

Dynamic roller compaction for earthworks and roller-integrated continuous compaction control: State of the art overview and recent developments

Dietmar Adam & Johannes Pistor
Institute of Geotechnics, Vienna University of Technology, Austria

ABSTRACT

This paper provides a state of the art overview of dynamic roller compaction and vibration based measurement systems used on vibratory and oscillatory roller compactors to continuously measure soil properties during and after earthwork compaction. Various dynamic rollers equipped with different kinds of exciters are available nowadays. Compaction of non-cohesive and cohesive soils, fill material, and industrial byproducts is usually accomplished by vibratory rollers; the vibration of the drum is generated by rotating eccentric masses. Moreover, dynamic rollers with different types of excitation have been developed in the last decades, including rollers with directed vibration, feedback controlled rollers and oscillatory rollers. The development of roller integrated measurement and continuous compaction control (CCC) has been initiated about 40 years ago; roller measurement values for vibratory rollers have since evolved towards the estimation of more mechanistic soil parameters such as the deformation modulus. Independent assessment of these measurement values has proven their efficacy. Recent developments of a measurement value for oscillatory rollers are presented in detail, thus, CCC is applicable for all dynamic roller types by now.

1. INTRODUCTION

The quality of earth structures highly depends on the compaction state of fill layers, which can be made up of a wide range of various materials, e.g. non-cohesive and cohesive soils, granular material, artificial powders, fly ashes, grain mixtures, and stabilized materials. Thus, both compaction equipment and compaction procedure needs to be selected carefully taking into account the used fill material since compaction mainly contributes to achieve sufficient bearing capacity and uniform settlement behaviour of the earth structure. The layer thickness has to be assessed considering material properties such as grain size distribution, maximum grain size, grain shape and degree of non-uniformity, water content, and water permeability, bearing in mind the roller type and machine parameters such as total roller weight, in particular static drum load, moreover, direction of the resulting dynamic contact force, excitation frequency, theoretical drum amplitude, roller speed, and the shape of the drum.

A high-levelled quality management requires continuous control all over the compacted area, which can be achieved only by work-integrated methods. Roller integrated measurement and continuous compaction control (CCC) result in time and cost savings. CCC provides relative values representing the evolution of the material stiffness all over the compacted area. These values have to be calibrated to relate them to customary values such as deformation modulus of static and dynamic load plate tests defined in contractual provisions and standards.

2. ROLLER COMPACTION

2.1. Vibratory roller compaction

The concept of vibratory excitation for drums was implemented for the first time in 1958 (Kernze 2005) and has become the commonly used type of excitation for dynamic drums. The major benefit of vibratory rollers compared to static rollers is their significantly higher vertical loading due to dynamic excitation, which results in a better compaction at depth.

2.1.1. Principle of vibrating rollers

The eccentric masses of a vibratory drum are shafted concentrically to the drum axis and rotate around this axis with a constant frequency. The rotation of the eccentric masses causes a cyclic translational vibration (see Figure 1). The excitation of the drum results in a mainly vertical loading of the soil. This implies the main characteristics of vibrating drums, the larger compaction depth and higher ambient vibrations compared to oscillating rollers.

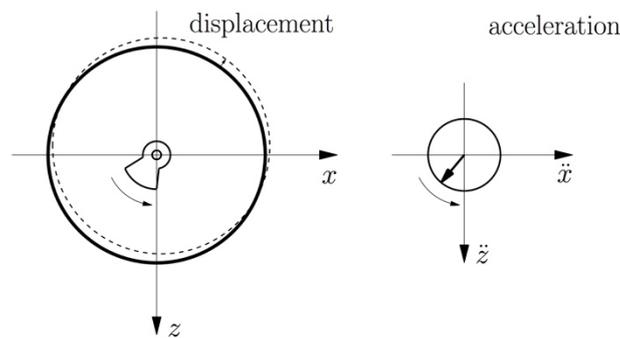


Figure 1: Drum excitation of a vibratory roller (Adam 1996).

2.1.2. Modes of operation

The vibrating drum and the underlying soil form a dynamic interaction system, which results in soil compaction and influences the motion behaviour of the drum at the same time. Soil stiffness, excitation frequency and amplitude, ratio between roller and drum mass, and roller speed have a significant impact on the interacting drum and soil. Depending on these factors among others typical modes of operation can be identified, which are described in the following due to their importance for both compaction efficacy and possible application of continuous compaction control (CCC) (see Figure 2).

2.1.2.1. *Continuous Contact*

No loss of contact between drum and soil takes place in the mode of operation “Continuous Contact”. Therefore, the soil must be able to follow the drum motion, which is the case only for very soft soils and loose fillings or small excitation amplitudes.

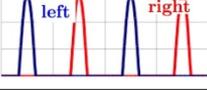
drum motion	interaction drum-soil	mode of operation	soil contact force	application of CCC	soil stiffness	roller speed	excitation amplitude
periodic	continuous contact	Continuous Contact		yes	low	fast	small
	periodic loss of contact	Partial Uplift		yes	↓	↓	↓
		Double Jump		yes			
		Rocking Motion		no			
chaotic	non-period. loss of contact	Chaotic Motion		no			

Figure 2: Modes of vibratory roller operation (modified after Adam 1996).

2.1.2.2. *Partial Uplift*

The mode of operation “Partial Uplift” is the typical mode for well-balanced rollers and most effective for compaction with vibrating rollers. The increasing vertical contact force pointing upwards causes a periodic loss of contact between drum and soil in each period of excitation.

2.1.2.3. *Double Jump*

Increased soil stiffness changes the drum motion; in the mode of operation “Double Jump” the motion is reproduced only every second period of excitation. The drum takes off from the soil and hits the ground alternately with a strong impact and a small impact. The energy transmitted into the soil by the strong impacts results in a better compaction but possibly in a re-loosening of the compacted material as well. However, it also causes a significant higher wear of the roller and also increased ambient vibrations.

2.1.2.4. *Rocking Motion*

When the soil stiffness increases further the longitudinal axis of the drum is alternately tilted to one side and then to the other one, consequently, a phase shift in the motion behaviour between the left hand and the right hand side of the drum can be observed.

The roller can hardly be handled in this so called mode of operation “Rocking Motion”; controlled compaction work is not possible any longer. Consequently, this mode of operation shall be avoided.

2.1.2.5. Chaotic Motion

A combination of very high soil stiffness and unfavourable machine parameters (large amplitude, high frequency, low speed) can cause the mode of operation “Chaotic Motion”. The motion behaviour is not periodic anymore and a roller handling is definitely not possible. Consequently, this mode of operation definitely has to be avoided.

2.2. Compaction with directed vibration

A further development of vibratory rollers was made by company Bomag in 1998 by producing the first roller with directed vibration, which was called Vario® roller.

2.2.1. Principle of directed vibration

The drum of a roller with directed vibration comprises two counter-rotating eccentric masses of the same mass and eccentricity shafted concentrically to the drum axis. Thus, the eccentric masses generate a directed vibration. The direction can be adjusted manually by rotating the whole excitation unit from horizontal to vertical in defined steps (see Figure 3).

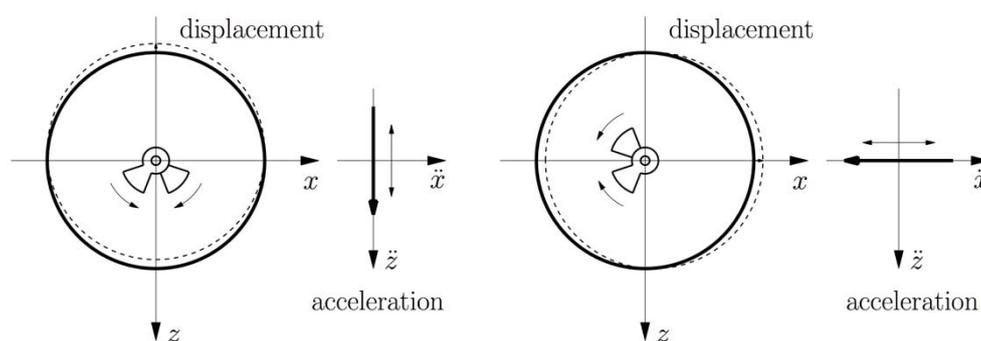


Figure 3: Drum excitation of a roller with directed vibration. Two counter-rotating eccentric masses generate a directed vibration; direction can be adjusted manually by rotating the whole excitation unit (Adam 1996).

If the excitation unit rotates vertically, the behaviour of the roller with directed vibration is similar to the behaviour of a vibratory roller. With decreasing inclination of the excitation unit the vertical component of the vibrations decreases synchronously while the horizontal component increases. If the excitation unit is fixed in horizontal position, the behaviour of the drum is similar to the behaviour of an oscillatory roller. However, there are still differences between a drum with directed vibrations in horizontal direction and an oscillatory drum since the horizontal vibrations represent a translational motion while the oscillatory drum performs a torsional motion around the drum axis.

The controllable regulation of the excitation unit enables the roller operator to influence the compaction process. The vertical position of the excitation unit is suitable for compacting in larger depths in particular during the first roller passes. Parallel to increasing compaction state of the soil the excitation unit shall be declined to avoid undesirable modes of operation such as “Double Jump”, “Rocking Motion”, and “Chaotic Motion”.

2.2.2. Modes of operation

For vertical and inclined positions of the excitation unit from about 30° to 90° (relating to the horizontal plane) the modes of operation of a roller with directed vibration are similar to those of a vibratory roller (Adam 1996). All the modes “Continuous Contact”, “Partial Uplift”, “Double Jump”, “Rocking Motion”, and “Chaotic Motion” can occur. However, the transition of one mode of operation to another highly depends on the inclination of the excitation unit. In case of an almost horizontal position of the excitation unit, the modes of operation of a roller with directed vibration are more similar to the modes of operation of an oscillatory roller, specifically “Stick”, “One-Sided Slip”, “Asymmetric Slip” and “Symmetric Slip”, which are discussed later on (see chapter 2.4).

2.3. Feedback controlled compaction (“intelligent compaction”)

2.3.1. Principle of feedback controlled rollers

The drum of a feedback controlled roller is in accordance with the drum of a roller with directed vibration. However, the inclination of the excitation unit is not adjusted manually but automatically controlled by defined control criteria.

In the 1990s Bomag introduced the Variocontrol® roller with counter-rotating eccentric masses and servo-hydraulic control of the vertical centrifugal force (see Figure 4). Likewise, Ammann introduced the ACE® roller with servo-hydraulic two-piece eccentric mass and frequency control (see Figure 5).

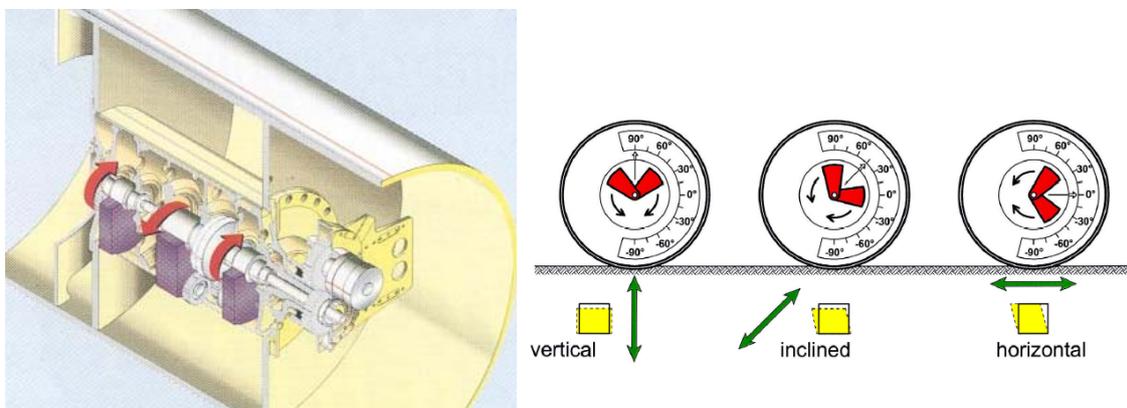


Figure 4: Bomag counter-rotating eccentric mass assembly and vectoring of assembly to vary vertical eccentric force amplitude (picture courtesy of Bomag).

The motion behaviour of the drum is measured using accelerometers in the bearing of the drum and the soil contact force is calculated. The motion behaviour and the soil contact force are usually used to define two control criteria, which are described in the following chapter.

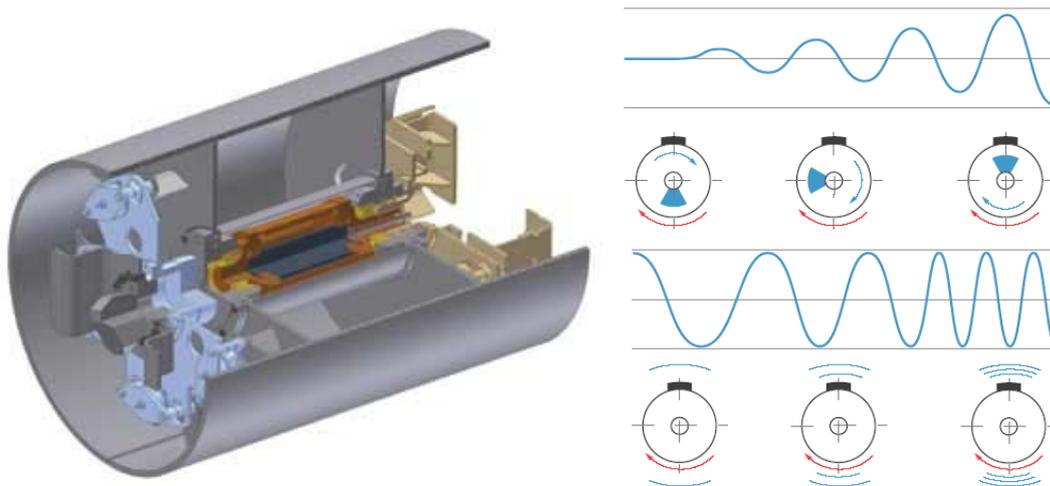


Figure 5: Ammann two-piece mass assembly and variable control of eccentric force amplitude and frequency (picture courtesy of Ammann).

2.3.2. Control criteria

2.3.2.1. *Double Jump criterion*

The double jump criterion is used to avoid the jumping mode “Double Jump”. The mode of operation can be identified by analysing the harmonics of the accelerations in the bearing of the drum. The excitation unit is then declined when “Double Jump” behaviour is sensed.

2.3.2.2. *Force criterion*

A maximum permissible soil contact force is defined depending on the type of roller. If the calculated soil contact force – based on the accelerations in the bearing of the drum – is exceeded, the excitation unit is declined to a more horizontal position.

The compaction process is started with the excitation unit in vertical position and continued until “Double Jump” behaviour is sensed or the maximum permissible soil contact force is exceeded. The excitation unit is then declined to fulfil the stated criteria. The feedback controlled roller continuously tries to incline the excitation unit to a more vertical position to achieve a maximum energy transmission into the soil. Therefore, a high efficiency of the compaction process is guaranteed since more compaction work is provided in areas of low stiffness. In addition, more homogeneous soil properties can be expected after compaction. Modern feedback controlled rollers also allow a fixation of the excitation unit in a more horizontal position to avoid undesired ambient vibrations in sensitive areas.

