

# Theoretical and experimental investigation of Continuous Compaction Control (CCC) systems

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## ABSTRACT

*Continuously improved compaction techniques in earthworks and geotechnical engineering require the use of adequate test equipment to assess the achieved compaction success. Conventional and spot like compaction testing methods, especially at large construction sites, are outdated and do not represent the state of the art anymore. Therefore, Continuous Compaction Control (CCC), a roller integrated system, has become the commonly used method for compaction control with vibratory rollers.*

*In the presented paper the leading CCC systems on the market (Compactometer, Terrameter, ACE) are discussed. Their structure, measurement principle and theoretical background is investigated.*

*Moreover, large-scale in situ tests were performed with a tandem roller with an oscillating and a vibrating drum. For the first time all three CCC systems and four CCC values are calculated from the accelerations of one single roller. The results of these large-scale tests are compared, dependencies of the CCC values on excitation parameters are investigated and advantages and disadvantages of the CCC systems are outlined.*

**Keywords: soil dynamics, compaction, roller, vibration, Continuous Compaction Control.**

## 1 INTRODUCTION

Continuous Compaction Control (CCC) is the state of the art method for the assessment of the achieved compaction success with vibratory rollers. CCC is, as the name suggests, a roller integrated compaction measurement method for dynamically excited rollers, that allows to measure the compaction success online and continuously and to document the results during the compaction process. CCC systems measure the accelerations in the bearing of vibratory drums and analyse the motion behaviour of the drum to calculate a stiffness proportional CCC value.

There are currently three leading CCC systems on the market, the *Compactometer*,

the *Terrameter* and the *ACE* system, which differ in their measurement principle and theoretical background.

These differences are investigated within this paper. Moreover, results of large-scale in situ tests are presented, where all three CCC systems and four CCC values were calculated from the accelerations of one single roller for the first time.

## 2 VIBRATING ROLLERS

Vibration is the commonly used type of excitation for dynamic drums. The biggest advantage of vibrating rollers in earthworks is their significantly higher vertical loading, which results in larger compaction depths.

2.1 Principle of vibrating rollers

The eccentric masses of a vibrating drum are shafted concentrically to the drum axis, resulting 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.

2.2 Modes of operation

The vibrating drum and the compacted soil form an interacting system, where the soil starts to vibrate because of the drum’s excitation, but also influences the drum’s motion behaviour. The soil stiffness, the speed of the roller, the excitation frequency and the ratio between roller and drum mass have a significant impact on the interacting system of drum and soil. Depending on these factors typical modes of operation can be identified (see Figure 1).

Double Jump

If the soil stiffness increases, the drum motion only reproduces with every second period of excitation. The drum is also uplifted during the mode of operation “Double Jump”, but falls back on the soil with one strike of high impact and one strike of lower impact. The high energy transmitted into the soil by the high impacts results in a high compaction. However, it also causes a significant higher wear of the roller, as well as increased ambient vibrations.

Rocking Motion

If the soil stiffness increases further, the longitudinal axis of the drum is alternately tilted to one side and the other and a phase shift in the motion behaviour of the drums left and right side can be observed. The roller can hardly be handled in “Rocking Motion” and controlled compaction work is not possible any longer.

Chaotic Motion

A combination of very high soil stiffness and unfavourable compaction parameters (large amplitude, high frequency, low speed) can cause “Chaotic Motion”. The motion behaviour is not periodic any longer and a roller handling is not really possible. Rocking motion and chaotic motion have to be avoided.

drum motion	Interaction drum-soil	operating condition	soil contact force	application of CCC	soil stiffness	roller speed
periodic	continuous contact	CONT. CONTACT		yes	low	fast
	periodic loss of contact	PARTIAL UPLIFT		yes	↓	↑
		DOUBLE JUMP		yes		
		ROCKING MOTION		no		
chaotic	non-periodic loss of contact	CHAOTIC MOTION		no	high	slow

Figure 1 Modes of vibratory roller operation (Adam, 1996).

