\ddot{x}_M|\ddot{z}_M$) form a reproducible shape, similar to a recumbent eight in a representation of horizontal accelerations $\ddot{x}_M$ on the abscissa and vertical accelerations $\ddot{z}_M$ on the ordinate. An example is given in Fig. 7.

The superposition of oscillatory motion and roller travel causes an asymmetry of the settlement trough and subsequently an asymmetry of the recumbent eight-shape of accelerations.

The processing of the measurement data obtained from the experimental field tests showed a reproducible formation of the recumbent eight-shape. Furthermore, an expansion of the shape with increasing number of roller passes and increasing soil stiffness was observed. These findings are the basis for a stiffness proportional CCC value for oscillatory rollers presented in the following.

In addition to the experimental field tests a simple mechanical model was defined to systematically investigate the correlation between soil stiffness and the formation of the recumbent eight-shape of drum acceleration. The results of this investigation can be found in [12,13].

Development of a CCC value for oscillatory rollers

The centrifugal forces of the two eccentric masses of an oscillatory drum cancel each other out. Therefore, the horizontal and vertical soil forces are the dynamic impact, which dominate the motion behaviour of the drum. The accelerations in the bearing of an oscillatory drum are proportional to the soil forces as shown in the results of the experimental investigations and can therefore be used for an assessment of the force path.