2.4. Oscillatory roller compaction

The principle of oscillatory roller compaction was developed by the Swedish company Geodynamik AB in the early 1980s (Geodynamik AB 1982). HAMM was the only roller

manufacturer, which produced oscillatory rollers under licence over two decades. However, in recent years also Bomag started with the development of oscillatory rollers (Bomag 2015). The dominant direction of compaction of oscillatory rollers results in a lower compaction depth compared to vibratory rollers of the 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 (Pistor et al. 2013). Therefore, oscillatory rollers can also be used in sensitive areas, such as inner city construction sites or on and near bridges.

2.4.1. Principle of oscillating 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 Figure 6). 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 travelling speed of the roller.

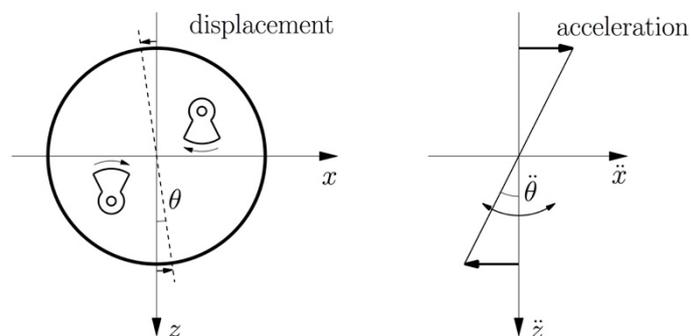


Figure 6: Drum excitation of an oscillatory roller. Two eccentric masses cause a torsional motion around the drum axis (Adam 1996).

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.

2.4.2. 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 of displacements respectively in the contact area between drum and soil (Kopf 1999). The modes of operation

of an oscillatory roller depend on soil stiffness, amplitude of excitation, excitation frequency, and traveling speed similar to the vibratory roller (see Figure 2); 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 Figure 7.

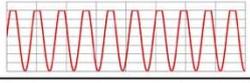
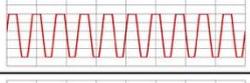
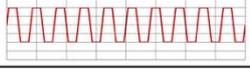
interaction drum-soil	mode of operation	horizontal acceleration in the bearing	app. of CCC	roller speed	soil stiffness	excitation amplitude	excitation frequency
continuous contact	Stick		yes	slow	low (Stick)	small (Stick)	low (Stick)
periodic loss of contact	One-sided Slip		yes	↓ fast	↓ high (Slip)	↓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

Figure 7: Modes of oscillatory roller operation (Pistol 2016).

2.4.2.1. Stick (Adhesion)

The static friction between drum and soil is not exceeded at any time in the mode of operation “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 be always observed also without any oscillation.

2.4.2.2. One-sided Slip

The oscillatory motion is superposed with the travelling motion of the roller. This can cause a one-sided exceedance of the static friction during the forward rotation of the oscillatory motion when the travelling motion increases the forward rotation. A slipping phase with corresponding displacement velocities between drum and soil occurs with every period of excitation.

This so called “One-sided Slip” can already be observed at very low soil stiffness. The slipping phase of one period of excitation increases with increasing soil stiffness.

2.4.2.3. Asymmetric Slip

The mode of operation “Asymmetric Slip” occurs 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 with every period of excitation since the static friction is also exceeded during the backward rotation of the drum. The slipping phase during the backward rotation of the oscillatory motion is usually shorter 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.

2.4.2.4. Symmetric Slip

A double periodic exceedance of the static friction with every period of excitation can occur as well; this operation mode 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 operation mode 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.

3. ROLLER-INTEGRATED CONTINUOUS COMPACTION CONTROL (CCC)

3.1. Principle and components of continuous compaction control systems

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 influencing 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 constant the roller properties, such as speed, excitation frequency and excitation amplitude, during CCC measurement. The second requirement for a CCC system is a continuous recording of the motion behaviour of the drum. This can be done 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.

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 covering the “Double Jump” operation mode). The processing unit also memorizes the CCC values. A display unit is provided for handling the system and to show the roller operator the calculated CCC 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.

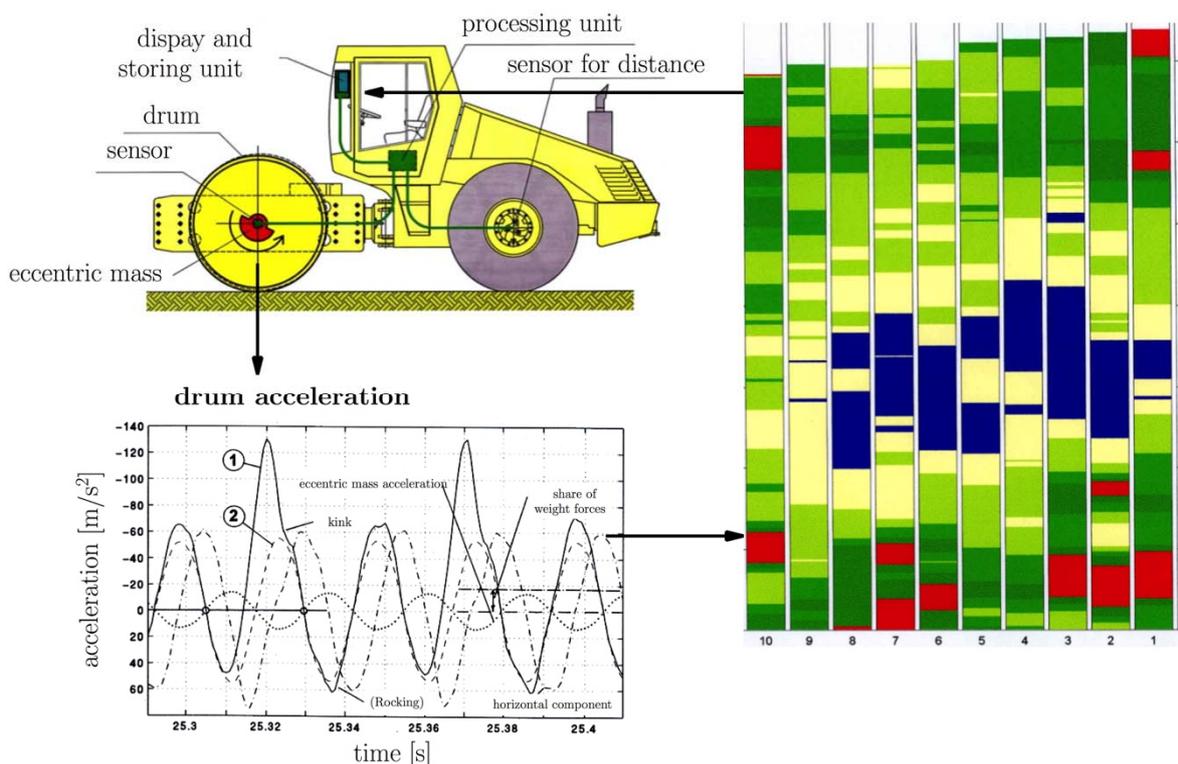


Figure 8: Components of CCC systems (top), measured drum acceleration (bottom) and visualization of the compaction process (right) (Adam and Kopf 2004).

3.2. CCC with vibratory rollers

3.2.1. History of CCC with vibratory rollers

The first considerations regarding vibration-integrated measurements during compaction were made with vibratory plates in the 1930s. The initial research development of roller integrated measurement dates to 1974 when Heinz Thurner performed field studies for the Swedish Highway Administration with a 5-ton tractor-drawn Dynapac vibratory roller instrumented with an accelerometer. The tests indicated that the ratio between the amplitude of the first harmonic and the amplitude of the excitation frequency could be correlated to the compaction effect and the stiffness of the soil as measured by the static plate load test. In 1975 Thurner founded the company Geodynamik with his partner Åke Sandström to continue the development of the roller-mounted compaction meter. In cooperation with Lars Forssblad (of Dynapac) Geodynamik developed and introduced the compaction meter and the compaction meter value (*CMV*) in 1978. The *CMV* is described in more detail below. The new method was introduced at the First International Conference on Compaction held in Paris, France, in 1980 (Thurner and Sandström 1980, Forssblad 1980). Many of the roller manufacturers, e.g., Caterpillar, Ingersoll Rand, subsequently adopted the Geodynamik *CMV* based system. In the late 1980s Bomag developed the *OMEGA* value and the corresponding Terrameter® system. The *OMEGA* value provided a continuous measure of compaction energy and at that time it served as the only CCC alternative to *CMV*. In the late 1990s Bomag then developed

the measurement value E_{vib} , which provided a measure of dynamic soil modulus (e.g., Kröber et al. 2001). Ammann followed suit with the development of a soil stiffness parameter k_B (Anderegg and Kauffmann 2004). These latter E_{vib} and k_B parameters signalled an important evolution towards the measurement of more mechanistic soil properties, e.g. soil stiffness and deformation modulus.

When Geodynamik first introduced the compaction meter and *CMV* vibratory drum technology was quite rudimentary. Vibration was initiated via a mechanical two-piece eccentric mass assembly (clam shell) within the drum that provided two eccentric force amplitudes. If rotated in one direction, the two eccentric masses would join together and provide maximum centrifugal force. Operated in the reverse rotational direction the centrifugal force would be a minimum.

The early efforts to model vibratory roller behaviour used lumped parameter one or two degree-of-freedom models and considered continuous contact behaviour (e.g., Yoo and Selig 1979). Adam (1996) first discovered and characterized the various modes of operation, namely, “drum/soil contact”, “partial loss of contact”, and various degrees of “jumping”, “bouncing”, and “chaotic behaviour”. Such operational modes depend on the vibration amplitude, frequency, and soil stiffness as already discussed in chapter 2 (see Figure 2).

The introduction of servo-controlled vibratory drum technology has catalysed a new initiative termed “intelligent compaction” (in particular in the U.S.), where the vibratory force amplitude and/or frequency is automatically adjusted to improve roller performance and compaction. Currently, the so-called “intelligence” of “intelligent compaction” is limited. Most rollers now automatically decrease the vertical vibration force when jumping mode (“Double Jump”) is sensed. Furthermore, some rollers (e.g., Bomag, Ammann) have the ability to automatically reduce the eccentric force amplitude when a user-defined threshold measurement value has been reached. In a broader sense, however, intelligent compaction is in its infancy. Considerable advances are anticipated in truly intelligent compaction over the next decade (Mooney and Adam 2007).

3.2.2. Compactometer

3.2.2.1. *Basic Principle*

The Compactometer® was the first commercially used system for continuous compaction control with vibratory rollers and is still used by the manufacturers Caterpillar, Dynapac, HAMM and Volvo.

The acceleration sensor (named A-Sensor) measures the vertical accelerations on an undamped part (e.g. the bearing) of the vibratory drum. The reaction of the soil to the dynamic excitation causes a distortion of the A-Sensors signal, which is still periodic but not harmonic any longer. The processing unit amplifies and filters the signal and performs a piecewise spectral analysis to evaluate the acceleration amplitude at the fundamental (operating) frequency ω and its multiples.

3.2.2.2. *CCC values*

Early research showed that various indices incorporating drum acceleration amplitude and the amplitude of its harmonics (i.e., multiples of the excitation frequency) could be correlated to soil compaction and underlying stiffness (Forssblad 1980). From this early research, the

compaction meter value (*CMV*) was proposed (Thurner and Sandstöm 1980) and is computed as:

$$CMV = C_1 \frac{A_{2\omega}}{A_\omega} \quad (1)$$

where A_ω is the amplitude of vertical drum acceleration at the fundamental (operating) frequency ω and $A_{2\omega}$ is the drum acceleration amplitude of the first harmonic, i.e. twice the eccentric excitation frequency. C_1 is a constant established during site calibration ($C_1 = 300$ is often used). The ratio of $A_{2\omega}/A_\omega$ is a measure of nonlinearity. In a truly linear roller-soil system a roller with an excitation frequency of 30 Hz would produce a 30 Hz drum acceleration response and $A_{2\omega}/A_\omega$ would equal zero. Because the roller-soil system is nonlinear (e.g. soil is non-linear elastic-plastic, partial loss of contact occurs, contact surface varies nonlinearly during each cycle of loading), the drum acceleration response is distorted and not purely sinusoidal. Fourier analysis can reproduce a distorted waveform by summing multiples of the excitation frequency. Therefore, the ratio $A_{2\omega}/A_\omega$ is a measure of the degree of distortion or nonlinearity.

CMV is determined by performing spectral analysis of the measured vertical drum acceleration over two cycles of vibration. The reported *CMV* is the average of a number of two-cycle calculations. Geodynamik typically averages the values over 0.5 s; however, this can be modified to meet the manufacturer needs.

A sister parameter called the resonance meter value (*RMV*) is defined as:

$$RMV = 100 \frac{A_{0.5\omega}}{A_\omega} \quad (2)$$

where $A_{0.5\omega}$ is a sub harmonic acceleration amplitude caused by jumping, i.e. the drum skips every other cycle. Therefore, the name of the parameter is misleading since no resonance effects but jumping mode is causing the sub harmonic acceleration amplitude.

The relationship between *CMV* and soil density, stiffness and modulus is empirical and is influenced by roller size, vibration amplitude and frequency, forward velocity, soil type and stratigraphy underlying the soil being compacted (Floss et al. 1991, Sandström and Pettersson 2004, Mooney et al. 2005). Therefore, the use of *CMV* in CCC requires careful calibration. The associated relationships developed during calibration must be strictly adhered to during subsequent site measurement.

3.2.3. Terrameter

3.2.3.1. Basic Principle

The Terrameter® system of Bomag also measures the accelerations in the bearing of the drum. The system uses two accelerometers, mounted with an inclination of 45° relative to the horizontal plane and arranged orthogonally to each other.

The Terrameter® analyses the equilibrium of forces on the drum in vertical direction (see Figure 9).

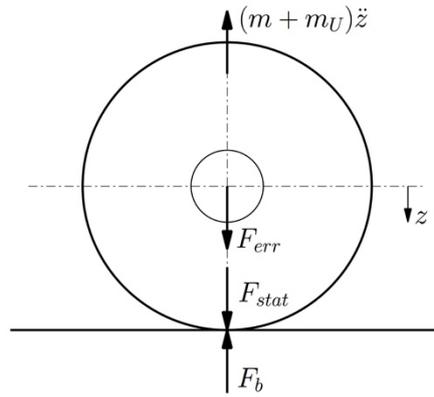


Figure 9: Equilibrium of vertical forces on the drum for the calculation of F_b .

The soil contact force F_b is calculated from the vertical acceleration \ddot{z} under consideration of the static force F_{err} , the mass of the drum m and the eccentric masses m_U (Adam 1996):

$$F_b = -(m + m_U)\ddot{z} + F_{stat} + F_{err} \quad (3)$$

The displacements z can be obtained from a two times integration of the acceleration signal. The displacements z and the soil contact force F_b can be used to draw a force-displacement diagram for each period of excitation (Figure 10).

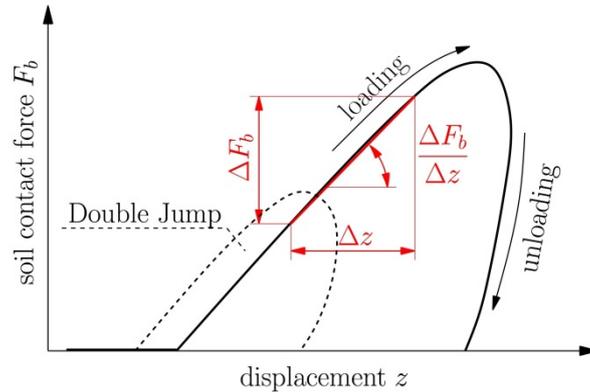


Figure 10: Force-displacement diagram of the vibrating drum for the calculation of $OMEGA$ and E_{vib} .