Continuous Contact

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

Partial Uplift

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

3 CCC FOR VIBRATING ROLLERS

3.1 Basic principle, components and existing CCC systems

In contrast to spot like testing methods the CCC is a roller and work integrated method for the assessment of the soil stiffness. The roller is not only used as a compaction device, but also serves as a measuring device at the same time.

The basic principle of a CCC system is to assess the soil stiffness by evaluating the motion behaviour of the drum. The parameters that influence the motion behaviour of the drum also influence the values of CCC systems. Therefore, the first condition for a CCC system is to keep the rollers properties of the compaction process

like speed, excitation frequency and excitation amplitude constant during the CCC measurements. The second condition for a CCC system is a sufficient recording of the motion behaviour of the drum. This condition can be fulfilled by recording the accelerations, velocities or displacements of the drum. Usually the accelerations are measured in the bearing of the drum in vertical and sometimes also horizontal direction.

The second part of a CCC system is a processing unit that calculates the corresponding CCC value for the piecewise analyzed acceleration signal (e.g. one CCC value for the time of two periods of excitation). The processing unit also saves the CCC values. Moreover, a display unit is used to show the calculated CCC values online.

Early CCC systems used sensors for distance and speed to assign the CCC values to a certain position on the construction site. Modern CCC systems use GPS for an exact assignment of the CCC values.

The first CCC system was built in the late 1970ies. Dr. Heinz Thurner noticed a correlation between the soil stiffness and the motion behaviour of a Dynapac vibratory roller during experimental field tests in 1974. He later developed the first CCC system, the *Compactometer*, together with Dr. Åke Sandström, Dr. Lars Forssblad and Dynapac (Thurner, 1978).

In 1982 the Bomag GmbH presented the *Terrameter*, an alternative CCC system, which analyzes the accelerations in the time domain to calculate the *OMEGA* value. In the late 1990ies Bomag improved the *Terrameter* and presented the vibration modulus  $E_{vib}$ .

The *ACE-System* of the swiss Ammann AG Group was introduced in 1999. It calculates the  $k_B$  value by analyzing the vertical accelerations in the time domain.

### 3.2 Compactometer

The processing unit of the Compactometer performs a piecewise fast Fourier transformation (FFT) of the measured vertical acceleration in the bearing of the drum to evaluate the shares of the FFT

spectrum at the excitation frequency and its multiples. Thurner and Sandström recognized a correlation between the relation of the shares at the excitation frequency and two times the excitation frequency and the soil stiffness.

Therefore, Thurner and Sandström defined the *CMV* (Compaction Meter Value) of the *Compactometer* as:

$$CMV = \frac{a(2\omega)}{a(\omega)} 300 \quad (1)$$

Where  $a(2\omega)$  is the share at two times the excitation frequency and  $a(\omega)$  is the corresponding share at the excitation frequency.

If the roller operates in the Double Jump mode, a peak at the half excitation frequency can be seen in the FFT spectrum. A second value, the *RMV* (Resonance Meter Value), was defined to detect the Double Jump mode:

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

The *Compactometer* was the first CCC system and is still used by the roller manufacturers Caterpillar, Dynapac, Hamm and Volvo.

### 3.3 Terrameter

The *Terrameter* analyzes the equilibrium of forces on the drum in vertical direction (see Figure 2).

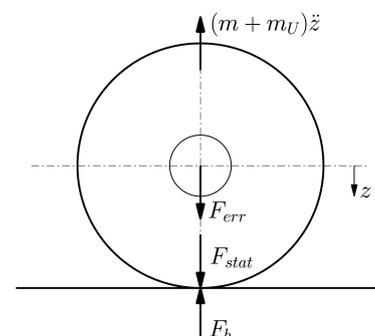


Figure 2 Equilibrium of vertical forces on the drum for the calculation of  $F_b$ .

The soil contact force  $F_b$  is calculated from the vertical acceleration  $\ddot{z}$  under

consideration of the static load  $F_{stat}$ , the excitation force  $F_{err}$ , the mass of the drum  $m$  and the eccentric masses  $m_U$ :

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

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 (see Figure 3).

