



# Continuous Compaction Control (CCC) with Oscillating Rollers

Johannes Pistol<sup>1</sup>, Sebastian Villwock<sup>2</sup>, Werner Völkel<sup>2</sup>, Fritz Kopf<sup>3</sup>, and  
Dietmar Adam<sup>1</sup>

<sup>1</sup> Vienna University of Technology, Austria  
johannes.pistol@tuwien.ac.at  
dietmar.adam@tuwien.ac.at

<sup>2</sup> HAMM AG, Tirschenreuth, Germany  
Sebastian.Villwock@hamm.eu  
Werner.Voelkel@hamm.eu

<sup>3</sup> FCP - Fritsch, Chiari & Partner ZT GmbH, Vienna, Austria  
kopf@fcp.at

## Abstract

CCC systems are the state of the art method for an assessment of the achieved compaction success with vibratory rollers. However, CCC systems were not available for oscillatory rollers, which differ from vibratory rollers not only in their construction, but also in their motion behaviour and way of dynamically loading the soil. Experimental field tests were performed to analyse the motion behaviour of an oscillatory drum and a CCC value for oscillating rollers is presented based on empirical observations and a semi-analytical modelling of the drum-soil interaction. Moreover, the algorithm of the CCC value is tested on measurement data of the experimental field tests and the influence of weak spots on the CCC values is investigated.

*Keywords:* soil dynamics, compaction, rollers, oscillation, Continuous Compaction Control, CCC

## 1 Introduction

### 1.1 Dynamic Roller Compaction

Dynamic roller compaction has become the commonly used method for near-surface compaction, because they are much more efficient compared to static rollers. However, the continuously improved compaction techniques in earthworks and geotechnical engineering also require the use of adequate test equipment to assess the achieved compaction success. Conventional spot like compaction testing methods, especially at large construction sites, are outdated and do not represent the state of the art anymore. Continuous Compaction Control (CCC) is a sufficient method to overcome the disadvantages of the spot like compaction testing methods.

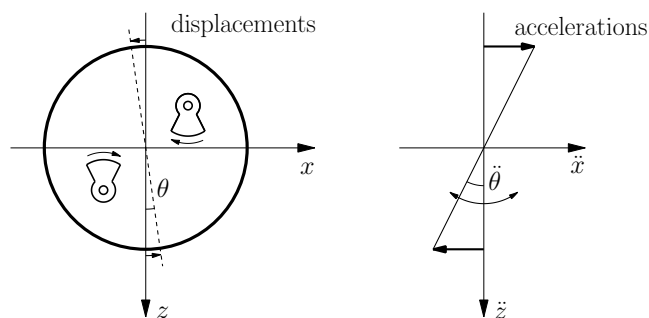


Figure 1: Excitation of an oscillating drum [1]

## 1.2 Oscillating Rollers

Two types of excitation are mainly used for dynamic roller compaction, the vibratory drum and the oscillatory drum.

The eccentric masses of a vibratory drum are shafted concentrically to the drum axis, resulting in a significantly higher vertical loading, but also increased ambient vibration.

The torsional motion of an oscillatory drum is caused by two opposed, rotating eccentric masses, which shafts are mounted eccentrically to the drum axis (see Figure 1). Soil is loaded horizontally by the drum motion and vertically by the dead load of the drum and roller.

While CCC systems have become the state of the art in compaction control for vibratory rollers during the last decades, the lack of a CCC system for oscillating rollers has been a major disadvantage of these rollers.

## 1.3 Continuous Compaction Control (CCC)

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. The roller is not only used as 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 dynamically excited drum. The parameters that influence the motion behaviour of the drum also have an influence on the values of CCC systems. Therefore, the first condition for a CCC system is to keep the rollers parameters 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 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 horizontal directions.

There are currently three leading CCC systems for vibratory rollers on the market, the *Com-pactometer*, the *Terrameter* and the *ACE* system, which differ in their measurement principle and theoretical background.

For the development of a CCC system for oscillating rollers large-scale in situ tests were performed with a tandem roller with an oscillating and a vibrating drum to get a better understanding of the motion behaviour of an oscillating drum.

## 2 Experimental Field Tests

### 2.1 Compaction Device

A HAMM HD<sup>+</sup> 90 VO tandem roller was used as compaction device. The roller comprises a total mass of 9,380 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.

The drum on the front of the roller is a vibrating drum, with a selectable amplitude of vibration of 0.34 mm or 0.62 mm respectively. It was used for investigations on CCC systems for vibratory rollers.

The oscillatory drum is mounted on the rear of the HD<sup>+</sup> 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.

### 2.2 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 2). The test field was filled on the highly compacted plane 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 plane 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 within this paper, but can be found in [3, 2, 1].

Four conventional mattresses were buried under test lane 2 to simulate uncompacted, 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 plane of the gravel pit before filling the first layer. Weak spot 1 was therefore buried in a depth of 0.4 m after filling the first layer and a depth of 0.7 m after filling the second layer. Weak spot 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 2 was located in a depth of 0.3 m beneath ground level (see Figure 2).