The force-displacement diagram in Figure 10 is the basis for the CCC values $OMEGA$ and E_{vib} .

3.2.3.2. CCC values

OMEGA

The $OMEGA$ value was the first CCC value of the Terrameter®. It is defined as the area under the force-displacement diagram for two consecutive periods of excitation T_E to minimize the influence of the operation mode double jump:

$$OMEGA = C_3 \oint_{2T_E} F_b z dt \quad (4)$$

Factor C_3 [1/Nm] is a roller dependent factor to make the *OMEGA* value a dimensionless and ranging from 0 and 1000. *OMEGA* is proportional to the energy transmitted into the soil.

Vibration Modulus (E_{vib})

In 1999 Bomag introduced the E_{vib} , which replaces the *OMEGA* value and is currently used with the Terrameter® system. In contrast to *OMEGA* the vibration modulus E_{vib} (MN/m²) is not a dimensionless value but a physically interpretable measure, which describes a soil stiffness by analysing the inclination of the force-displacement curve between two defined points (40% and 90% of the maximum contact force). The E_{vib} is calculated recursively using a Poisson's ratio of $\nu = 0.25$:

$$\frac{\Delta F_b}{\Delta z} = \frac{E_{vib}(2b_0)^3 \pi}{16(1 - \nu^2)(m + m_U + m_R)gr} \quad (5)$$

with:

$$C_E = \frac{E_{vib} 2b_0 \pi}{2(1 - \nu^2)\{2.14 + 0.5 \ln C_E\}} \quad (6)$$

where r and b_0 are the radius and the half width of the drum and m_R is the mass of the roller frame respectively.

3.2.4. Ammann Compaction Expert (ACE)

3.2.4.1. Basic Principle

The ACE® system (Ammann Compaction Expert) was developed by the Ammann Group for feedback controlled rollers. It calculates the CCC value k_B in the time domain. The soil stiffness parameter k_B with the unit MN/m is a physically interpretable parameter, such as the vibration modulus E_{vib} .

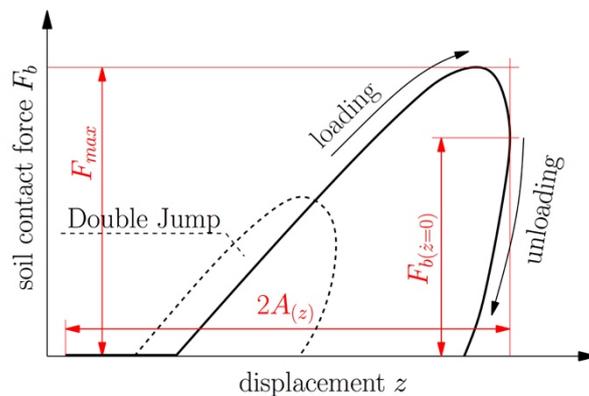


Figure 11: Force-displacement diagram of the vibrating drum for the calculation of k_B .

Considering the lumped parameter model of Figure 9 to represent the vertical kinematics of the soil-drum-frame system the soil is represented with a Kelvin-Voigt spring-viscous dashpot model. Ammann determines the drum inertia force and eccentric force time histories via measurement of drum acceleration and eccentric position (frame inertia neglected). The drum displacement amplitude z is determined via spectral decomposition and integration of the measured peak drum accelerations (Andregg and Kaufmann 2004). The resulting F_b - z response is graphically illustrated in Figure 11 for partial uplift behaviour.

3.2.4.2. CCC values

The ACE® system uses two different equations for the calculation of k_B depending on the mode of operation. For continuous contact the k_B value can be calculated as:

$$k_B = \omega^2 \left[(m + m_U) + \frac{(m_U e_U \text{Vario}) \cos \varphi}{A_{(z)}} \right] \quad (7)$$

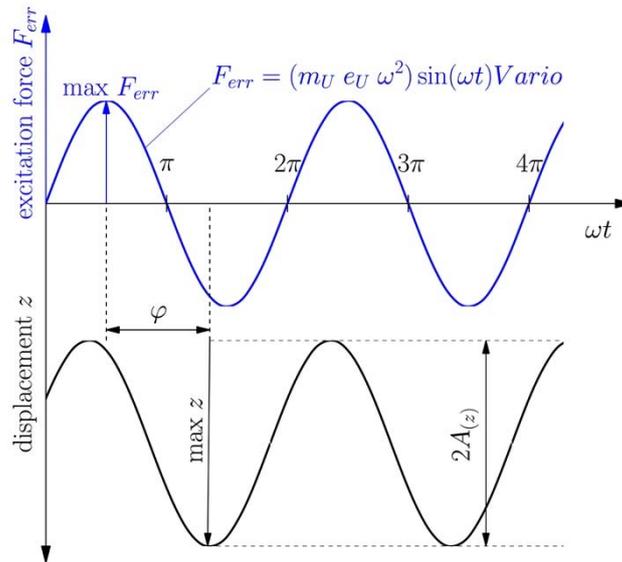


Figure 12: Excitation force F_{err} and displacement z for the calculation of k_B .

where $A_{(z)}$ is the amplitude of the displacement and φ is the angle of phase change (see Figure 12). The dimensionless factor *Vario* is used for a reduction of the dynamic excitation. In case of a periodic loss of contact the k_B is calculated using the contact force at the change from the loading to the unloading phase ($F_{b(\dot{z}=0)}$) and the corresponding amplitude of the drum displacement $A_{(z)}$:

$$k_B = \frac{F_{b(\dot{z}=0)} - (m + m_U + m_R)g}{A_{(z)}} \quad (8)$$

Ammann introduced a modern CCC value with the soil stiffness parameter k_B that allows a reliable assessment of the compaction quality. However, the ACE® system does not consider

the drum geometry, which results in a higher dependence of the k_B value on machine parameters.

3.2.5. Review of CCC values CMV , $OMEGA$, E_{vib} and k_B

Both experimental and numerical studies proved the suitability of all available CCC values for vibratory rollers. They clearly depend on the soil stiffness but the development is significantly influenced by the modes of operation. In Figure 13 and Figure 14 the results of a numerical study is illustrated exhibiting the dependency of CCC values on the drum amplitude and the elasticity modulus E_d of the ground.

CMV and $OMEGA$ drop down considerably when passing to “Double Jump” mode and show a significant dependency on the drum amplitude. $OMEGA$ is closely related to the energy transferred to the ground, which explains the strong link to the drum amplitude.

E_{vib} and k_B are less influenced by the modes of operation and show a minor dependency on the drum amplitude as expected due to their definition as stiffness values.

Nevertheless, a perfect independency of machine parameters cannot be achieved. Since the level and the development of all CCC values depend on the roller parameters they have to be adjusted and need to be kept constant for the whole measurement procedure.

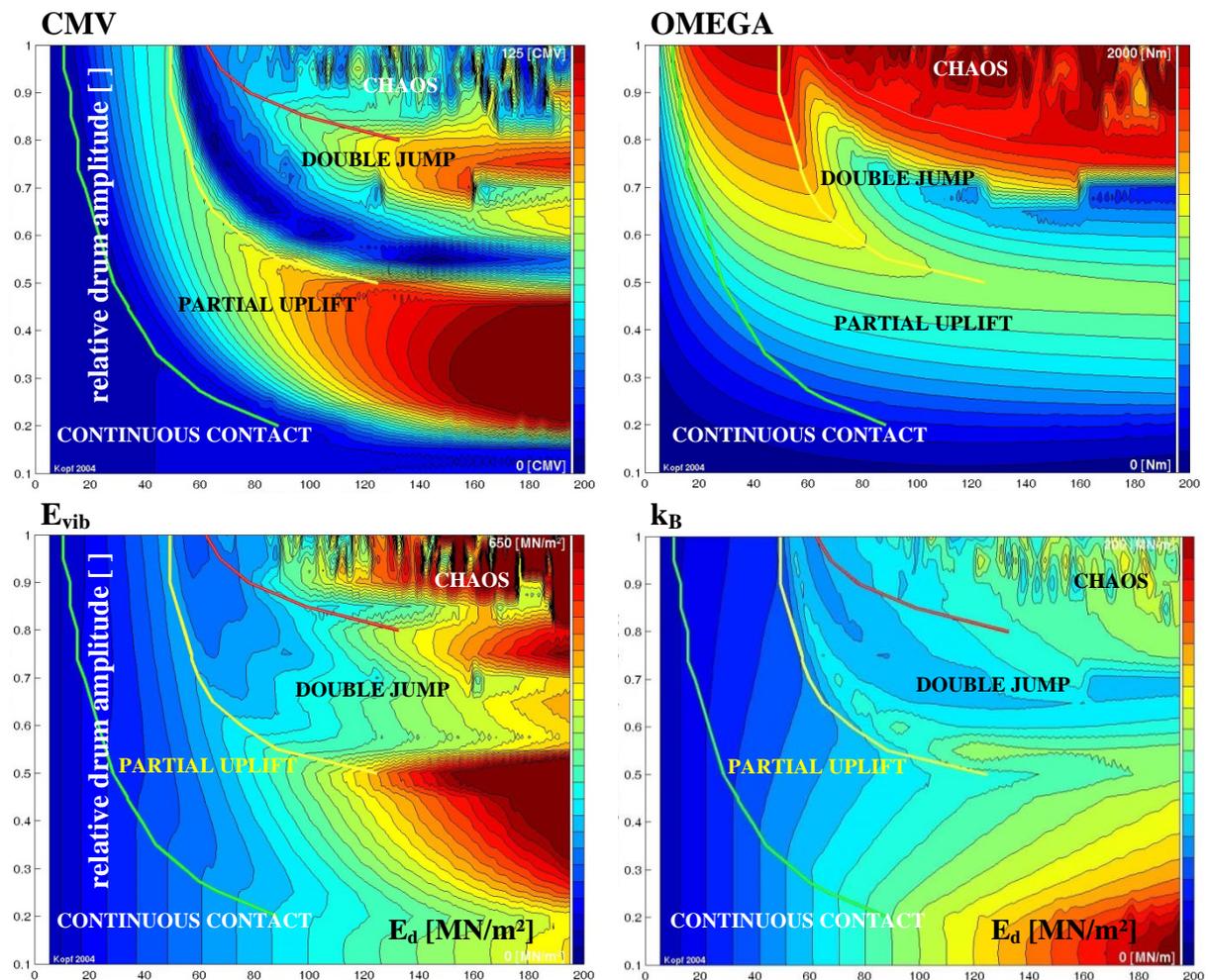


Figure 13: Influence of modes of operation on CCC values (Adam and Kopf 2004).

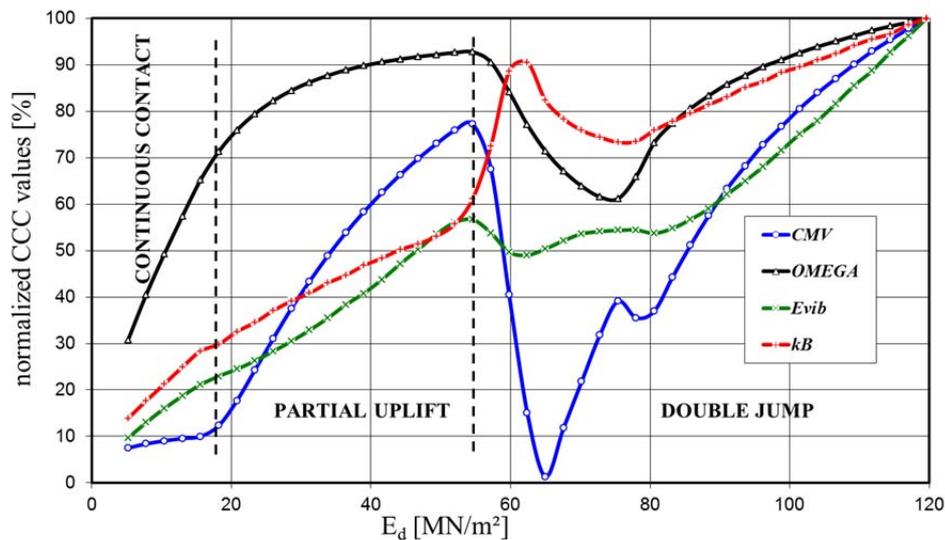


Figure 14: Influence of modes of operation on CCC values for relative drum amplitude of 0.8 according to Figure 13 (Adam and Kopf 2004).

3.3. CCC with rollers using directed vibration

Rollers using directed vibration such as the Vario® roller with counter-rotating eccentric masses (see Figure 4) and the ACE® roller with servo-hydraulic two-piece eccentric mass and frequency control (see Figure 5) can be used with CCC systems. When the roller is used as a measurement device the inclination and settings of the excitation unit have to remain constant since the vertical amplitude of the excitation has a large influence on the level of CCC values. A minimum inclination of 30° relative to the horizontal plane is needed for the fixed excitation unit of rollers using directed vibration to ensure a mainly vertical excitation, which results in a motion behaviour similar to a vibratory drum. CCC is not available for a mainly horizontal vibration at the moment.

3.4. CCC with feedback control rollers (“Intelligent compaction”)

The principle of feedback control rollers contradicts generally the concept of CCC, which states that with constant excitation parameters a change in the motion behaviour of the drum must be a result of the drum-soil interaction. However, feedback control rollers adapt the excitation parameters to continuously improve the compaction process.

Despite efforts on creating a roller and parameter independent CCC value (Anderegg and Kaufmann 2004, Kopf 1999) a change of the excitation parameters still has a significant influence on the measuring depth of a CCC system and therefore on the level of CCC values (Adam 1996, Kopf 1999). A misinterpretation of CCC readings above weak spots in the subsoil can be the consequence.

On this account the same criteria for the use of CCC systems with feedback control rollers apply as for rollers using directed vibration. A reliable assessment of the soil stiffness can only be achieved by using constant machine parameters and a fixed excitation unit.

3.5. CCC with oscillatory rollers

3.5.1. 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. Various 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. Therefore, the system never went into production and until a short time ago no working CCC system existed for oscillating rollers.

The basic principle and the CCC value of the Oszillometer® are described in the following to illustrate the hitherto existing state of the art.

3.5.1.1. *Basic Principle of the Oszillometer®*

The Oszillometer® was introduced by the Swedish company Geodynamik AB in 1997 (Geodynamik AB 1997). The setting and components are similar to those of the Compactometer® of the same company. However, the A-Sensor of the system measures the accelerations in the bearing of the drum in horizontal direction. Furthermore, a different processing unit (called POM) is used for the signal processing.

3.5.1.2. *CCC value of the Oszillometer®*

The CCC value of the Oszillometer® is called *OMV* (Oscillometer-Value) and has the theoretical unit of m/s^2 . The *OMV* is calculated by multiplying the absolute value of the time derivate of the horizontal accelerations at their zero crossing with the time of one excitation period. The processing of the accelerations is performed in sections for the time of a half excitation period, whereby the accelerations are approximated with a third-order parabola. The parabola is calculated using a least squares approximation. One *OMV* value is calculated for each period of excitation by averaging one parabola segment with negative time derivate and one parabola segment with positive time derivate (Geodynamik AB 1997).