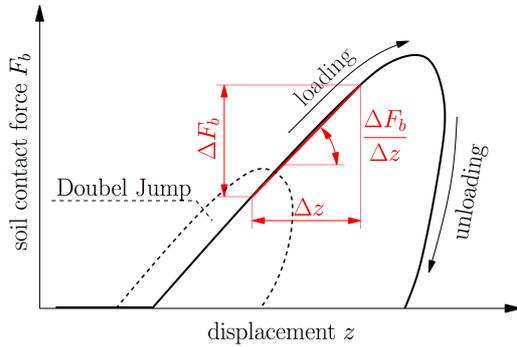


Figure 3 Force-displacement diagram of the vibrating drum for the calculation of OMEGA and  $E_{vib}$ .

The force-displacement diagram in Figure 3 is the basis for the CCC values OMEGA and  $E_{vib}$ .

The OMEGA value was the first CCC value of the Terrameter. It is the area under the force-displacement diagram for two consecutive excitation periods  $T_E$ :

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

OMEGA is proportional to the energy transmitted into the soil.

The newer CCC value of the Terrameter system, the vibration modulus  $E_{vib}$  (MN/m<sup>2</sup>) describes a soil stiffness by analyzing 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  $\nu = 0.25$ :

$$\frac{\Delta F_b}{\Delta z} = \frac{E_{vib} 2b_0 \pi}{2(1-\nu^2) \{2.14 + 0.5 \ln C\}} \quad (5)$$

with:

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

Where  $r$  and  $b_0$  are the radius and the half width of the drum respectively.

### 3.4 Ammann Compaction Expert (ACE)

The ACE system calculates the  $k_B$  value (MN/m) by processing the acceleration signals in the time domain. The significant point in the force-displacement diagram for the evaluation is the change from the loading to the unloading phase, where the displacement has its maximum and  $\dot{z} = 0$  (see Figure 4).

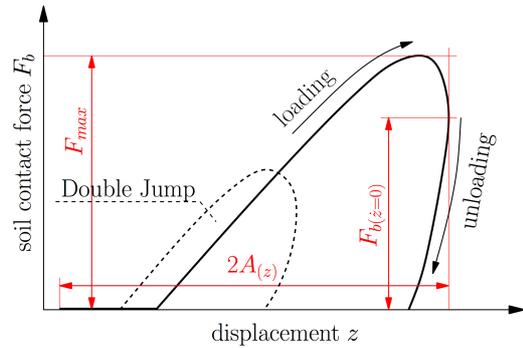


Figure 4 Force-displacement diagram of the vibrating drum for the calculation of  $k_B$ .

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:

$$k_B = \omega^2 \left[ (m + m_U) + \frac{(m_U e_U \text{Vario}) \cos \varphi}{A_{(z)}} \right] \quad (5)$$

Where  $A_{(z)}$  is the amplitude of the displacement and  $\varphi$  is the angle of phase shift (see Figure 5).

In case of a periodic loss of contact, the  $k_B$  value is calculated using the contact force at the change from the loading to the unloading phase  $F_{b(z=0)}$ :

$$k_B = \frac{F_{b(z=0)} - (m + m_U + m_R)g}{A_{(z)}} \quad (5)$$

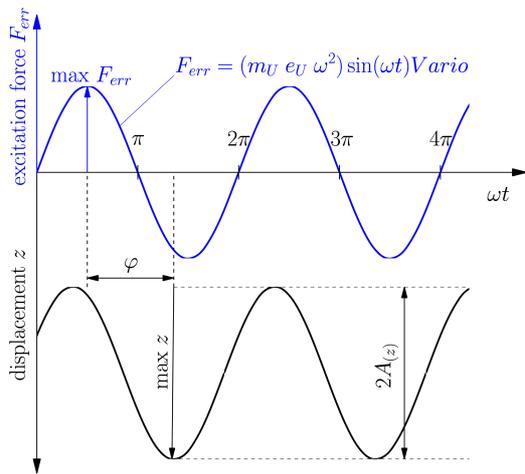


Figure 5 Excitation force  $F_{err}$  and displacement  $z$  for the calculation of  $k_B$ .