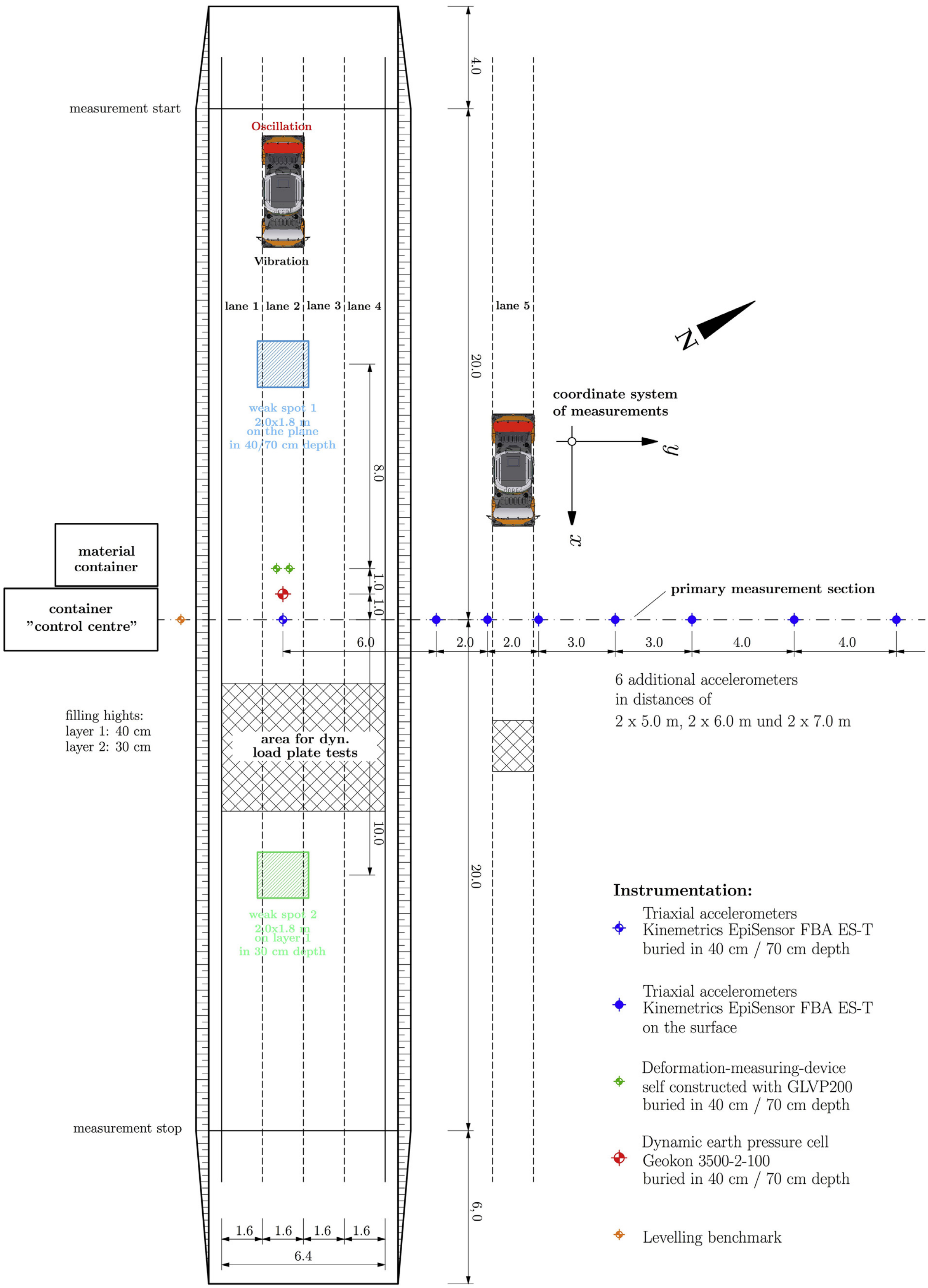


Fig. 4. Test layout of the experimental field tests [12].

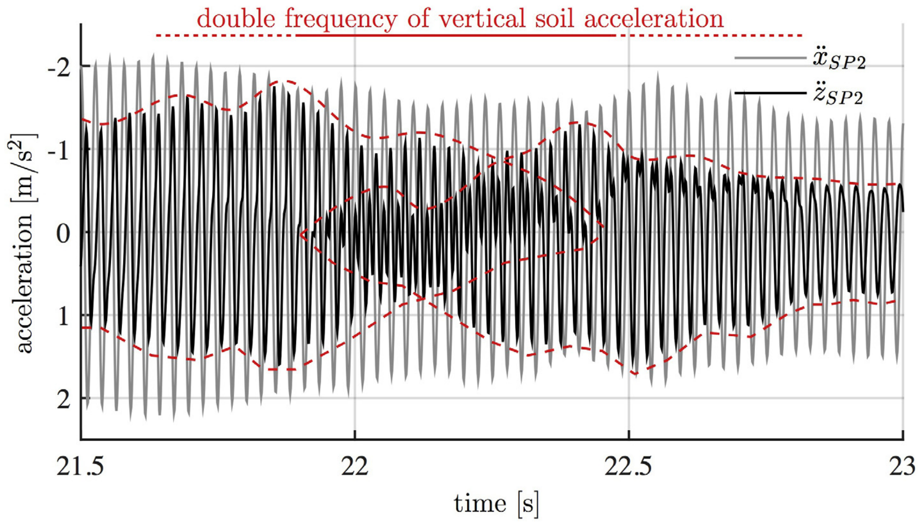


Fig. 5. Horizontal and vertical soil accelerations in a depth of 0.7 m BGL in point P2.2 under the impact of an oscillatory drum.

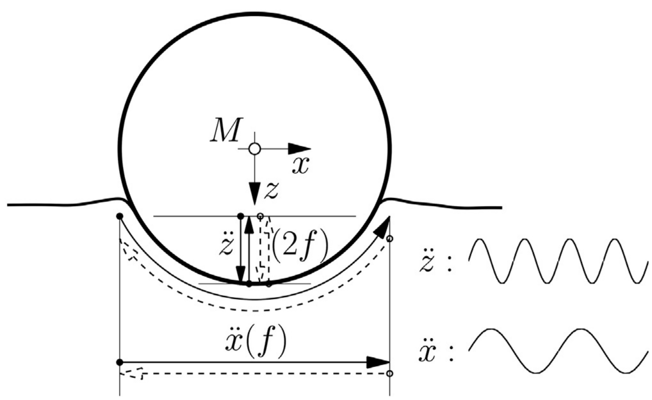


Fig. 6. Principle of motion of an oscillatory drum in its settlement depression and formation of the double frequency in the vertical drum accelerations $\ddot{z}_M$ of the drum center M [12].