Although one *OMV* is calculated for each period of excitation, the values are averaged for one full rotation of the drum to compensate imbalances and periodicities. This has a significant negative effect on the accuracy of the system. If a drum diameter of 1 m is assumed, only one single *OMV* can be provided for the length of 3.14 m. Weak spots in the compacted soil are therefore hardly to detect.

3.5.2. Challenges of CCC with oscillating rollers

According to the basic principle of CCC the drum-soil interaction is used for detecting 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 discussed

earlier in this paper (see also Figure 2). Own investigations showed a significantly smaller impact of the soil stiffness on the motion behaviour of an oscillatory drum. The oscillatory drum carries out the fast forward-backward rotation generated by the dynamical excitation and is far less influenced by the soil conditions compared to a vibratory drum.

These facts result in two challenges and requirements of CCC systems for oscillatory rollers: Firstly, the measuring equipment for the recording of the motion behaviour of the drum has to provide data in a quality to identify also 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 and no translational motions occur; 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.

Horizontal and vertical accelerations are also measured in the bearing of the drum during practical operation of the drum but only after contact initialization between drum and soil. Horizontal forces are transmitted into the contact area between drum and soil as a result of the oscillatory excitation. The contact forces then cause horizontal accelerations in the bearing of the drum, which are proportional to the forces in the contact area. In addition to the horizontal accelerations also secondary vertical accelerations can be measured in the bearing of the drum as a result of the drum motion in its own settlement depression. The settlement depression beneath the drum is bounded by a bow wave in front of the drum and a rear wave behind the drum. The upward motion onto the bow and rear wave during each period of excitation causes additional vertical forces and furthermore, secondary vertical accelerations in the bearing of the oscillatory drum.

The vertical and horizontal accelerations, which are proportional to the forces in the contact area and can be used within a CCC system for oscillatory rollers, can also be observed with imbalanced oscillatory drums. However, in measurements it is hardly possible to distinguish between accelerations caused by the interaction with the soil and accelerations caused by imbalances. Therefore, it is mandatory to reduce the imbalances as a result of the drum production to a minimum and to produce a drum as perfectly balanced as possible to be able to use the oscillatory roller not only as a compaction device but also a measuring device.

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 (Kopf 1999) first identified various causes; his findings are discussed in the following. Usually a combination of multiple causes results in the periodicity of an oscillatory drum.

3.5.2.1. *Static imbalance of a drum*

A static imbalance can be observed, if the centre of mass S is shifted from the geometrical axis of the drum (see Figure 15). The dynamic centre of rotation is not in the drum axis under oscillatory excitation but moves towards the centre of mass. A directed noise signal is measured in the bearing of the drum, which rotates together with the drum. This results in a periodicity of the drum, which can also be found in calculated CCC values.

A static imbalance can easily be identified by uplifting the drum. Independently of the initial position the drum will always rotate into the position with the centre of mass exactly beneath the drum axis.

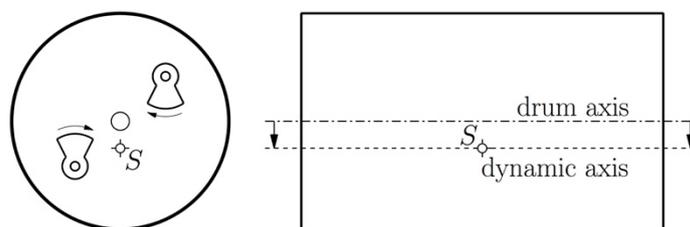


Figure 15: Static imbalance of an oscillatory drum (Kopf 1999).

A static imbalance might be the result of a poor drum design. However, also the production of the drum can cause imbalances of such a kind. A steel sheet (the roll sheet) is rolled-up during production and welded in longitudinal direction. The resulting tube is not perfectly round especially close to the longitudinal weld. Therefore, the outer shell of the drum is processed in lathe after installing the round blanks on each side. As a result of the processing the cross section of the outer shell represents a perfect circle. However, the thickness of the roll sheet varies along the circumference resulting in an imbalanced mass distribution and a shifted centre of mass.

3.5.2.2. Dynamic imbalance of a drum

The centre of mass of a dynamically imbalanced drum is in the drum axis; thus, the drum is statically balanced. However, the centres of mass of the left and right half of the drum are shifted from the drum axis (see Figure 16). In contrast to a statically imbalanced drum the dynamic axis is not shifted but tilted.

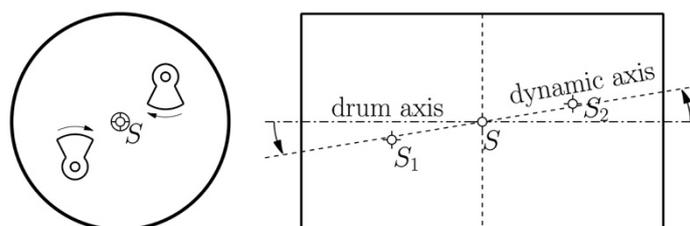


Figure 16: Dynamic imbalance of an oscillatory drum (Kopf 1999).

In case of a fast rotation of the drum the drum shows a rocking motion. Moreover, the measurements on the left hand side of the drum can differ from the measurements on the right hand side of the drum.

The previously described process of production can also cause dynamic imbalances. Moreover, the drive of the shafts of the eccentric masses is usually positioned asymmetrically. The gear wheel of one shaft is positioned on the left side while the gear wheel of the second shaft is positioned on the right side. The resulting dynamic imbalance can be compensated by additional masses inside the drum.

3.5.2.3. Different moments of excitation

The moment of excitation of one eccentric mass is the result of multiplying the mass with the eccentricity. The moments of excitation of both eccentric masses have to have exactly the same size to ensure a balanced drum. A larger mass or eccentricity of one eccentric mass causes an imbalance and a corresponding distortion of the measured accelerations (see Figure 17).

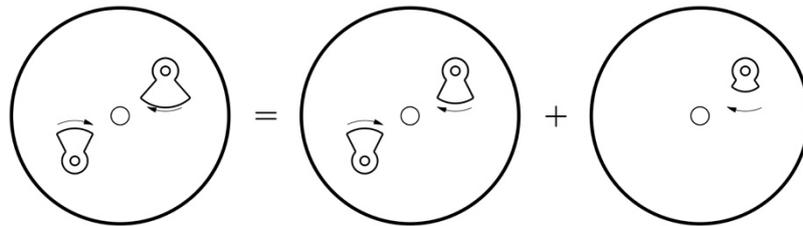


Figure 17: Excitation with different moments of excitation = oscillatory excitation + interferential part of the excitation (Kopf 1999).

Depending on the position of the drum, different moments of excitation result in a more or less distinctive influence on the accelerations in the bearing of the drum and a periodicity of the drum.

Therefore, minimum tolerances should be applied for the production of the eccentric masses to guarantee the same masses and eccentricities.

3.5.2.4. Distorted eccentric masses

Distorted eccentric masses can result from poor assembly. This defect causes a superposition of the oscillatory excitation with an additional vibratory excitation (see Figure 18).

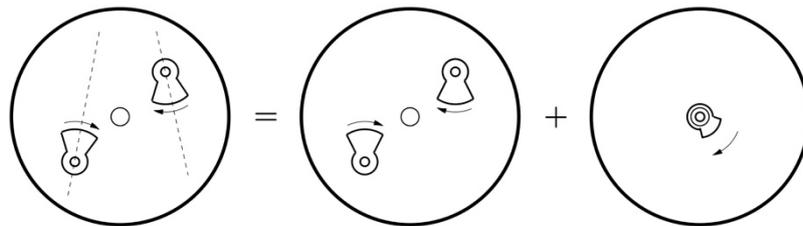


Figure 18: Excitation with distorted eccentric masses = oscillatory excitation + interferential part of a vibratory excitation (Kopf 1999).

In conjunction with the travelling motion and therefore a rotation of the drum, the oscillatory and the vibratory excitation show different frequencies since the rotation of the drum increases the fictitious vibratory eccentric mass. The additional vibratory excitation continuously changes the static linear load of the drum and therefore the conditions of contact between the drum and the surface of the compacted soil layer. A distinctive periodicity of the drum and distortion of the accelerations in the bearing of the drum are the result of this imbalance.

If the fictitious case of a 180° distortion of one eccentric mass is considered, the oscillatory drum becomes a vibratory drum. The periodicity of the drum is compensated in this case.

3.5.2.5. *Shifted shafts of the eccentric masses*

Another reason for a periodicity of the drum might be asymmetric positioning of the shafts of the eccentric masses (see Figure 19). The distances between the shafts and the centre of the drum can differ (left hand side of Figure 19) or the fictitious connecting line between the shafts does not cross the centre of the drum (right hand side of Figure 19).



Figure 19: Shifted shafts of the eccentric masses. Different distances between the shafts and the centre of the drum (left). The fictitious connecting line between the shafts does not cross the centre of the drum (right) (Kopf 1999).

Despite such deficiencies in the production of oscillatory drums shifted shafts of the eccentric masses have no influence on the oscillatory excitation and therefore do not cause any periodicities. The horizontal and vertical forces still cancel each other out and the torsional moment around the drum axis generates the only excitation.

Moreover, shifted shafts of the eccentric masses are a rather unrealistic scenario since templates are used in the production process to guarantee an exact positioning of the shafts.

3.5.2.6. *Differences in the drive of the shafts of the eccentric masses*

The engine for the oscillatory excitation is usually positioned in the centre of one side of the drum propelling a shaft in the centre of the drum. Gear wheels and belts are used for propelling the shafts of the eccentric masses. A uniform tension of the belts is mandatory to avoid periodicities. Therefore, usually tension pulleys are used for an adjustment of the tension during production.

3.5.3. Experimental field tests for the development of a novel CCC value for oscillating rollers

A comprehensive research project on the compaction with oscillating rollers was launched by the German roller manufacturer HAMM AG in 2011 in cooperation with the Institute of Geotechnics at Vienna University of Technology. The aim of the project, which will be continued until September 2016, is a better understanding of the motion behaviour of an oscillating drum and its impact on the compacted soil as well as the development of a CCC system for oscillating rollers and, moreover, the indication of wear of the drum during operation. Within this project large-scale in situ tests were performed with a tandem roller possessing an oscillating drum and a vibrating drum in a gravel pit near Vienna Airport.

3.5.3.1. *Compaction device*

A tandem roller HAMM HD⁺ 90 VO (HAMM AG 2015) was used as compaction device. The roller comprises a total mass of 9,830 kg and two drums of about 1,900 kg vibrating mass each. The typical speed during compaction work for this type of roller is 4 km/h and was used throughout the majority of the tests.

Depending on the rotational direction of the eccentric masses the vibratory drum at the front of the roller operates with vertical amplitude of 0.34 mm or 0.62 mm respectively. For the smaller amplitude a frequency of 50 Hz was used most of the time while 40 Hz was the standard frequency for vibratory compaction with the large amplitude.

The oscillatory drum is mounted on the rear of the HD⁺ 90 VO roller. It uses a tangential amplitude of 1.44 mm and a typical excitation frequency of $f = 39$ Hz. However, the roller for the experimental field tests was modified to be able to use frequencies from $f = 20$ Hz up to $f = 70$ Hz.

3.5.3.2. *Test layout and measuring equipment*

A test area was prepared and equipped in a gravel pit near Vienna for the experimental field tests. The test area comprised four parallel test lanes of loose sandy gravel (to be compacted) with a length of 40 m and two layers of 0.4 m and 0.3 m thickness (see Figure 20). The test field was filled on the highly compacted ground of the gravel pit. The four test lanes were intended for static, oscillatory, vibratory, and combined oscillatory and vibratory compaction. Two ramps at the beginning and at the end of the test lanes served for roller handling, speeding up and down the roller as well as lane changes. A fifth test lane was prepared on the highly compacted ground of the gravel pit.

The test field was equipped with tri-axial accelerometers, a deformation-measuring-device and an earth pressure cell to evaluate the impact of the roller on the soil and the surrounding area. The majority of the results of these measurements is not discussed in this paper, but can be found in literature (Pistrol 2016, Pistrol et al. 2015, and Pistrol et al. 2013).

Four conventional mattresses were buried under test lane 2 to simulate non-compacted, weak spots in the test field and to investigate the influence of these weak spots on CCC values. Two mattresses were placed on the highly compacted ground of the gravel pit before filling the first layer. Weak spot No. 1 was therefore buried in a depth of 0.25 m after filling the first layer and a depth of 0.55 m after filling the second layer. Weak spot No. 2 was prepared by placing two mattresses on top of the first layer after finishing all tests on the first layer. After filling the second layer, weak spot No. 2 was located in a depth of 0.15 m beneath ground level (see Figure 20).

The oscillatory drum of the roller was equipped with four accelerometers with a sensitivity of ± 10 g and the vibratory drum with accelerometers with a sensitivity of ± 30 g. The accelerometers were mounted on the left and the right hand side of the bearing of the drum to measure the accelerations in horizontal and vertical direction on the undamped drum. The positive direction of the horizontal accelerations \ddot{x} was defined in the driving direction; the positive vertical accelerations \ddot{z} pointed downwards (see Figure 6 and Figure 20). The accelerometer signals and all other measurement data were recorded with a sampling rate of 1,000 Hz.

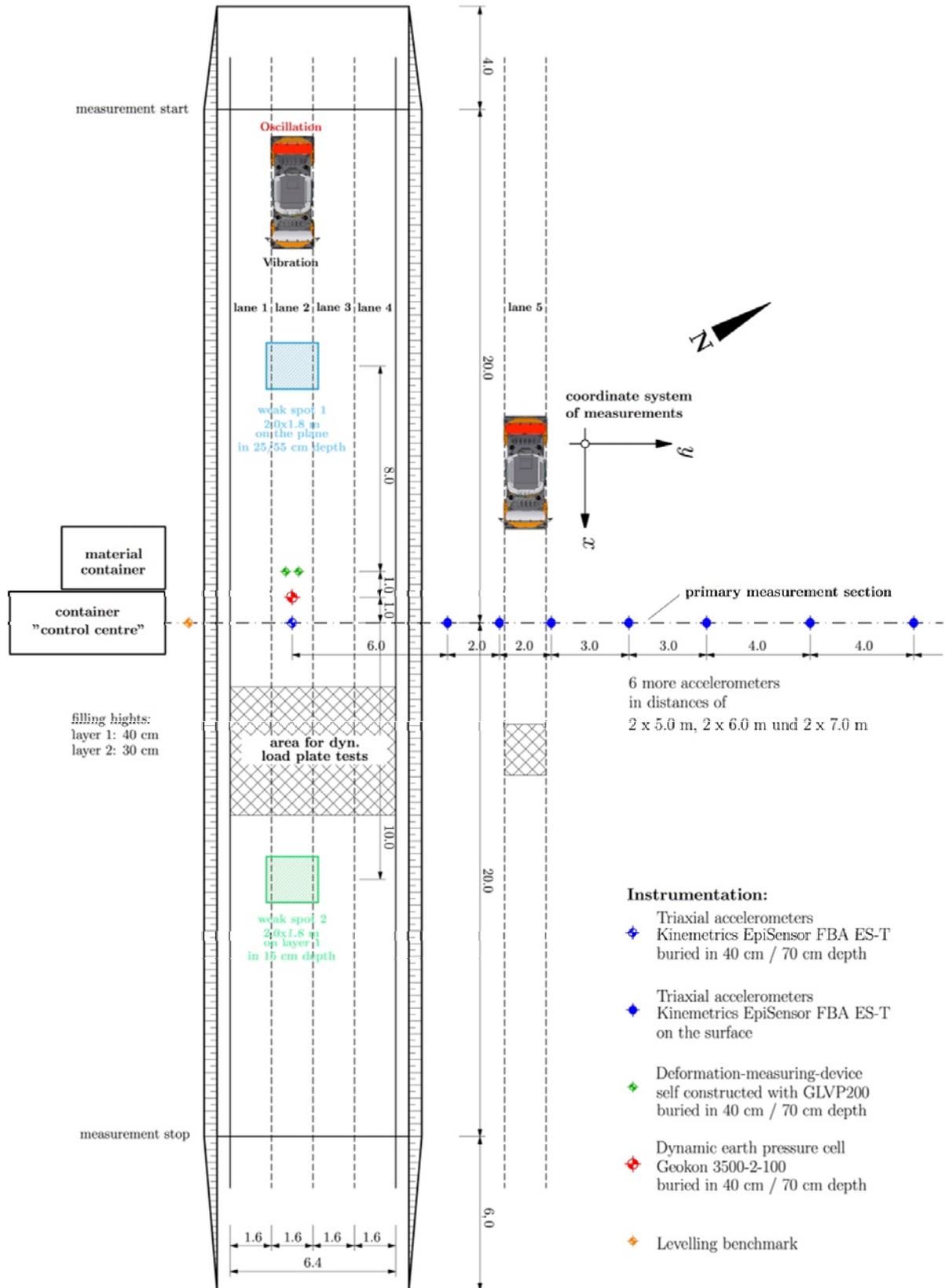


Figure 20: Test layout of the experimental field tests (Pistol 2016).