#### 4 EXPERIMENTAL FIELD TESTS

##### 4.1 Compaction device

A HAMM HD<sup>+</sup> 90 VO tandem roller 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 a 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 drum on the rear of the roller is an oscillatory drum that uses a tangential amplitude of 1.44 mm.

##### 4.2 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 20 m and a thickness of 0.5 m (see Figure 6). The test field was filled on the highly compacted plane of the gravel pit. The typical layer thickness for compaction with the used roller ranges from about 20 cm to 30 cm. However,

the thickness was chosen larger to be able to run more tests without over-compacting the layer. The four test lanes were intended for static, vibratory, oscillatory, and combined vibratory and oscillatory 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 for lane changes.

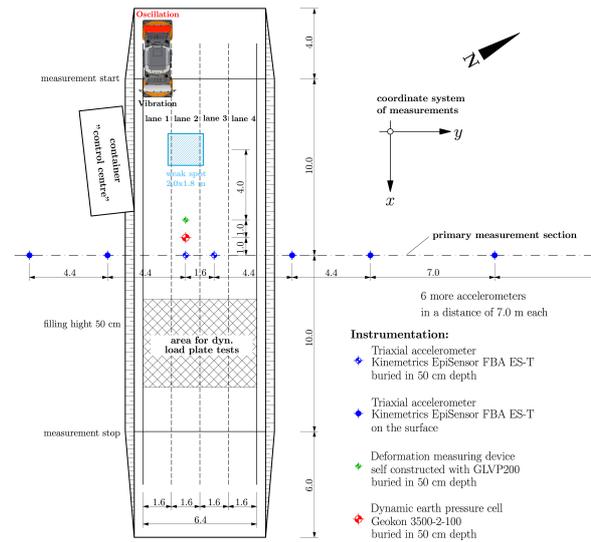


Figure 6 Test layout of the experimental field tests (Pistol, 2015).

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 results of these measurements are not discussed within this paper but can be found in Pistol et al. (2013), Pistol et al. (2015) and Pistol (2015).

Two conventional mattresses were buried in a depth of 0.5 m under test lane 2 to simulate an uncompacted, weak spot in the test field and to investigate its influence on the CCC values (see Figure 6).

The vibratory drum of the roller was equipped with 4 accelerometers with a sensitivity of  $\pm 30$  g. The accelerometers were mounted on the left and right side bearing of the drum to measure the accelerations in horizontal and vertical direction on the undamped drum. The accelerometer signals were recorded with a sampling rate of 1,000 Hz.

The tandem roller also had a preinstalled *Compactometer* CCC system, which was used as a reference for the calculation of the CCC values.

## 5 RESULTS OF THE EXPERIMENTAL FIELD TESTS

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

Figure 7 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 test lane 2 of the test field. An excitation frequency of 50 Hz was used and the roller was accelerated during 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, the soil seems 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 half a meter.

The CCC values remain largely constant on the homogenous part of the test lane, named "mean". However, the values  $E_{vib}$ ,  $k_B$  and  $OMEGA$ , which are based on the force-