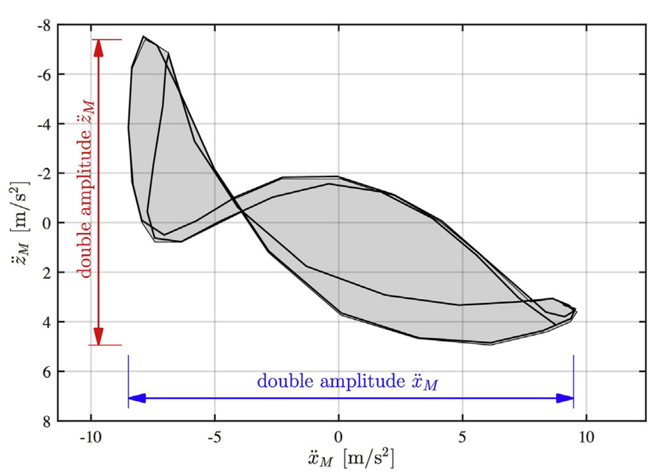


Fig. 7. Horizontal and vertical accelerations in the bearing of the oscillatory drum for two periods of excitation during the eleventh pass on lane 2 [12].

Definition of the CCC value

The formation of the recumbent eight-shape of drum accelerations changes depending on the soil stiffness. Various characteristics of the described shape can be used for assessing the soil stiffness. These include the extent in horizontal and vertical direction, gradient and curvature of various regressions, or the area circumscribed by the eight-shape. The described area showed the greatest significance of all characteristics, tested on measurement data. However, the calculation of this area cannot be done easily, especially when real measurement data shall be processed. Therefore, an algorithm has been developed to approximate the area of the eight-shape with sufficient accuracy [13].

The calculated area was defined as novel CCC value for oscillatory rollers and adopts the theoretical unit of m^2/s^4. A factorisation of the presented CCC value with process parameters or machine parameters, e.g. drum diameter, static line load, vibrating mass or unbalance torque, can be used to obtain more practical CCC readings.

Validation of the CCC value

The algorithm for the novel CCC value for oscillatory rollers was evaluated in the scope of experimental field tests. For the calculation of CCC values a time frame of 1024 sampling points was considered, which corresponds to approximately one CCC value per second. The calculated CCC curves for the roller passes 1, 2, 4 and 8 on layer 2 of lane 2 of the test field (see Fig. 4) are depicted in Fig. 8. During the first pass on the loosely filled second layer, fairly constant CCC values can be observed in Fig. 8. By avoiding any pre-compaction by other construction machines, very soft conditions during the first pass of the roller result in an average CCC value of 25 m^2/s^4. The level of CCC values increases with increasing number of roller passes, which matches the expectations of compaction work. Thereby, the increase is significant during the first four passes, from 25 m^2/s^4 after the first pass to 55 m^2/s^4 after the fourth pass. During the passes five to eight an increase of the CCC values by only 15 m^2/s^4 could be gained, ending up at 70 m^2/s^4 after the eighth pass. This is in accordance with the experience that the first passes of a roller on low-compacted soil gain the largest increase in soil stiffness. When the soil approaches the state of maximum compaction the increase in soil stiffness becomes asymptotically smaller with each roller pass. Comparison of the CCC curves for the various passes reveals a clear reproducibility of the CCC readings.