3.5.3.3. Ground accelerations

The ground accelerations were measured in three axes as described in chapter 2.1. The horizontal accelerations in Figure 21 and Figure 22 correspond to the accelerations measured in the driving direction (x in Figure 20). The horizontal accelerations perpendicular to the direction of compaction (y in Figure 20) are not depicted. Positive sign is defined downwards.

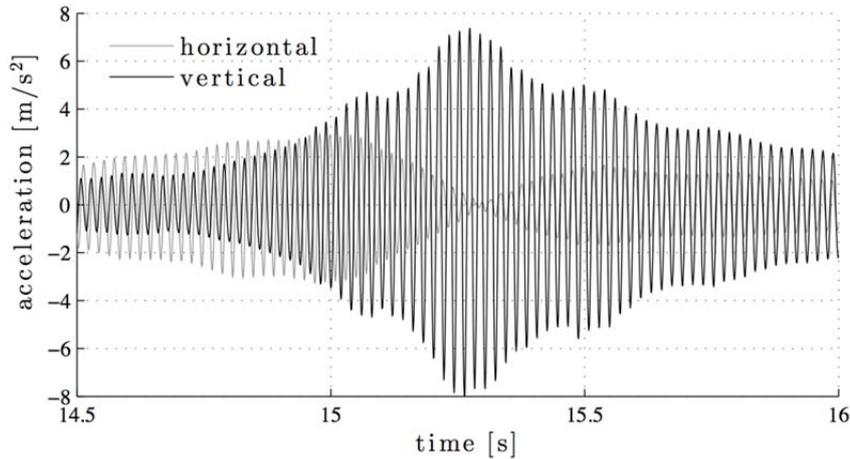


Figure 21: Ground accelerations of a vibratory test run (Pistol et al. 2015).

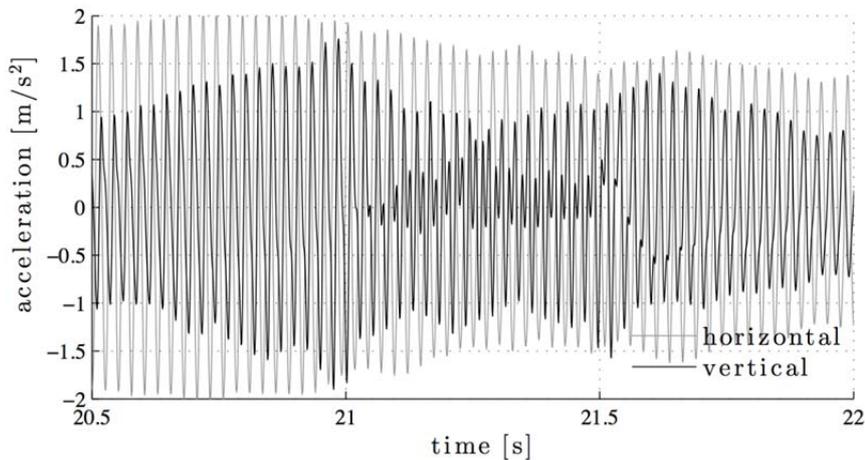


Figure 22: Ground accelerations of an oscillatory test run (Pistol et al. 2015).

The comparison of accelerations of both types of excitation in Figure 21 and Figure 22 shows higher values in vertical direction for the vibratory drum. The reasons for that are the type of excitation and the different time periods when the tests were performed. The vibratory test run was performed subsequently when the layer of sandy gravel was already compacted and therefore showed a stiffer reaction. For the vibratory drum the direction of dynamic loading matches the direction of the measured vertical accelerations, resulting in larger values in vertical direction. The vertical acceleration shows a maximum when the drum is exactly above the accelerometer while the horizontal component of the soil acceleration shows a node

and phase change at the same time. The dominant frequency of both components is the frequency of excitation (50 Hz).

The fast forward-backward-rotation of the oscillating drum causes mainly horizontal accelerations in the direction of compaction (see Figure 22). The horizontal accelerations with almost constant amplitude represent the excitation frequency. The vertical accelerations show a different behaviour. A continuous phase change can be observed when the oscillatory drum passes the accelerometer. The curve of the horizontal acceleration indicates the formation of a secondary vibration when the drum approaches the sensor, which increases until the frequency of the vertical acceleration is twice the frequency of the horizontal acceleration or the excitation acceleration 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. The explanation for the observed behaviour is the settlement depression under the oscillatory drum and the formation of bow wave and rear wave. One forward-backward-rotation corresponds to one period of horizontal movement and acceleration. Because of the upward movement of the drum onto the bow wave during the forward motion and the upward movement onto the rear wave during the backward motion, two periods in vertical direction occur during the same time of one period in horizontal direction (see Figure 23 for the principle of the oscillatory drum movement). Hence, the vertical acceleration shows a double frequency compared to the frequency of the horizontal acceleration.

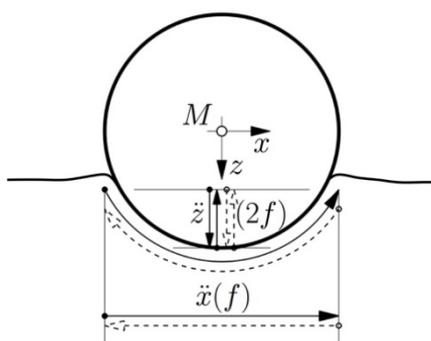


Figure 23: Principle of the movement of an oscillatory drum in its settlement depression and formation of the double frequency in the vertical acceleration \ddot{z} (Pistol 2016).

3.5.4. Investigation of the motion behaviour of oscillating rollers

The formation of a secondary vibration with a double frequency compared to the excitation was observed in the vertical soil accelerations throughout all of the performed experimental tests (Pistol 2016).

The motion behaviour of the oscillatory drum described in section 3.5.4 and depicted in Figure 23 both causes the typical formation of a secondary vibration in the vertical soil accelerations and influences the general motion behaviour of the drum.

The horizontal (\ddot{x}_M) and vertical (\ddot{z}_M) accelerations in the axis of the oscillatory drum are depicted to illustrate the characteristic formation of the accelerations; for the second pass of the oscillatory roller on lane 2 in Figure 24 and for the eleventh pass in Figure 25.

An increase in the acceleration in the bearing, both horizontal and vertical, can be observed between the passes two and eleven.

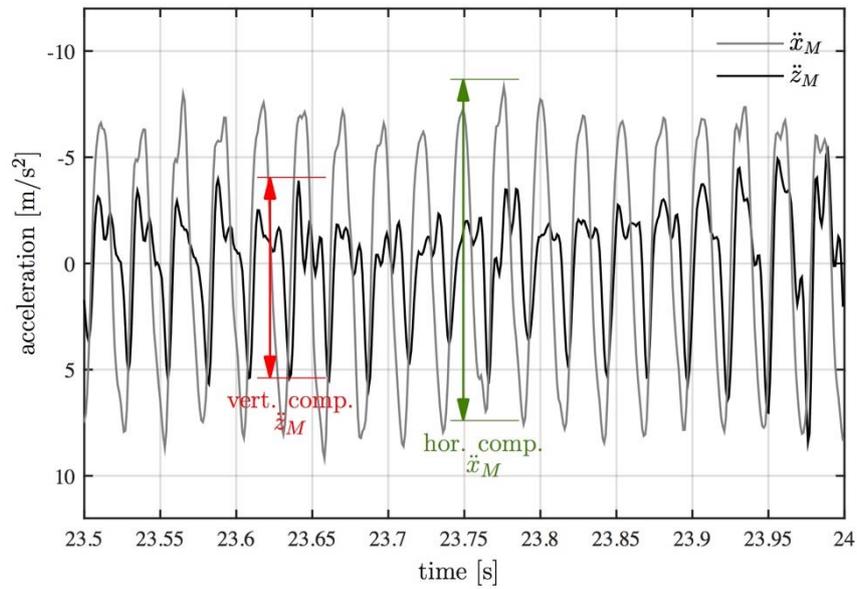


Figure 24: Horizontal (\ddot{x}_M) and vertical (\ddot{z}_M) accelerations in the axis of the oscillatory drum for the second pass on lane 2 with oscillation, $f = 39$ Hz, $v = 4$ km/h (Pistol 2016).

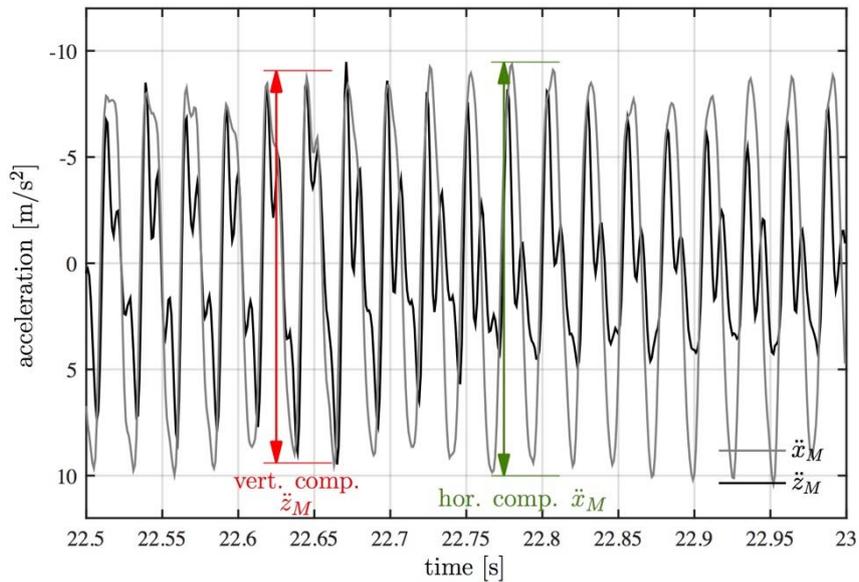


Figure 25: Horizontal (\ddot{x}_M) and vertical (\ddot{z}_M) accelerations in the axis of the oscillatory drum for the eleventh pass on lane 2 with oscillation, $f = 39$ Hz, $v = 4$ km/h (Pistol 2016).

The horizontal accelerations in Figure 24 and Figure 25 show a periodic, sinusoidal curve. The peaks of the sine are partially capped, which indicates an exceedance of the static friction between drum and soil and a change from operation mode “Stick” to some of “Slip” (see section 2.4.2). The double frequency of the vertical accelerations is clearly visible.

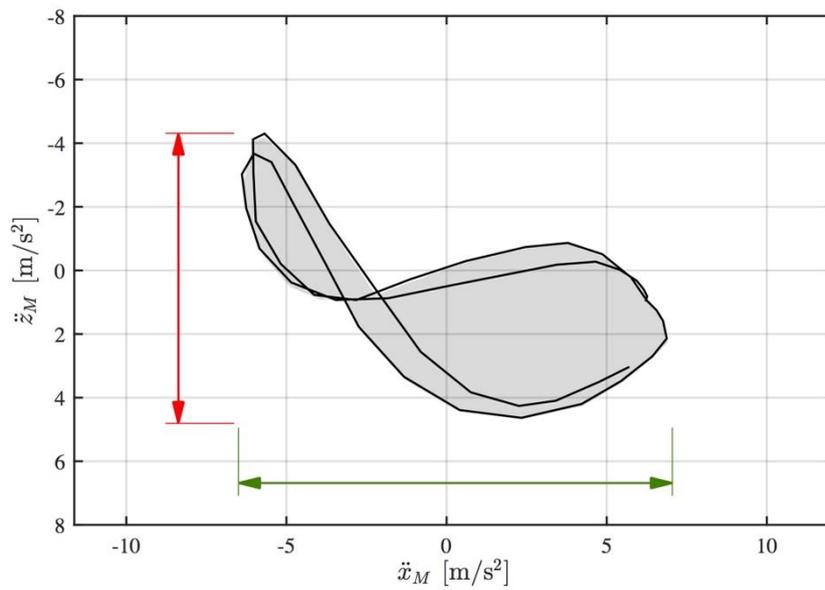


Figure 26: Horizontal (\ddot{x}_M) and vertical (\ddot{z}_M) accelerations in the axis of the oscillatory drum for two periods of excitation during the second pass on lane 2 with oscillation, $f = 39$ Hz, $v = 4$ km/h (Pistol 2016).

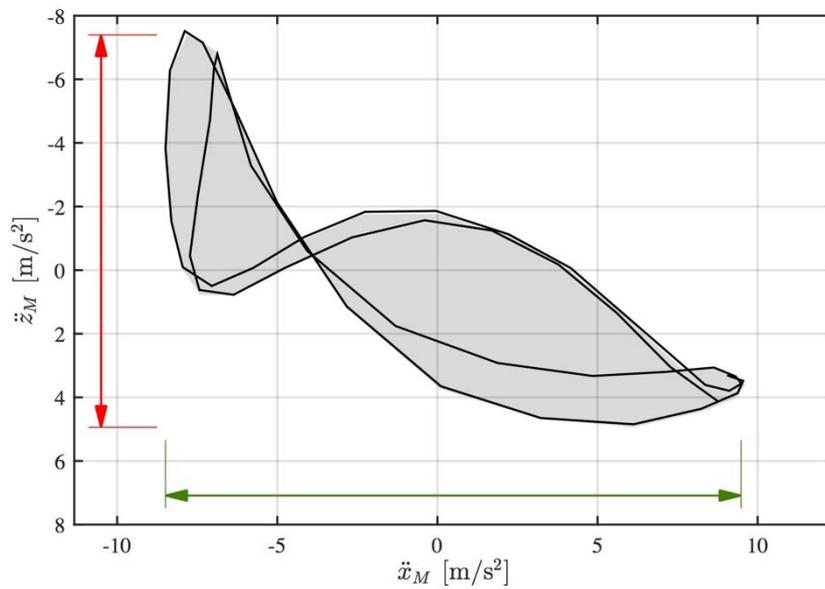


Figure 27: Horizontal (\ddot{x}_M) and vertical (\ddot{z}_M) accelerations in the axis of the oscillatory drum for two periods of excitation during the eleventh pass on lane 2 with oscillation, $f = 39$ Hz, $v = 4$ km/h (Pistol 2016).