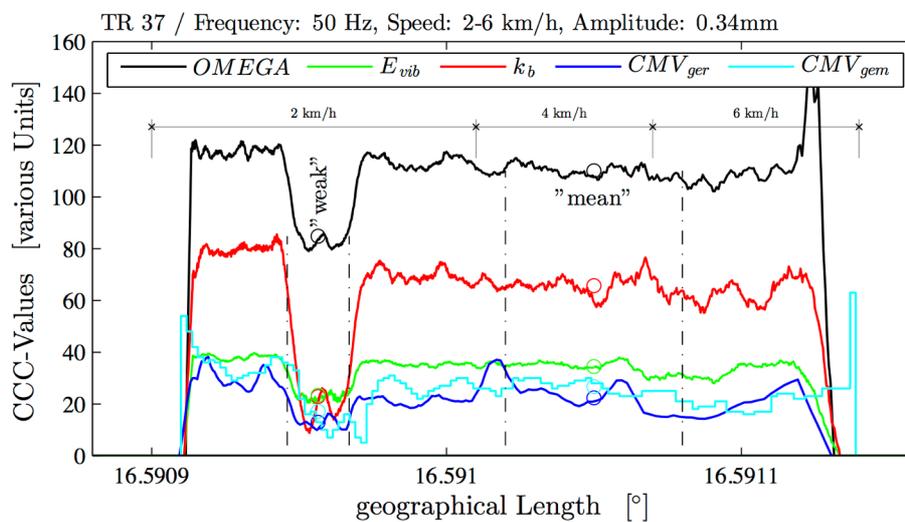


Figure 7 Comparison of all CCC values for test run 37 on lane 2 of the test field.

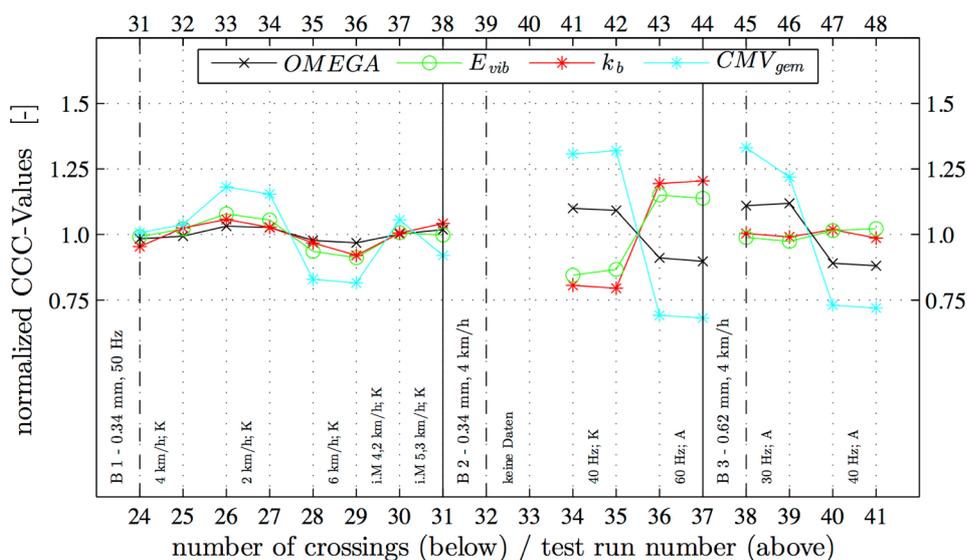


Figure 8 Normalized CCC values for the homogenous part "mean" on test lane 2 for various test runs.

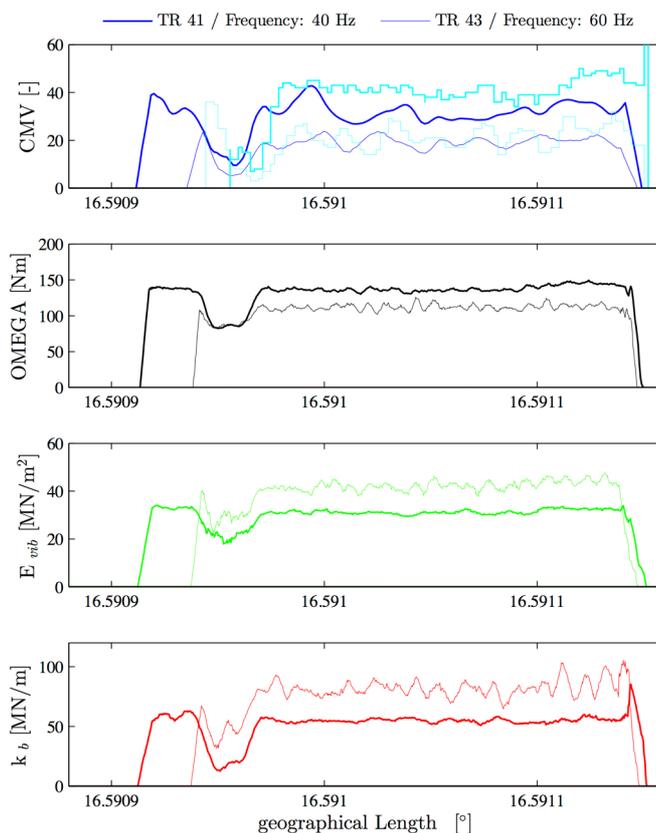


Figure 9 Comparison of two test runs with a frequency of 60 Hz (thin line) and 40 Hz (thick line) respectively and a constant speed of 4 km/h and an amplitude of 0.34 mm.