The shallow weak spot 2 in lane 2 (“W2” in Fig. 8), which was set in a depth of 0.15 m below ground level, can already be noticed in the CCC readings of the second pass. The location of this weak spot with linear elastic behaviour, which was used to simulate non-compacted soil, becomes more apparent in the readings of passes four and eight. While the level of CCC values increases in the virtually homogenous areas between the two weak spots, compaction is almost impossible above weak spot 2 and the CCC values remain very low; even after eight passes. The filled material between the buried mattress and the soil

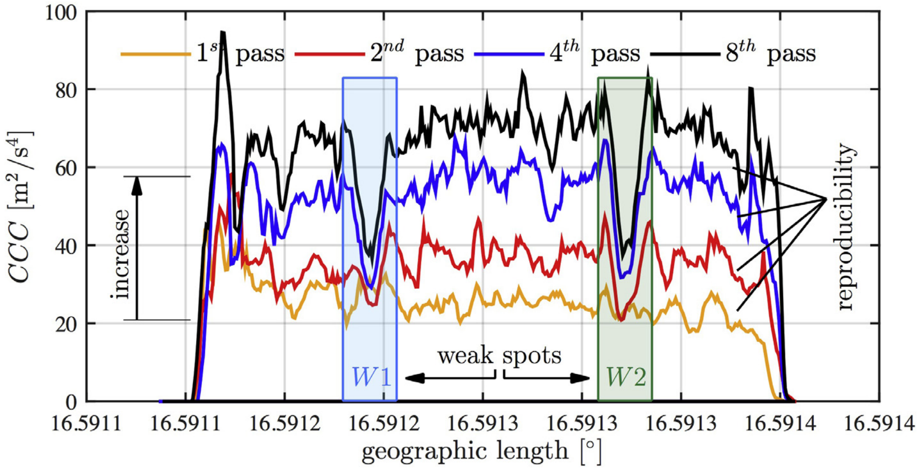


Fig. 8. Curves of the calculated CCC value for the roller passes 1, 2, 4 and 8 on layer 2 of lane 2 on the test field [13].

surface can hardly be compacted because the dynamic excitation lacks resistance from the subgrade. In the CCC curves of roller passes four and eight the lower situated weak spot 1 is clearly visible as well. A minor increase in compaction can be gained above weak spot 1 ("W1" in Fig. 8). However, the compaction achieved is significantly smaller compared to virtually homogenous areas of the test lane. Due to the increased cover of the lower situated weak spot with fill material (0.55 m below ground level) the oscillatory drum is capable of causing shear strains in the material to a certain extent and therefore gain compaction. In conclusion, Fig. 8 shows the capability of the novel CCC value for oscillatory rollers to properly reflect the increase in soil stiffness with increasing number of roller passes and to deliver reproducible results. Moreover, the artificial weak spots in a depth of 0.15 m and 0.55 m respectively can be clearly localized.

Further analysis of the measurement data obtained from the experimental tests highlighted a considerable influence of the process parameters excitation frequency and velocity of roller travel on the results of the CCC calculations. This influence is best investigated on constant soil conditions, which were found on the highly compacted subgrade of lane 5. Due to the high (and constant) stiffness of the subgrade no additional compaction could be gained with additional roller passes. Mean CCC values (one CCC value for each test run) for various roller passes with different excitation frequencies on lane 5 are compared in Fig. 9, which confirms the good reproducibility of the CCC values stated before. However, it also highlights the significant impact of the excitation frequency on the level of CCC values. Lower excitation frequencies yield to lower CCC values, while larger excitation frequencies result in lager CCC values.

A low frequency of $f = 20$ Hz enables the soil to follow the oscillatory motion of the drum easier. Moreover, the low excitation frequency results in smaller tangential accelerations on the drum surface and therefore also smaller accelerations in the bearing of the drum. The two mentioned reasons yield to lower CCC values at smaller excitation frequencies for the same soil stiffness. The reverse conclusion applies to larger excitation frequencies like $f = 60$ Hz.