In Figure 26 and Figure 27 the same horizontal and vertical accelerations for two consecutive periods of excitation are plotted in a diagram with the horizontal accelerations on the x-axis

and the vertical accelerations on the y-axis. The double frequency of the vertical accelerations causes an eight-shape in this type of representation. Since the horizontal and vertical accelerations increase with increasing soil stiffness, the eight-shape expands as well (Pistol 2016). This expansion of the eight-shape corresponds to the increase of the soil stiffness and therefore it can be used to assess a CCC value.

3.5.5. Development of a novel CCC value for oscillating rollers

The experimental field tests showed a significant influence of the soil stiffness on the motion behaviour of the oscillatory drum. A mechanical model was defined to systematically investigate the correlation between the soil stiffness and the formation of the eight-shape of composed of horizontal and vertical accelerations.

3.5.5.1. Semi-analytic model of the drum-soil interaction

The oscillatory drum is modelled in its own settlement depression (see Figure 5). The drum is described as a rigid disc with a radius r , a mass m , and a rotatory moment of inertia I with the real measures of the HAMM HD⁺ 90 VO roller used for the experimental field tests (see chapter 3.5.3.1). The horizontal and vertical spring rates k_H and k_V as well as the dashpot coefficients c_H and c_V and the resonant soil mass Δm are calculated for various soil stiffness using a horizontal and vertical cone model according to (Wolf 1994). The equations of motion were derived (Pistol 2016) and solved numerically using MATLAB®. A detailed description of the model, including all equations and the derivation of the soil parameters is given in (Pistol 2016).

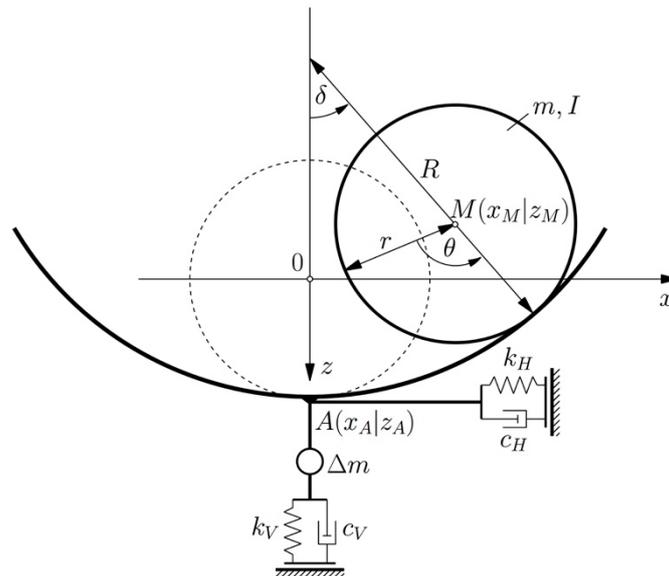


Figure 28: Mechanical model of an oscillatory drum in its own settlement depression (Pistol 2016).

In Figure 29 the horizontal (\ddot{x}_M) and vertical (\ddot{z}_M) accelerations in the drum axis (M in Figure 28) are evaluated for a variation of the dynamic shear modulus G_d of the soil. Figure 29 clearly shows the expansion of the eight-shape with increasing soil stiffness. The vertical

expansion of the eight-shapes is smaller than observed during the experimental field tests and symmetric with regard to the vertical axis because the travelling motion of the roller is neglected in the mechanical model.

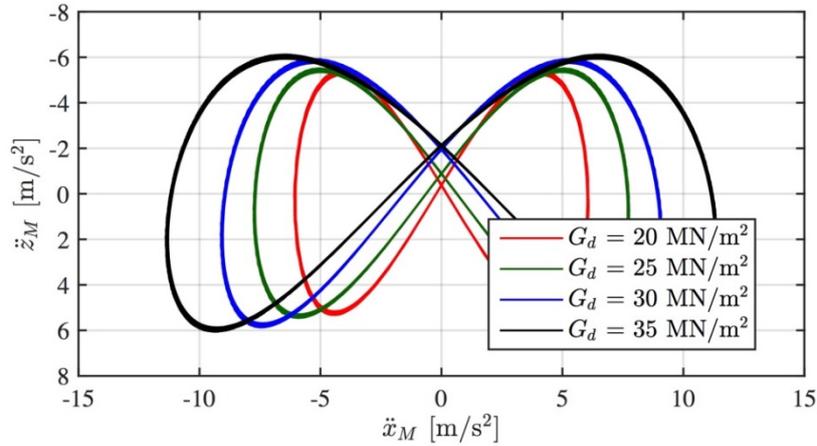


Figure 29: Accelerations (\ddot{x}_M, \ddot{z}_M) in the axis (M) of an oscillatory drum according to the mechanical model in Figure 28 for a variation of the shear modulus G_d of the soil (Pistol 2016).

3.5.5.2. A novel CCC value for oscillating rollers

A novel CCC value for oscillating rollers can be found by appropriately describing the eight-shapes given in Figure 29. One option is the calculation of the area circumscribed by the eight-shape. However, the calculation of this area cannot be done easily, especially when real measurement data shall be processed. The shape changes continuously and if one period of excitation is considered, the last measurement point of the shape does not necessarily equal the first measurement point. Therefore, an algorithm has been developed to approximate the area of the eight-shape with sufficient accuracy.

Each sampling point in a diagram according to Figure 29 is defined by a horizontal (\ddot{x}_M) and a vertical (\ddot{z}_M) acceleration. When all sampling points of one period of excitation are connected chronologically they result in the discussed eight-shape (see Figure 30).

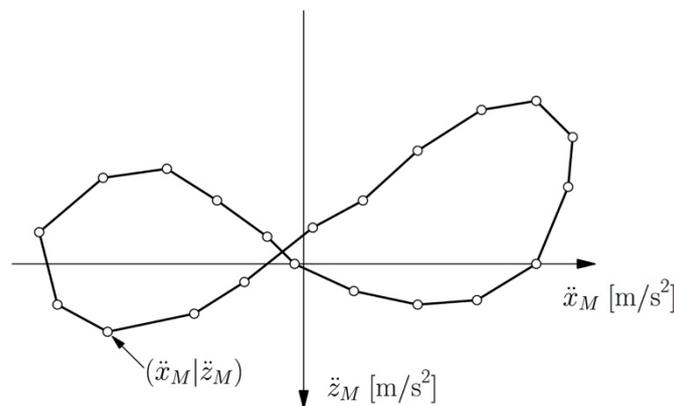


Figure 30: Digital acceleration data ($\ddot{x}_M | \ddot{z}_M$) for one period of excitation sorted and connected in chronological order (Pistol 2016).

However, the sampling points can also be sorted and connected according to the values of the horizontal accelerations. The result is a zig-zag-pattern (see Figure 31). Furthermore, the upper and lower envelopes are calculated by identifying and connecting local maximum and minimum points of the zig-zag-pattern (see Figure 31). The area of the eight-shape can be assessed by calculating the area between the upper envelope and the lower envelope by trapezoidal integration. The calculated area equals the CCC value for oscillating rollers and adopts the theoretical unit of m^2/s^4 .

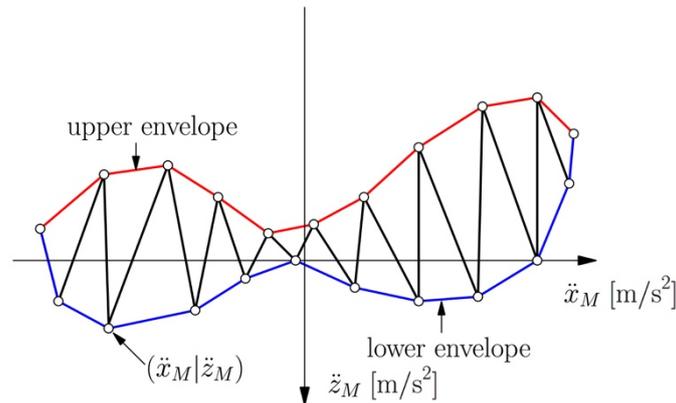


Figure 31: Digital acceleration data ($\ddot{x}_M | \ddot{z}_M$) for one period of excitation sorted and connected according to the increasing horizontal accelerations (zig-zag-pattern), and upper and lower envelopes as basis for the calculation of the CCC value (Pistol 2016).

3.6. Validation and comparison of CCC systems

3.6.1. The novel CCC value for oscillating rollers tested in theory and on basis of real measurement data

The algorithm presented in chapter 3.5.5.2 for the calculation of a CCC value for oscillating rollers was verified using the results obtained from the mechanical model in section 3.5.5.1.

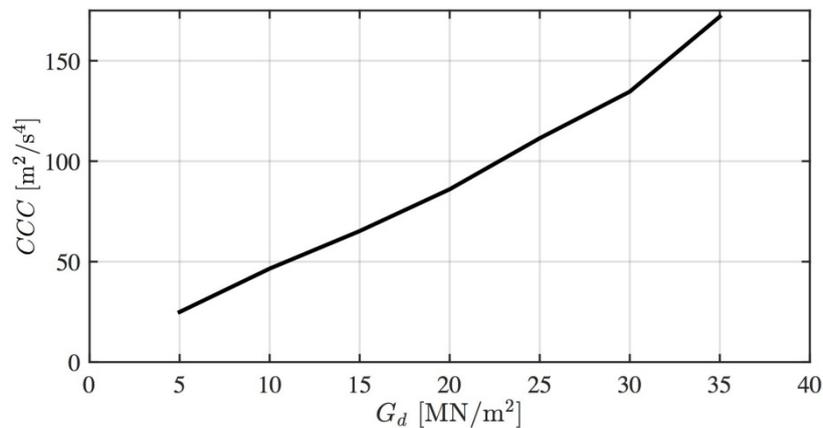


Figure 32: Development of the CCC value for oscillating rollers with increasing soil stiffness G_d (Pistol 2016).

Figure 32 shows the development of the CCC value (according to the enclosed area of eight-shape) for oscillating rollers with increasing soil stiffness G_d . It illustrates the nearly linear relationship between the two indicators of soil stiffness. The calculations are based on the evaluation of the eight-shapes in Figure 29.

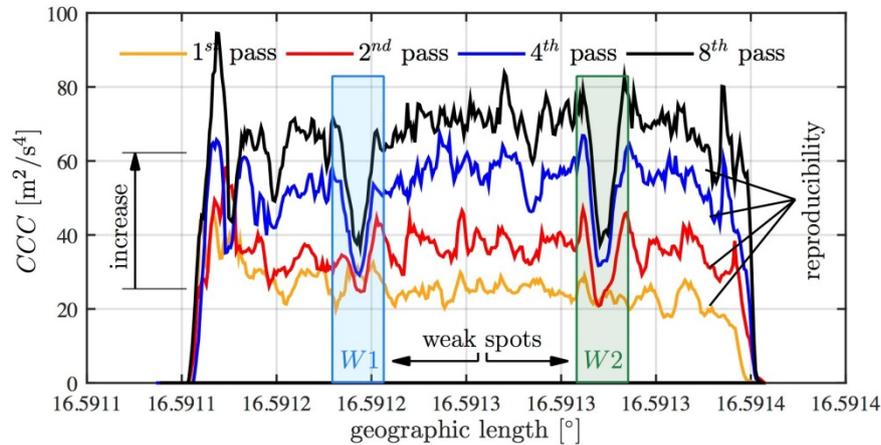


Figure 33: Curves of the calculated CCC values for the passes 1, 2, 4 and 8 on layer 2 of lane 2 on the test field (Pistrol 2016).

Moreover the CCC value for oscillating rollers was evaluated in the scope of the experimental field tests discussed in section 3.5.3. For the calculation of CCC values a time frame of 1,024 sampling points was chosen, which equals approximately 1 CCC value for each second. In Figure 33 the trends of the calculated CCC values are shown for the passes 1, 2, 4 and 8 on layer 2 of lane 2 of the test field (see Figure 20). Comparison of the CCC curves for the various passes reveals a clear reproducibility and an increase of the level of the CCC values can be observed. Figure 33 shows a significant increase within the first four passes on lane 2 and another smaller increase from passes 5 to 8. 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 gets closer to maximum compaction state the increase in soil stiffness becomes asymptotically smaller with each roller pass.

The two artificial weak spots beneath lane 2 (see Figure 20) cannot be located in the measurement development of the first pass on non-compacted soil. However, their location becomes more and more apparent with every pass of the roller. Weak spot 2 was buried in a depth of only 15 cm and shows a linear elastic behaviour. The soil above this weak spot can hardly be compacted and the CCC values of the eighth pass are only slightly larger than the CCC values of the first pass. Although weak spot 1 was buried in a depth of 55 cm beneath ground level of lane 2, it is still clearly visible in the CCC development in Figure 33.

The presented CCC value for oscillating rollers is properly reflecting the increase in soil stiffness with increasing number of roller passes. Moreover, the linear elastic weak spots in a depth of 15 cm and 55 cm respectively can be clearly localized.

3.6.2. Validation and comparison of CCC systems for vibrating rollers

Several CCC values for vibrating rollers, which were discussed in section 3.2, were calculated on the basis of one single set of measurement data for the first time ever in the scope of the

experimental field tests. Selected results are presented in the following, detailed results can also be found in (Hager 2015).

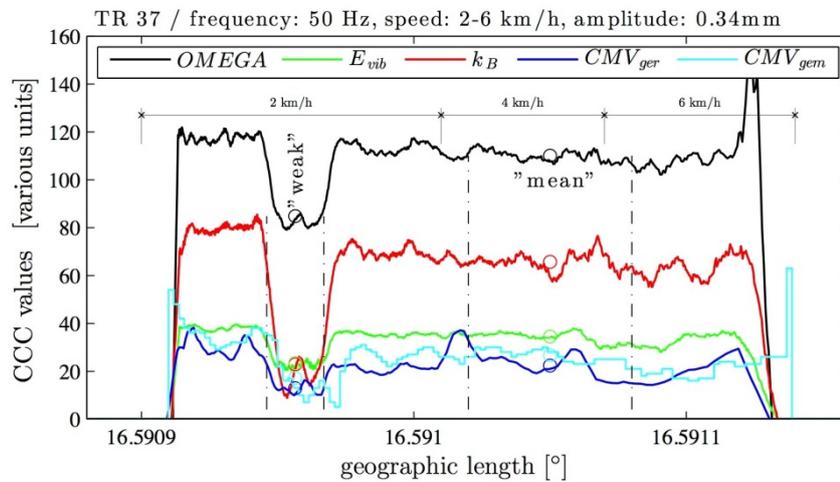


Figure 34: Comparison of all CCC values for test run 37 on layer 1 of lane 2 on the test field (Hager 2015).

Figure 34 shows a comparison of the CCC values $OMEGA$, E_{vib} , k_B and two versions of CMV , a calculated one and the one recorded by the preinstalled Compactometer®, for test run 37 on layer 1 of lane 2 of the test field. An excitation frequency of 50 Hz was used and the roller was accelerated during the test run from 2 km/h at the beginning of the test lane to 6 km/h at the end. All CCC values show a slight decrease due to the higher roller speeds. This means that the soil seems to be weaker with higher roller speeds.

All CCC values clearly show the weak spot under test lane 2 caused by the two mattresses buried in a depth of 25 cm.