displacement diagrams in Figures 3 and 4 are calculated in the time domain and seem a bit more stable.

The calculated  $CMV_{ger}$  accords to the  $CMV_{gem}$  of the built in *Compactometer*, although a phase shift between the two curves can be noticed. This phase shift is most likely 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 8. 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 8 shows test runs 31 to 38 with a constant excitation frequency of 50 Hz, where the influence of different roller speeds was investigated.

A lower speed of the roller (2 km/h) causes increased CCC values, while high roller speeds indicate weaker soil conditions. The

variation of the roller speed has the largest impact on the  $CMV$  values.

The influence of a change of the vibration frequency on the CCC values was investigated within test runs 39 to 44. Again the  $CMV$  values are most sensitive and show a significant decrease with higher frequencies. The  $OMEGA$  values also decrease, while the  $E_{vib}$  and  $k_B$  values show a contrary behaviour and increase with higher excitation frequencies. The influence on  $E_{vib}$  and  $k_B$  is in the same range.

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 when the test runs 41, 42 are compared to 47, 48. The  $E_{vib}$  and  $k_B$  values increase slightly, while the  $OMEGA$  and  $CMV$  decrease, the latter in a significant way. The frequency change from 30 Hz to 40 Hz combined with the large amplitude of excitation has a very small influence on the  $E_{vib}$  and  $k_B$  values.

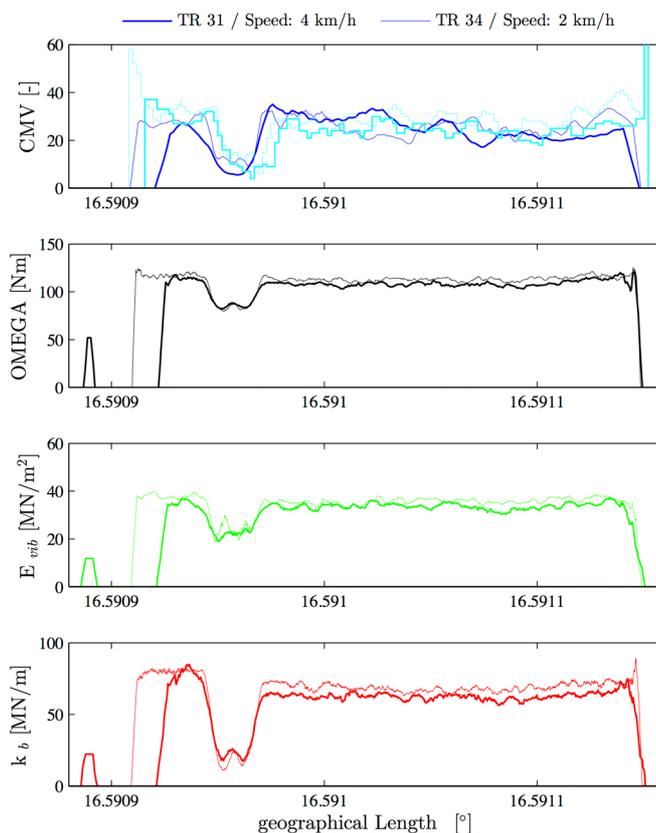


Figure 10 Comparison of two test runs with a speed of 2 km/h (thin line) and 4 km/h (thick line) respectively and a constant frequency of 50 Hz and an amplitude of 0.34 mm.

The CCC values of two complete test runs with only one parameter variation are depicted in Figures 9, 10 and 11 to illustrate the conclusions of Figure 8.