The oscillatory drum of the roller was equipped with four accelerometers with a sensitivity of  $\pm 10$  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 positive direction of the horizontal accelerations  $\ddot{x}$  was defined in the direction of compaction, the positive vertical accelerations  $\ddot{z}$  were pointing downwards (see Figures 1 and 2). The accelerometer signals were recorded with a sampling rate of 1,000 Hz.

### 2.3 Motion Behaviour of the Oscillatory Roller

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 tests [1, 2]. The explanation for this behaviour is the fast forwards-backwards rotation of the oscillatory drum

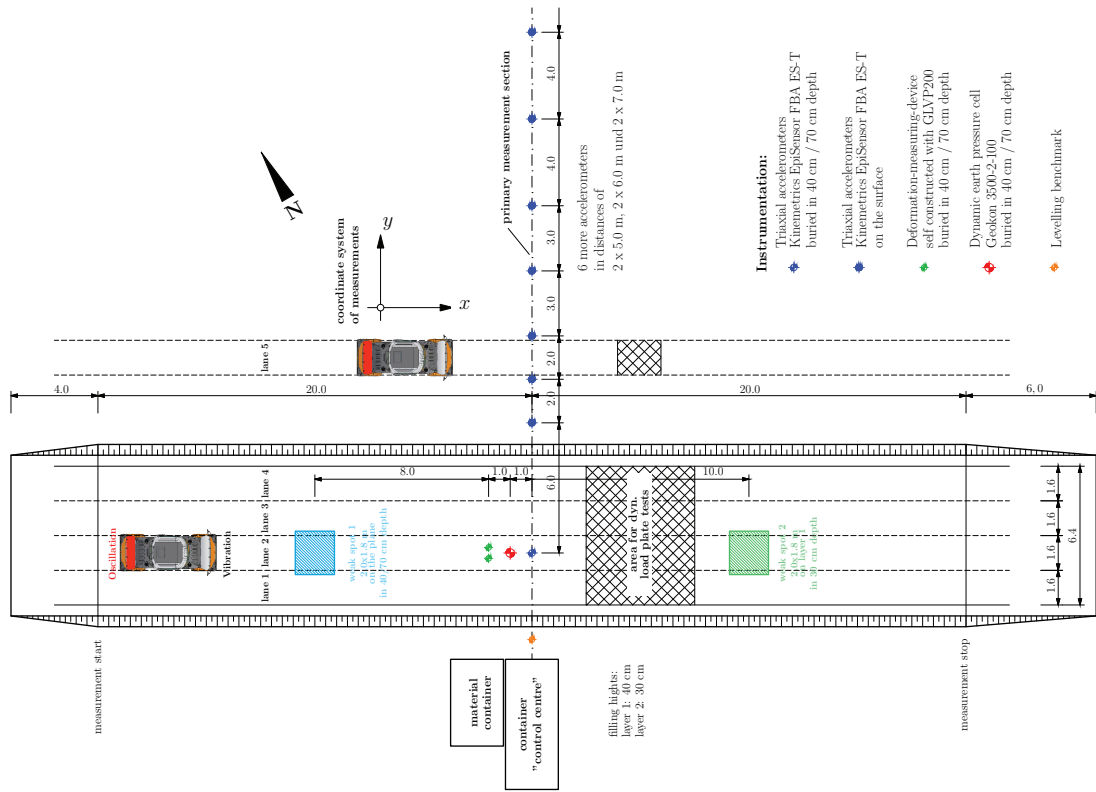


Figure 2: Test layout of the experimental field tests [1]

in its own settlement depression. The oscillatory drum goes up on the bow wave in front of the drum and up on the rear wave behind the drum during each period of excitation.

This behaviour does not only cause the typical formation of a secondary vibration in the vertical soil accelerations, but also has an influence on the general motion behaviour of the drum itself. To illustrate the characteristic formation of the accelerations, the horizontal ( $\ddot{x}$ ) and vertical ( $\ddot{z}$ ) accelerations in the bearing of the oscillatory drum are depicted in Figure 3 for the eleventh pass of the oscillatory roller on lane 2.

The horizontal accelerations in Figure 3 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. The double frequency of the vertical accelerations is clearly visible.

In Figure 4 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 [1]. An appropriate characterization of this eight shape can be used to assess the soil stiffness and therefore as a CCC value.