CCC values remain largely constant on the homogenous part of the test lane, named “mean”. However, values E_{vib} , k_B and $OMEGA$ based on the force-displacement diagrams in Figure 10 and Figure 11 are calculated in the time domain and seem to be a bit more stable.

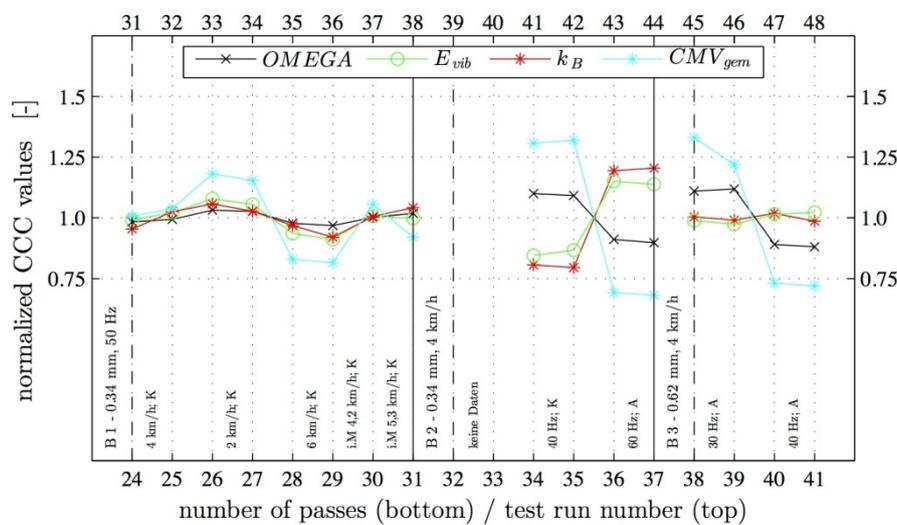


Figure 35: Normalized CCC values for the homogenous part “mean” on layer 1 of lane 2 for various test runs (Hager 2015).

The calculated CMV_{ger} corresponds to the CMV_{gem} of the built in Compactometer® although a phase shift between the two curves can be noticed. This phase shift is caused by the online processing of the accelerations and a slight smoothing of the calculated CMV values to increase the readability of the Compactometer® display.

The influence of various roller parameters on CCC values is depicted in Figure 35. An average CCC value is calculated for the section “mean” for each test run and normalized since all CCC values have different levels and units. Section 1 in Figure 35 shows test runs 31 to 38 with a constant excitation frequency of 50 Hz, in which the influence of different roller speeds was investigated. A lower roller speed (2 km/h) indicates slightly increased CCC values while high roller speeds lower ones. The amplitude of vibratory excitation was changed from 0.34 mm to 0.62 mm for the test runs 45 to 48 with an additional variation of the frequency. The direct influence of the large amplitude can be observed by comparison of test runs 41, 42 with 47, 48. E_{vib} and k_B values increase slightly while $OMEGA$ and CMV decrease. The change of frequency from 30 Hz to 40 Hz combined with the large amplitude of excitation has only a very small influence on E_{vib} and k_B values.

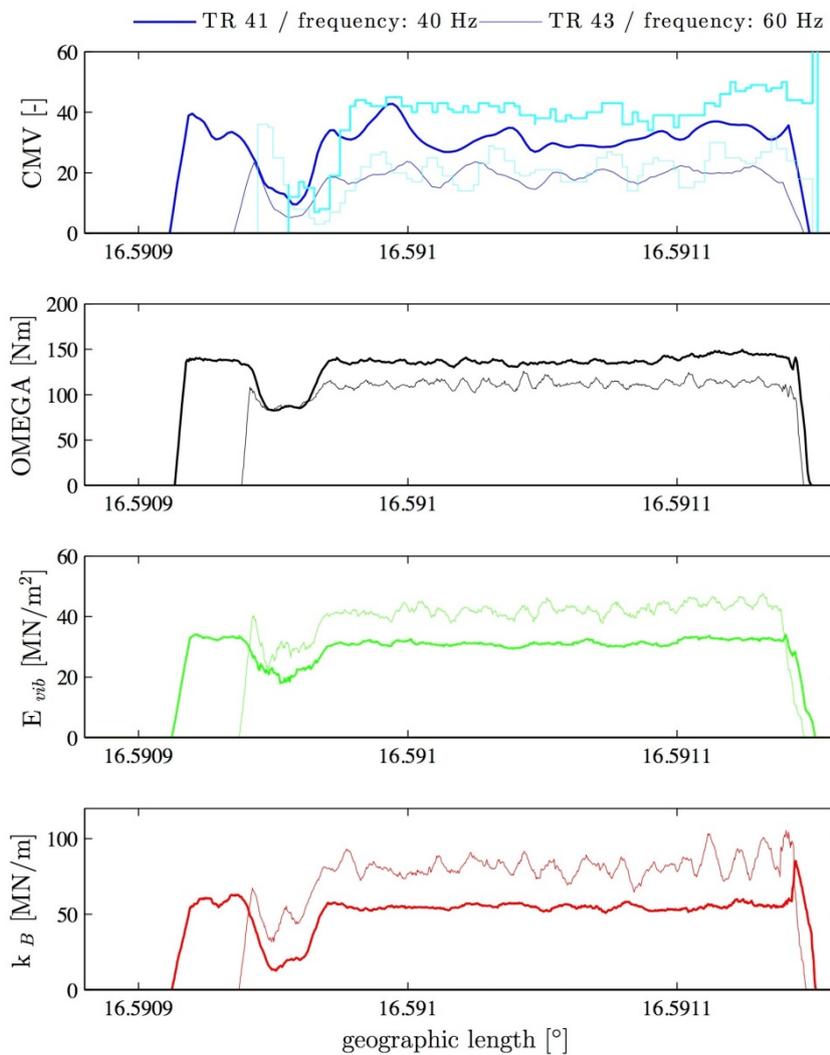


Figure 36: Comparison of two test runs with a frequency of 60 Hz (thin line) and 40 Hz (bold line) respectively and a constant speed of 4 km/h and an amplitude of 0.34 mm (Hager 2015).

The CCC values of two complete test runs with only one parameter variation are depicted in Figure 36, Figure 37, and Figure 38 to better illustrate the conclusions of Figure 35.

Figure 36 shows a comparison of two test runs with excitation frequencies of 40 Hz and 60 Hz respectively, a constant speed of 4 km/h, and small vibration amplitude of 0.34 mm. The CMV and $OMEGA$ values decrease with higher frequencies while E_{vib} and k_B increase. The time domain based CCC values show a constant level on the homogenous part of the test field. The frequency domain based CMV of the Compactometer® does not seem to be as stable. All CCC values and in particular the k_B value oscillate around the average value of the homogenous part with larger amplitude in case of the higher frequency 60 Hz. The higher frequency does not only affect the CCC values but also the motion behaviour of the vibratory drum. The change to an excitation frequency of 60 Hz very likely also changes the mode of operation from partial uplift to double jump (see section 2.1.2).

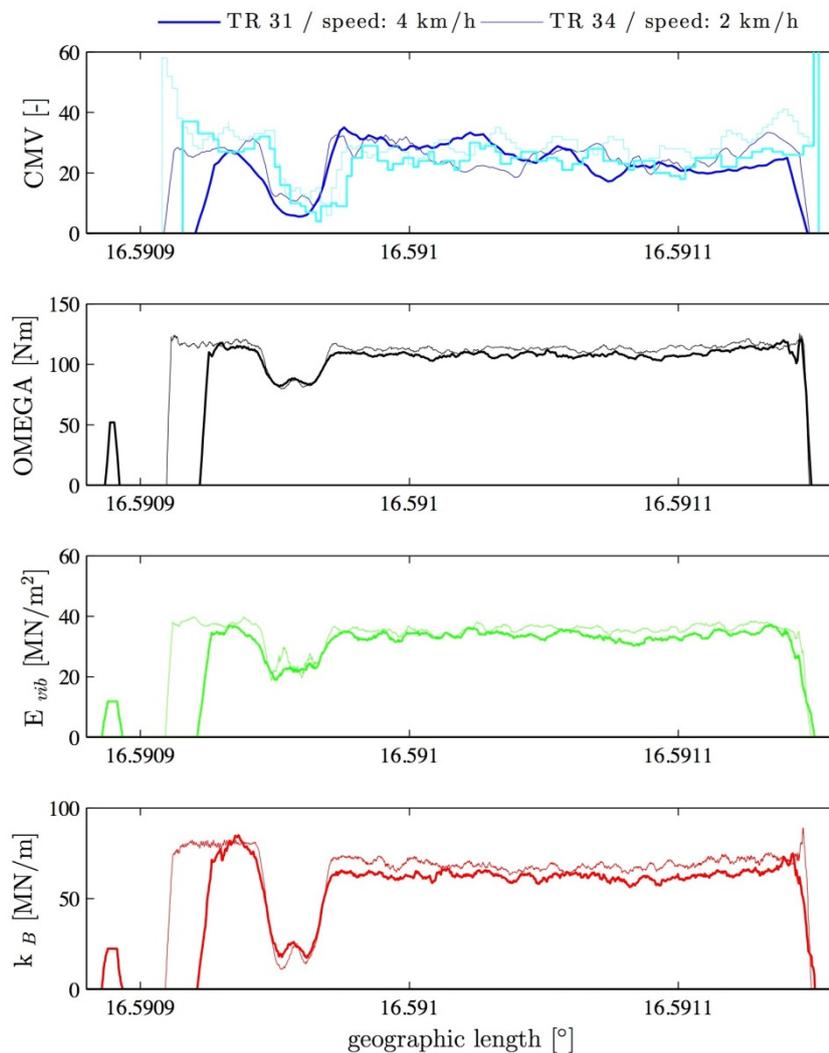


Figure 37: Comparison of two test runs with a speed of 2 km/h (thin line) and 4 km/h (bold line) respectively and a constant frequency of 50 Hz and an amplitude of 0.34 mm (Hager 2015).

Figure 37 shows the influence of the roller speed on the CCC values. The reduction of the standard speed of 4 km/h to 2 km/h has only a small impact on the CCC values of the Terrameter® and the ACE® system. The influence on the CMV value is rather small as well.

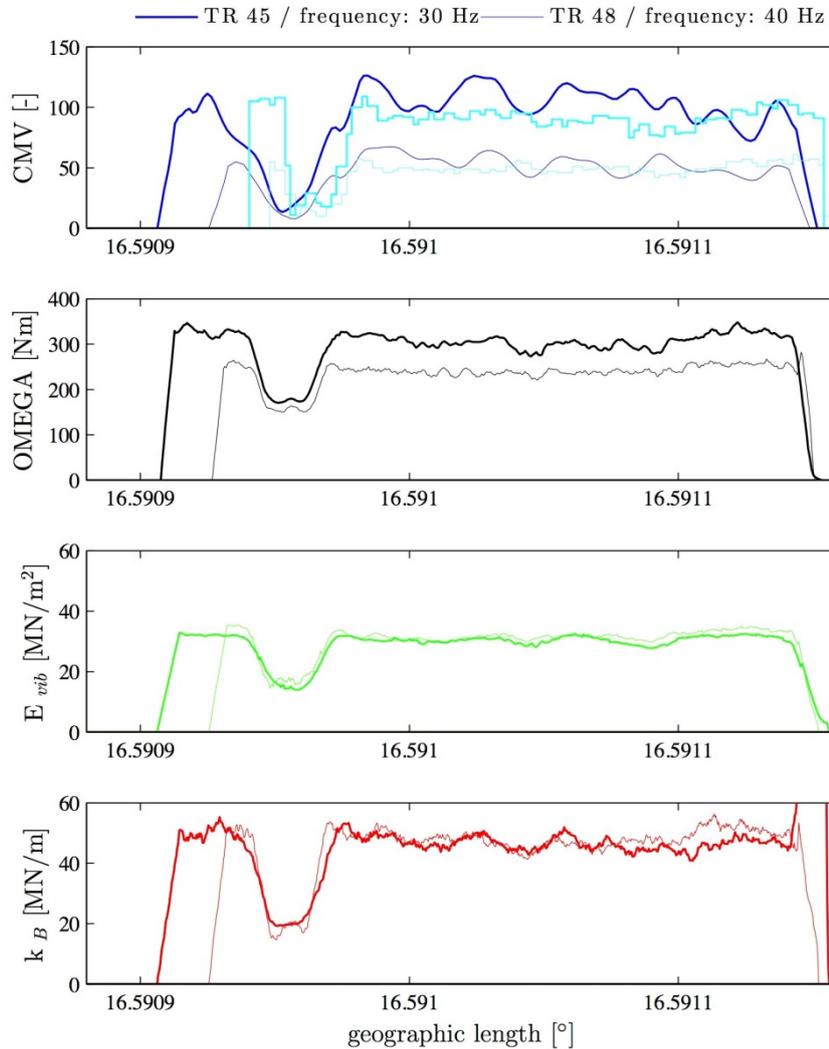


Figure 38: Comparison of two test runs with a frequency of 40 Hz (thin line) and 30 Hz (bold line) respectively and a constant speed of 4 km/h and an amplitude of 0.62 mm (Hager 2015).

The large vibration amplitude of 0.62 mm was used for the test runs depicted in Figure 38. Moreover, the frequency was decreased from the standard frequency of the large amplitude of 40 Hz to 30 Hz. This frequency variation has virtually no influence on the E_{vib} and k_B values, but causes an increase of CMV and $OMEGA$ values.

3.6.3. Comparison of CCC systems with vibrating rollers and oscillating rollers

In the following the results of the calculated CCC values for oscillating rollers are compared to the measured and calculated CCC values for vibratory rollers for selected test runs on layer 2 of lane 2 of the test field in order to evaluate the accuracy and significance of the developed

CCC value for oscillating rollers. The CCC values for the oscillating roller and the CCC values for vibrating rollers cannot be calculated on the basis of the measurement data of one single test run. Therefore, measurement data of two consecutive test runs on the already compacted second layer of lane 2 of the test field are used for the evaluation.

Figure 39 compares the CCC value for oscillating rollers to the measured and calculated CCC values obtained from a subsequent vibratory test run. The oscillatory test run was performed with a frequency of excitation $f = 39$ Hz and a constant speed $v = 4$ km/h; the small amplitude and a vibratory frequency $f = 50$ Hz and a constant speed $v = 4$ km/h was used for the vibratory test run. Figure 39 outlines that the CCC value for oscillating rollers is able to describe the state of compaction with at least the same quality as the CCC values for vibratory rollers. It is also capable of identifying the two weak spots with accuracy. It is noted that such a comparison is only possible for homogenous subgrade conditions because of the different measuring depth of oscillating and vibrating rollers. The varying measurement depth is a result of the different types of excitation. While oscillating rollers mainly transmit dynamic horizontal forces into the soil vibrating rollers show a nearly vertical excitation of the soil, which results both in a larger compaction depth and also in an increased measurement depth of CCC systems for vibrating rollers.