Figure 9 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 a 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* seems not as stable. All CCC values and especially the  $k_B$  value oscillate around the average value of the homogenous part with a larger amplitude in case of the higher frequency of 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.

Figure 10 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 a negligible small impact on the CCC values of the *Terrameter* and the *ACE* system. The influence on the  $CMV$  value is very small as well.

The large vibration amplitude of 0.62 mm was used for the test runs depicted in Figure 11. Moreover, the frequency was decreased from the standard frequency of the large amplitude of 40 Hz to 30 Hz. This frequency variation has no influence on the  $E_{vib}$  and  $k_B$  values, but causes an increase of the  $CMV$  and  $OMEGA$  values.

It is very important for CCC systems to not only be consistent within themselves, but also have a good accordance to conventional compaction tests like the static load plate test and the dynamic load plate test. National and international standards, as well as construction contracts usually refer to the deformation modulus. Therefore, the CCC systems have to be calibrated with the results of static or dynamic load plate tests, before

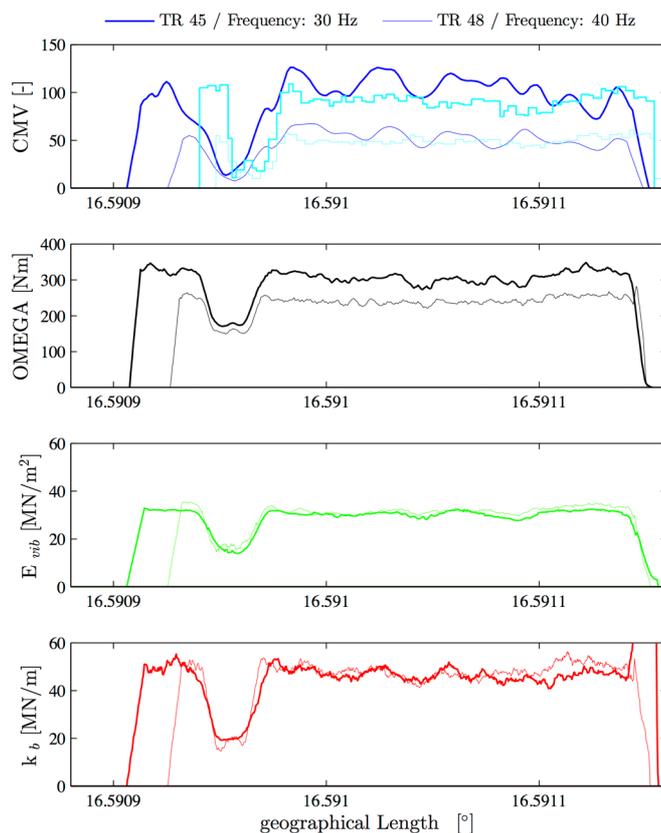


Figure 11 Comparison of two test runs with a frequency of 40 Hz (thin line) and 30 Hz (thick line) respectively and a constant speed of 4 km/h and an amplitude of 0.62 mm.

they can be used to document the compaction success.

Spots on the compacted soil are selected to compare the CCC values to the deformation modulus of the load plate test. 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 all CCC values show a dependence on the roller parameters, the parameters have to remain constant for the whole calibration. Moreover, a calibration is valid for only one type of roller, one construction site and one set of parameters. The results of the calibration are 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.

A correlation analysis was performed for test runs of the experimental field tests with a small amplitude of 0.34 mm, a excitation frequency of 50 Hz and a constant speed of

4 km/h. The correlations between the dynamic deformation modulus  $E_{vd}$  and all investigated CCC values are depicted in Figure 12.

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.

The defined criteria is exceeded by all CCC values. The correlation coefficients for the  $CMV$  and  $OMEGA$  values are around 0.85, while  $E_{vib}$  and  $k_B$  show correlation coefficients of 0.9 and larger.

## 6 CONCLUSIONS

The theoretical background of the three leading CCC systems on the market, the *Compactometer*, the *Terrameter* and *ACE* system was discussed in this paper.