Comparison of the CCC value for oscillatory rollers with other testing methods

Comparison with results of dynamic plate load tests

The presented CCC value for oscillatory rollers as well as the existing CCC values for vibratory rollers do not represent physical soil parameters and are dependent on numerous parameters, like machine parameters and process parameters. Hence, CCC values cannot be defined as requirements in standards, guidelines or contracts and the requirements refer to the results of conventional testing methods instead. Therefore, the CCC values obtained from the experimental field tests are compared to the dynamic deformation modulus E_{vd}, which was measured after each roller pass with the dynamic load plate test by

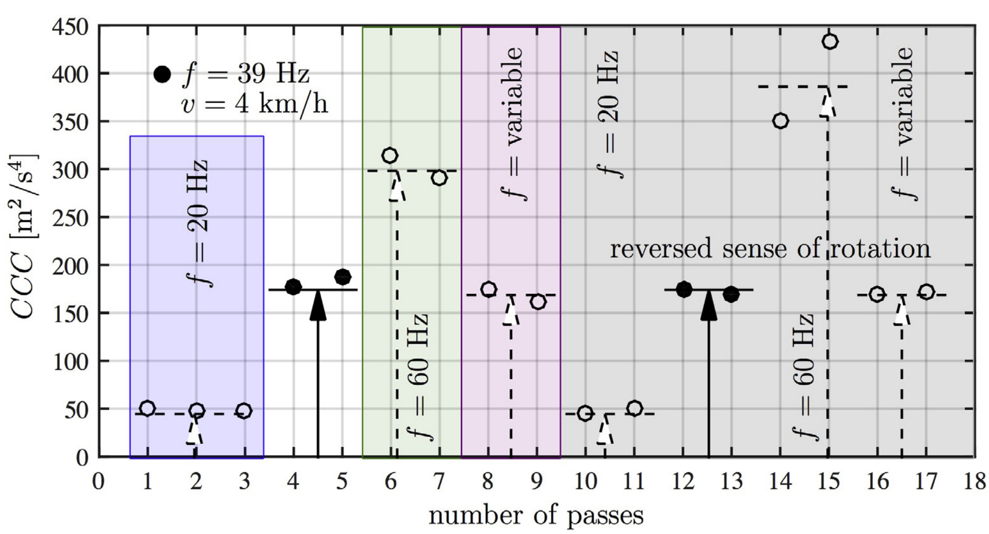


Fig. 9. Average CCC values for 17 test runs on the highly compacted subgrade of lane 5 [13].

means of the Light Falling Weight Device.

The described comparison is depicted in Fig. 10 for selected test runs on layer 2 of lane 2 of the experimental field tests. The evaluation of the dynamic deformation modulus was performed after the static reverse pass of each test run and is independent of the roller's process parameters, of course. Hence, E_{vd} values for each test run and additionally for the non-compacted layer 2 are plotted in Fig. 10. The CCC value for oscillatory rollers depends on process parameters, as discussed previously and a comparison of the results with conventional testing methods is only useful for test runs with constant process parameters. For Fig. 10 all test runs utilising the standard parameters of the oscillatory roller ($f = 39$ Hz, $v = 4$ km/h) were considered. The CCC values for each test run are represented by a mean value, evaluated for the homogenous area between the two weak spots (see Fig. 4).

The difference in the level of CCC values and E_{vd} values impedes a comparison. Therefore, both compaction measures depicted in Fig. 10 (in black) were normalised by dividing the single values by the mean value of all CCC values or E_{vd} values, respectively. The CCC value and E_{vd} show an almost identical development with increasing number of roller passes. Most of the compaction is gained during the first passes of the roller. Both compaction measures indicate, that the maximum state of compaction is reached after roughly eleven passes and remain about constant from the thirteenth pass on. For practical applications, the results shown in Fig. 10 suggest, that all passes after the twelfth pass were irrelevant for compaction but might have caused extensive wear of the drum and the roller. Further compaction could only have been gained with a heavier compaction device or a modification of the soil's water content.