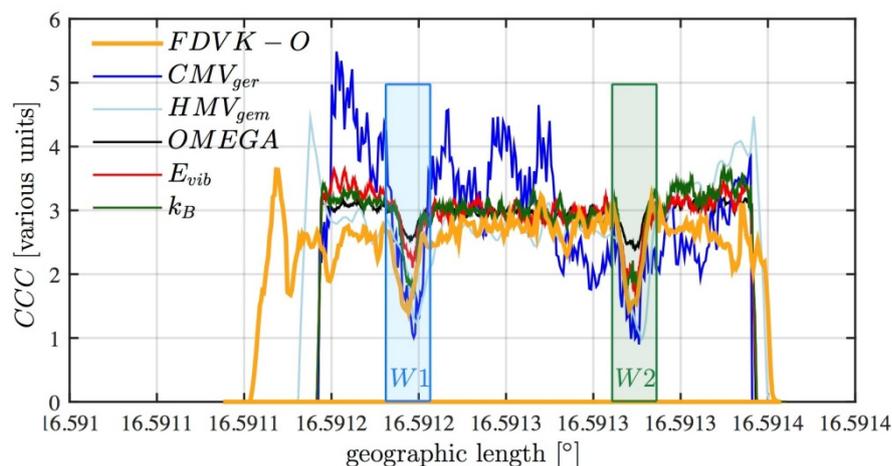


Figure 39: CCC value for oscillating rollers compared to CCC values for vibrating rollers on the compacted layer 2 of lane 2 of the test field. Oscillation: $f = 39$ Hz, $v = 4$ km/h. Vibration: small amplitude, $f = 50$ Hz, $v = 4$ km/h (Pistorl 2016).

The differences in the measurement depth of CCC systems become even more important with heavy rollers or in case of large amplitude of excitation, as shown in Figure 40.

The smaller measurement depth of the CCC for oscillating rollers does not necessarily have to be interpreted as a disadvantage. In fact, it enables an assessment of the stiffness of the soil layer which actually was compacted by the roller. In contrast to this, it is not possible to distinguish between weak spots as a result of poor compaction work and weak spots in the subgrade by evaluating the readings of CCC systems for vibrating rollers.

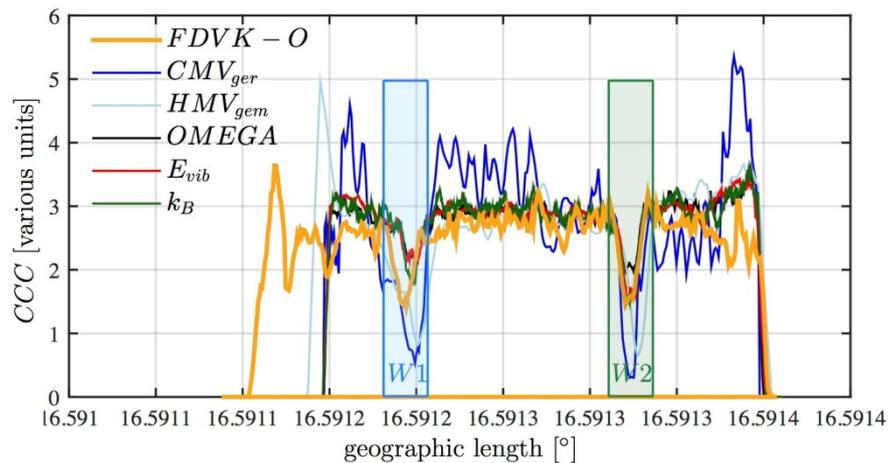


Figure 40: CCC value for oscillating rollers compared to CCC values for vibrating rollers on the compacted layer 2 of lane 2 of the test field. Oscillation: $f = 39$ Hz, $v = 4$ km/h. Vibration: large amplitude, $f = 40$ Hz, $v = 4$ km/h (Pistrol 2016).

3.7. Comparison of CCC with conventional compaction control methods and calibration of CCC values

As previously presented the different CCC systems are consistent and show a good correlation amongst each other. Nevertheless, it is vitally important that CCC values also correlate to conventional compaction parameters, such as degree of compaction, deformation modulus of static and dynamic load plate test. National and international standards and contractual provisions usually refer to 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 to fulfil the requirements of standards and contractual provisions. Usually spots are selected on the compacted soil layer to compare the CCC values with the deformation modulus of the load plate test. E.g., the Austrian guideline RVS 08.03.02 (1999) suggests to select spots with low, medium and high stiffness for the calibration to cover a wider range of soil conditions. Since the level of all CCC values depends on the roller parameters, they have to be adjusted and remain constant for the whole calibration procedure. Moreover, a calibration is valid only for one type of roller, one construction site respectively earth structure, and one set of parameters. The results of the calibration shall be plotted in a diagram with the results of the load plate tests on the x-axis and the corresponding CCC values on the y-axis. A linear regression then defines the correlation between deformation modulus and CCC value.

In the scope of the experimental field tests a correlation analysis was exemplarily performed for all vibratory test runs with small amplitude of 0.34 mm, an excitation frequency of 50 Hz, and a constant roller speed of 4 km/h. The correlations between the dynamic deformation modulus E_{vd} and all investigated CCC values for vibrating rollers are depicted in Figure 41. The correlation coefficient r has to be larger than 0.7 to fulfil the criteria for a valid calibration according to RVS 08.03.02 (1999).

The defined criterion is met by all CCC values. The correlation coefficient for CMV and $OMEGA$ values are around 0.85, while E_{vib} and k_B shows correlation coefficients of about 0.9.

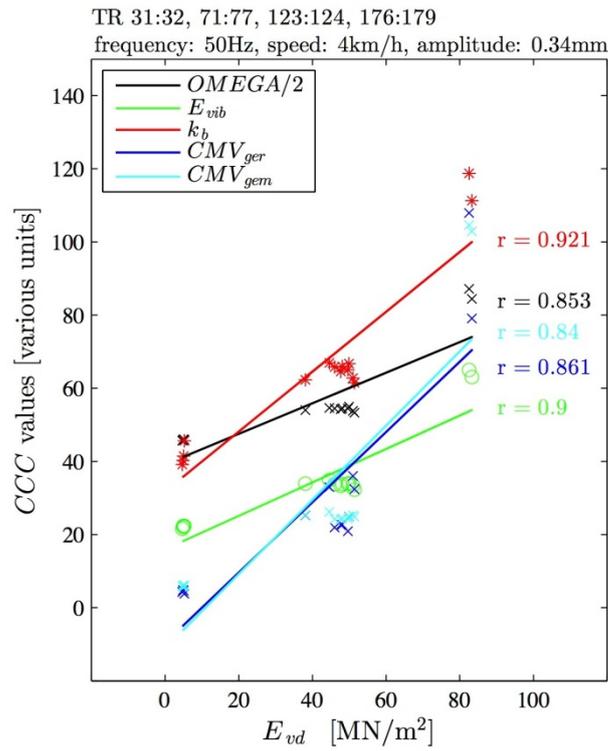


Figure 41: Correlations between the dynamic deformation modulus E_{vd} and all investigated CCC values for vibrating rollers (Hager 2015).

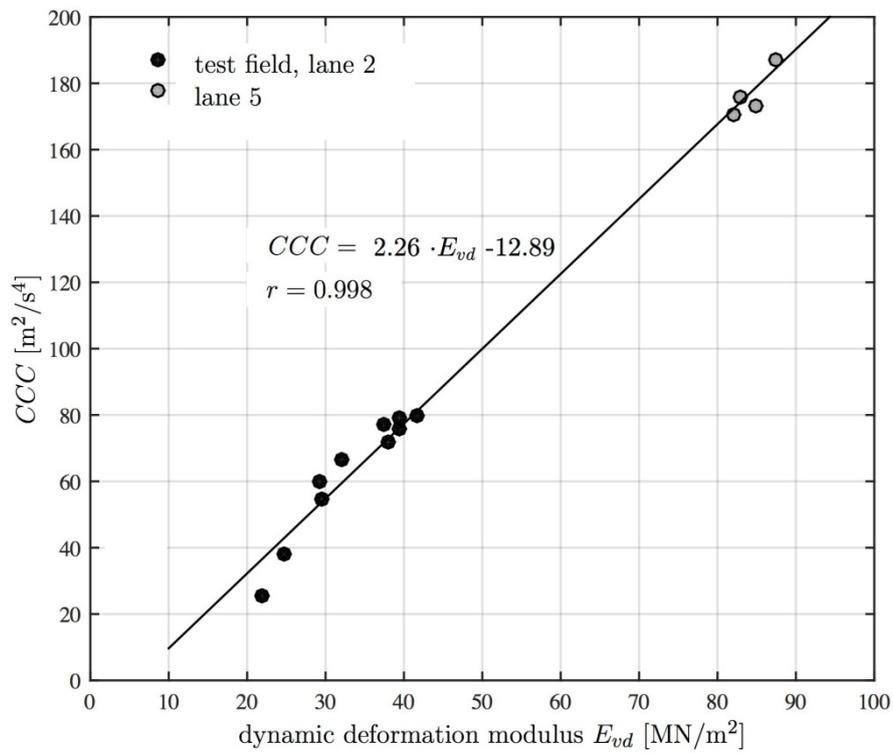


Figure 42: Correlation between the dynamic deformation modulus E_{vd} and the CCC values for oscillating rollers (Pistol 2016).

A correlation between the dynamic deformation modulus E_{vd} and the novel CCC value for oscillatory rollers was also calculated for test runs with a frequency of excitation $f = 39$ Hz and a constant roller speed $v = 4$ km/h; the result is illustrated in Figure 42. All test runs on lane 2 of the test field and on lane 5 on the highly compacted subgrade were taken for the correlation. Figure 42 shows a correlation of excellent accuracy throughout the entire range of investigated soil stiffness ($E_{vd} \approx 20 - 90$ MN/m²). The correlation coefficient yields to $r = 0.998$, which means that the demanded correlation coefficient $r > 0.7$ of the Austrian standard RVS 08.03.02 (1999) is significantly exceeded. The excellent relationship between the dynamic deformation modulus and the CCC value of oscillatory compaction can be explained by the similar measurement depth and confirms the validity and significance of the novel CCC system for oscillatory rollers.

4. CONCLUSIONS

A state of the art overview of dynamic roller compaction and vibration based measurement systems used on vibratory and oscillatory roller compactors to continuously measure soil properties during and after earthwork compaction is provided in this paper.

The background of dynamic roller compaction with vibrating rollers, rollers with directed vibration, feedback controlled rollers, and oscillating rollers has been presented in the beginning. The basic principles and the different modes of operation for several types of dynamic drum excitation have been introduced and discussed.

Moreover, history, principle and components of roller-integrated continuous compaction control systems (CCC) have been outlined and critically reviewed. The three leading CCC systems for vibrating rollers, the Compactometer®, the Terrameter®, and ACE® system, are nowadays in common use for high-class compaction control in earthworks. Over the last decades roller measurement values for vibratory rollers have evolved towards the estimation of more mechanistic soil parameters such as the deformation modulus. Independent assessment of these measurement values has proven their efficacy.

Early and recent developments of CCC with oscillating rollers highlight the challenges, which had to be overcome to establish a novel CCC system for this roller type. In the scope of a comprehensive research project experimental field tests were performed to investigate the motion behaviour of an oscillating drum and its impact on the compacted soil. A semi-analytic model for the simulation of the drum-soil interaction of oscillating rollers was established to verify the results of the experimental field test. Hence, a new CCC value for oscillating rollers was developed on the basis of the experimental and theoretical findings. The pre-commercial development of the new CCC system for oscillating rollers was validated on the basis of real measurement data of additional experimental field tests. The comparison of the evaluated data with CCC values for vibrating rollers and the excellent correlation with the dynamic deformation modulus of dynamic load plate tests show promising results that CCC is applicable for all dynamic roller types in the near future.

Acknowledgements

The financial support granted by the German company HAMM AG made the research on oscillating rollers possible and is gratefully acknowledged.

REFERENCES

- Adam, D. (1996). *Continuous Compaction Control (CCC) with vibrating rollers*, Doctoral thesis (in German), Vienna University of Technology.
- Adam, D. and Kopf, F., (2004). "Operational devices for compaction optimization and quality control (Continuous Compaction Control & Light Falling Weight Device). " *Proc. Intl. Seminar on Geotechnics in Pavement and Railway Design and Construction*, 97-106, December 16-17, 2004, Athens, Greece.
- Anderegg, R., and Kaufmann, K. (2004). "Intelligent compaction with vibratory rollers." *Transportation Research Record 1868*, Transp. Research Board, Washington D.C., 124-134.
- BOMAG GmbH. (2015). *Brochures*.
- Floss, R. et al. (1991). "Dynamische Verdichtungsprüfung bei Erd- und Straßenbauten." *Forschung Straßenbau und Straßenverkehrstechnik*, Heft 612.
- Forsblad, L. (1980). "Continuous meter on vibrating rollers for improved compaction control." *Proceedings of the International Conference on Compaction*, Paris, 541-546.
- Geodynamik AB. (1982). *Oscillatory roller*.
- Geodynamik AB. (1997). *Verfahren zum Bestimmen des Verdichtungsgrades beim Verdichten einer Verdichtungsmaschine u. Vorrichtung zur Durchführung des Verfahrens*, Patent: DE 35 90 610.
- Hager, M. (2015). *Values of the Continuous Compaction Control (CCC) in a theoretical and experimental comparison*, Master's thesis (in German), Vienna University of Technology.
- HAMM AG (2015). *Datasheet HD+90 VV / HD+90 VO*.
- Kernze, F. (2005). *Faszination Straßenbau*, Motorbuch Verlag, Stuttgart, Germany.
- Kopf, F. (1999). *Continuous Compaction Control (CCC) during compaction of soils by means of dynamic rollers with different types of excitation*, Doctoral thesis (in German), Vienna University of Technology.
- Kröber, W. et al. (2001). "Dynamic soil stiffness as quality criterion for soil compaction." *Geotechnics for Roads, Rail Tracks and Earth Structures*, Tokyo.
- Mooney, M. et al. (2005). "Vibratory Roller Integrated Measurement of Earthwork Compaction: An Overview." *Proceedings of the seventh International Symposium on Field Measurements in Geotechnics*.
- Mooney, M., and Adam, D. (2007). "Vibration Based Health Monitoring During Earthwork Construction." *Journal of Structural Health Monitoring*, 2(4), 137-152.
- Pistrol, J. et al. (2013). "Ambient vibration of oscillating and vibrating rollers." *Proceedings of the Vienna Congress on Recent Advances in Earthquake Engineering and Structural Dynamics 2013 (VEESD 2013)*, Paper No. 167.
- Pistrol, J. et al. (2015). "Movement of vibrating and oscillating drums and its influence on soil compaction." *Proceedings of XVI European Conference on Soil Mechanics and Geotechnical Engineering*, 349-354.
- Pistrol, J. (2016). *Compaction with oscillating rollers*, Doctoral thesis (in German), Vienna University of Technology.
- RVS 08.03.02. (1999). *Technische Vertragsbedingungen. Erdarbeiten. Kontinuierlicher walzenintegrierter Verdichtungsnachweis*.
- Sandström, A.J., and Petterson, C.B. (2004). "Intelligent systems for QA/QC in soil compaction." *Proceedings of the TRB 2004 Annual Meeting*, CD-ROM.
- Turner, H., and Sandström, Å. (1980). "Continuous Compaction Control, CCC." *Proceedings of the International Conference on Compaction*, Paris, 237-245.
- Wolf, J.P. (1994). *Foundation and Vibration Analysis Using Simple Physical Models*, Prentice-Hall, Inc., Englewood Cliffs, N.J.
- Yoo, T-S., Selig, E.T. (1979). "Dynamics of Vibratory-Roller Compaction." *Journal of the Geotechnical Engineering Division, ASCE*, 105 (GT10), 1211-1231.