Experimental field tests were performed with a tandem roller to calculate all CCC values for one roller. The dependence of the CCC values on various compaction parameters was tested and the influence of a weak spot on these values was investigated.

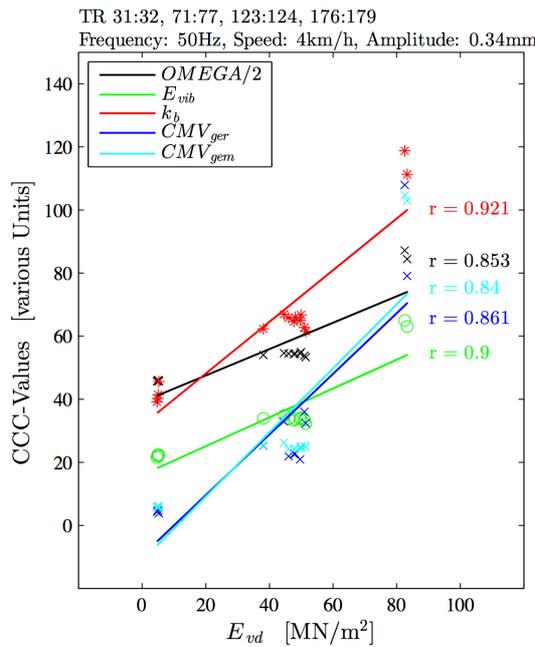


Figure 12 Correlations between the dynamic deformation modulus  $E_{vd}$  and all investigated CCC values.

All CCC systems were able to locate the weak, uncompacted spot and fulfil the criteria for a valid calibration according to the Austrian guideline RVS 08.03.02.

By introducing the  $E_{vib}$ , Bomag managed to compensate the disadvantages of the old *OMEGA* value of the *Terrameter* system. The  $E_{vib}$  is least influenced by a variation of the compaction parameters. Moreover, it is the only CCC value, which takes the geometry of the vibratory drum (diameter and width) into account. Therefore, *Terrameter* systems on different rollers are more likely to provide comparable results.

The  $k_B$  value of *Ammann's* ACE system showed a sensitivity to frequency variations and amplitude changes, but delivered the second best overall results. A disadvantage of the system is the calculation of  $k_B$  using two different equations, depending on the motion behaviour of the drum.

The *Compactometer's*  $CMV$  is the oldest CCC value, but it is still used intensively. However, it showed a significant dependence on the excitation frequency and amplitude. The reason for the distinct frequency dependence is the signal processing in the frequency domain.

The *OMEGA* values of the *Terrameter* system show similar dependencies as the

$CMV$  values, but to a less extent. The disadvantages of the *OMEGA* value have been largely compensated by the introduction of the  $E_{vib}$ .

## 7 REFERENCES

- Adam, D. (1996). Continuous Compaction Control (CCC) with vibrating rollers (Doctoral thesis in German). Vienna University of Technology.
- Hager, M. (2015). Messwerte der Flächendeckenden Dynamischen Verdichtungskontrolle (FDVK) im theoretischen und experimentellen Vergleich (Master thesis in German). Vienna University of Technology.
- Pistol, J., Kopf, F., Adam, D., Villwock, S. & Völkel, W. (2013). Ambient vibration of oscillating and vibrating rollers. Proceedings - Vienna Congress on Recent Advantages in Earthquake Engineering and Structural Dynamics 2013 (VEESD 2013), Vienna, Austria, Paper No. 167.
- Pistol, J., Adam, D., Villwock, S., Völkel, W. & Kopf, F. (2015). Movement of vibrating and oscillating drums and its influence on soil compaction. Proceedings of XVI European Conference on Soil Mechanics and Geotechnical Engineering, Edinburgh, Scotland. 349-354.
- Pistol, 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.
- Thurner, H. (1978). Verfahren und Vorrichtung zur Beurteilung des Verdichtungsgrades beim Verdichten einer Unterlage mit vibrierendem Verdichtungsgerät. Patent: Germany. Offenlegungsschrift 2710811; Aktenzeichen P 27 10 811.8.