Furthermore, in Fig. 10, the compaction measures are evaluated additionally for both weak spots (in blue and green[1]). Dynamic load plate tests were performed on the homogeneous part of the test field after each pass of the roller, but only occasionally above the weak spots. The good correlation between CCC values and the results of the dynamic load plate tests is confirmed for the areas between the weak spots. A compaction of the filled material can be achieved above the low lying weak spot in 0.55 m depth below ground level. However, the material is less compacted compared to homogenous areas of the test field and the maximum compaction achieved is lower. Hardly any compaction can be gained above the shallow weak spot in just 0.15 m depth below ground level.

The significant influence of the weak spots on the results of the dynamic load plate tests matches the expectations and experience. The weak spots were implemented by burring conventional mattresses. Their behaviour – especially when loaded in vertical direction – is similar to a linear elastic spring. The decrease of CCC values on weak spots might not be obvious, because of the mainly horizontal loading of the soil by oscillatory rollers. However, the vertical accelerations are of significant importance for the formation of the characteristic recumbent eight-shape of horizontal and vertical accelerations and its area, which is the basis of the presented CCC value for oscillatory rollers. The vertical accelerations in the bearing of the oscillatory roller are smaller above weak spots, resulting in lower CCC values. The oscillatory roller is not able to compact the thin soil layer of 0.15 m above the shallow weak spot due to the lack of subgrade resistance.

Another comparison of both compaction measures is depicted in Fig. 11. The results of the conventional tests are plotted on the abscissa with the corresponding mean CCC values of the homogenous area on the ordinate. The same kind of diagram is used for the calibration of CCC systems.

If the same type of soil is tested (sandy gravel on lanes 2 and 5), a correlation of excellent accuracy throughout the entire range of investigated soil stiffness ($E_{vd} = 20 – 90$ MN/m^2) can be found. The

[1] For interpretation of color in Fig. 10, the reader is referred to the web version of this article.

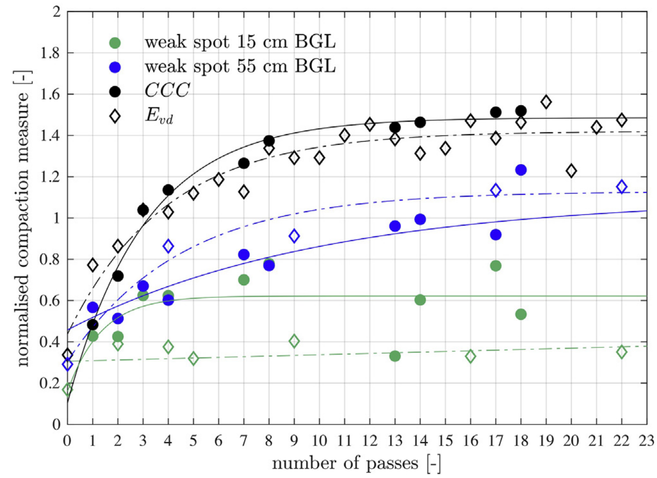


Fig. 10. Development of mean CCC values for oscillatory rollers and dynamic deformation modulus E_{vd} with increasing number of roller passes.

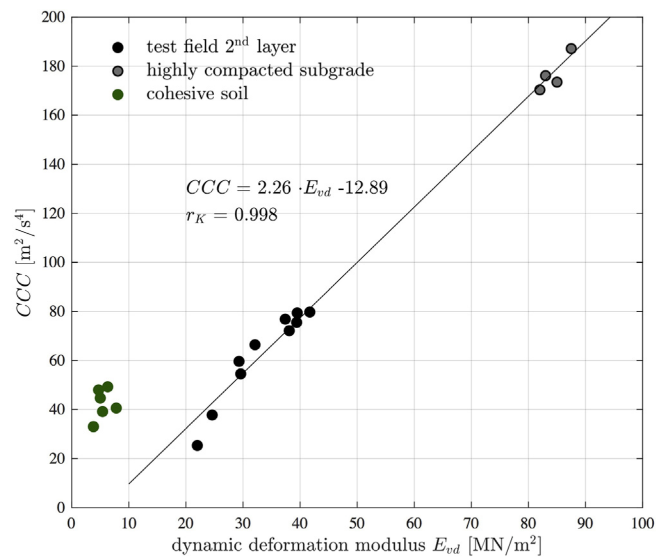


Fig. 11. Correlation between the dynamic deformation modulus E_{vd} and the CCC values for oscillatory rollers [12].

coefficient of correlation $r_K = 0.998$ for example exceeds the required coefficient $r_K \geq 0.7$ according to the Austrian guideline RVS 08.03.02 [14] significantly.

The comparison of CCC values and results from dynamic load plate tests indicates a similar measurement depth of both systems, which results in a good correlation between the two compaction measures.

However, Fig. 11 also illustrates the reason for national standards and guidelines to limit valid calibrations on constant soil types, machine parameters, and process parameters. The cohesive soil, which could not be compacted during the test runs, causes a completely different behaviour of the CCC values. The low stiffness of the cohesive soil ($E_{vd} = 7$ MN/m^2) results in CCC values of approximately 40 m^2/s^4. Soil cohesion might result in a higher resistance of the bow wave in front of the drum and the rear wave behind the drum, which subsequently yields to larger CCC values. However, this assumption needs to be verified in additional investigations.

Comparison with CCC values for vibratory rollers

In addition to a correlation of the CCC values for oscillatory rollers with the results of spot-like testing methods, a comparison with similar

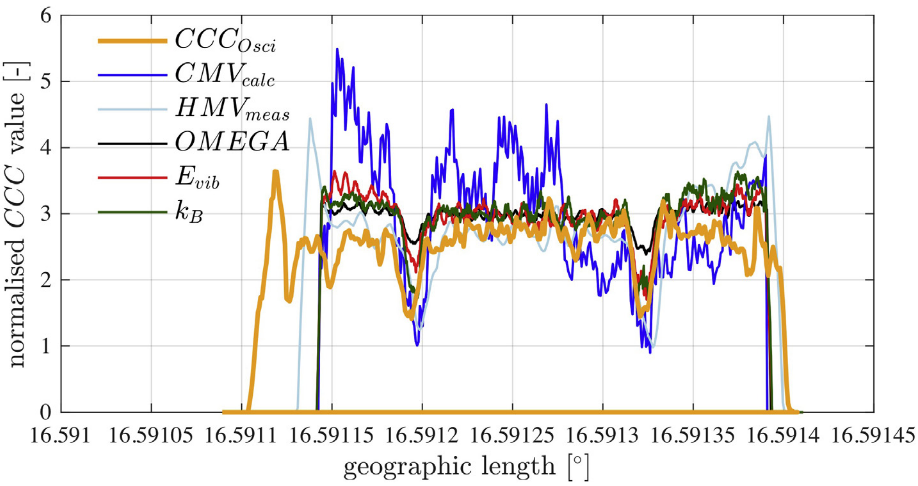


Fig. 12. Normalised comparison of the CCC value for oscillatory rollers and CCC values for vibratory rollers.

systems is of great interest. Due to the lack of other CCC systems for oscillatory rollers, a comparison with the results of CCC measurements with vibratory rollers is discussed in the following.

In the scope of the experimental field tests, additional test runs were performed utilising the vibratory drum of the tandem roller. The HAMM roller was equipped with the company's current CCC system, the HCQ monitor, which calculates a CCC value (*HMV*) based on an evaluation of the vertical drum accelerations in the frequency domain. Moreover, the vertical and horizontal accelerations were measured on the bearing of the vibratory drum to calculate four of the most popular CCC values (*CMV*, *OMEGA*, E_{vib} and k_B). Details on the calculation and the characteristics of these CCC values can be found in [6].

In Fig. 12 the CCC values for the oscillatory excitation are compared to all four calculated CCC values for vibratory excitation and the measured *HMV* value of the roller. The CCC values were normalised by dividing all single values of each CCC system by the corresponding mean value. A comparison of different CCC values is preferably based on one set of measurement data. Therefore, all five CCC values for vibratory compaction were derived from the same test run. However, the two different types of excitation preclude a comparison with the oscillatory CCC values based on the same set of acceleration measurements. To overcome this drawback, two consecutive test runs – an oscillatory test run followed by a vibratory test run – were used for the comparison in Fig. 12. Both test runs were performed on the fully compacted test field at the end of the test series, when no further compaction of the material was possible. The standard parameters ($f = 39$ Hz, $v = 4$ km/h) were used for the oscillatory test run. For the vibratory test run, the small amplitude of 0.34 mm was used with $f = 50$ Hz and $v = 4$ km/h. E_{vib} and k_B were calculated for two periods of excitation.

The calculated CMV_{calc} and the measured HMV_{meas} perfectly show the influence of the two artificial weak spots on the level of CCC values, like the CCC_{Osci} for oscillatory rollers. However, the calculated CMV_{calc}, which is based on the same theory as the HMV_{meas}, shows significant scatter, also in the homogeneous parts of the test field. The HMV_{meas} of the roller integrated system is obviously subjected to some kind of smoothening. The *OMEGA* value is almost constant for the homogenous parts of the test field but is also less affected by the weak spots. In accordance with the results of [6], the CCC algorithms of E_{vib} and k_B are the most advanced CCC values for vibratory rollers.

The comparison with CCC values for vibratory rollers demonstrates the novel CCC for oscillatory rollers' ability to compete with existing systems and to deliver the same reliable results construction companies are used to. In connection with the comparison in Fig. 12, the influence of the measurement depth has to be considered. Due to the mainly vertical loading of the soil with vibratory rollers, the measurement depth of CCC systems for vibratory rollers is significantly larger compared to the system for oscillatory rollers and also exceeds the compaction depth by far. Therefore, the CCC system for oscillatory rollers can be used to detect weak spots in the compacted layer and about 0.2–0.3 m below but not for low lying weak spots in the subgrade. This drawback is an advantage at the same time. The measurement depth of the system for oscillatory rollers is similar to the one of conventional testing methods (static and dynamic load plate test), resulting in better correlations between these compaction measures.

Benefits of CCC with oscillatory rollers

The excellent correlation between the dynamic deformation modulus and the novel CCC value for oscillatory rollers in Fig. 11 can be explained at least to a certain extent by the similar measurement depth of both testing methods. The measurement depth of CCC systems for vibratory rollers is significantly larger, which challenges a correlation with conventional spot tests.

Moreover, the CCC value for oscillatory rollers obviously does not depend on the mode of operation (compared to vibratory rollers). This fact is a major advantage for the application of CCC systems and calibration of CCC values.

Conclusions

The fundamentals of dynamic roller compaction and Continuous Compaction Control with oscillatory rollers were explained at the beginning of the present paper.

Experimental field tests were conducted to investigate the motion behaviour of an oscillatory drum and its impact on the compacted soil. A characteristic formation of a secondary vibration with a double frequency compared to the excitation frequency was observed in the vertical soil accelerations. The characteristic double frequency can also be found in the vertical accelerations in the bearing of the drum and served as basis for the novel CCC value for oscillatory rollers. The precommercial development of the new CCC system for oscillatory rollers was validated on the basis of real measurement data of additional experimental field tests. The comparison of the evaluated CCC readings with the results of conventional dynamic plate load tests revealed an excellent correlation. Moreover, the CCC values of consecutive roller passes were reproducible and weak spots in a depth of 0.15 m and 0.55 m below ground level could be localized precisely. The CCC value for oscillatory rollers was also compared to the results of established CCC systems for vibratory rollers with promising results.

The presented algorithm has already been implemented into a realtime CCC system for oscillatory rollers by the German roller manufacturer HAMM AG. Future work will focus on testing the CCC system on site and including the applicability of this novel technology in national standards and guidelines.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trgeo.2018.09.010.

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