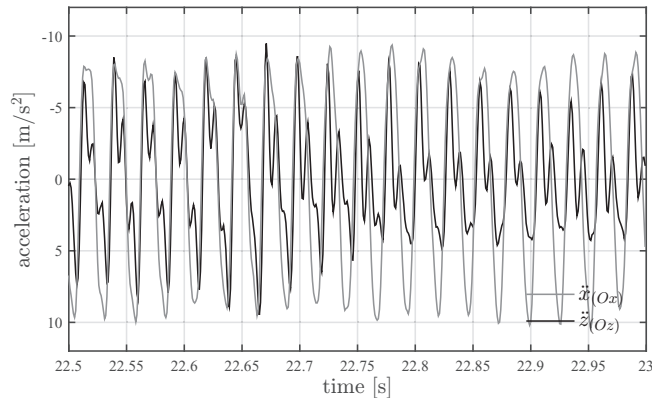


Figure 3: Horizontal ( $\ddot{x}$ ) and vertical ( $\ddot{z}$ ) accelerations in the bearing of the oscillatory roller during the eleventh pass on lane 2 with  $f = 39$  Hz and  $v = 4$  km/h

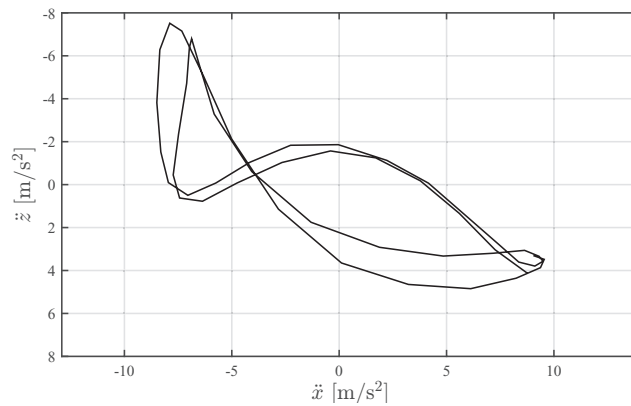


Figure 4: Horizontal ( $\ddot{x}$ ) and vertical ( $\ddot{z}$ ) accelerations in the bearing of the oscillatory roller for two periods of the eleventh pass on lane 2 with  $f = 39$  Hz and  $v = 4$  km/h

### 3 Development of a 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 horizontal and vertical accelerations.

#### 3.1 Semi-Analytic Modelling 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  $I$ . 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  $\Delta m$  are calculated for various soil stiffnesses using a horizontal and vertical cone model according to *Wolf* [4]. The *Lagrangian* equations of motion were derived manually [1] and solved numerically using *MATLAB*. A detailed description of the model,

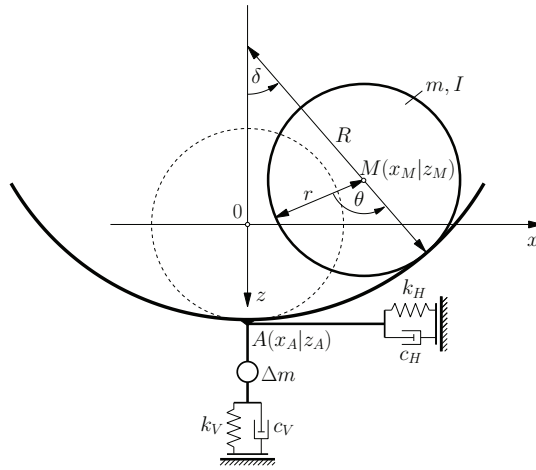


Figure 5: Mechanical model of an oscillatory drum in its own settlement depression [1]

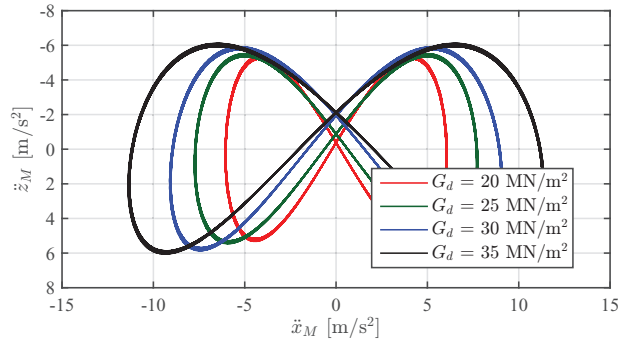


Figure 6: Accelerations ( $\ddot{x}_M, \ddot{z}_M$ ) in the axis ( $M$ ) of an oscillatory drum according to the mechanical model in Figure 5 for a variation of the shear modulus  $G_d$  of the soil [1]

including all equations and the derivation of the soil parameters is given in [1].

In Figure 6 the horizontal ( $\ddot{x}_M$ ) and vertical ( $\ddot{z}_M$ ) accelerations in the drum axis ( $M$  in Figure 5) are evaluated for a variation of the dynamic shear modulus  $G_d$  of the soil. Figure 6 clearly shows the expansion of the eight shape with increasing soil stiffness.

### 3.2 A CCC Value for Oscillating Rollers

A CCC value for oscillating rollers can be found by appropriately describing the eight shapes in Figure 6. One option is the calculation of the area circumscribed by the eight shape. However, the calculation of this area can not be done easily, especially when it comes to real measurement data. 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 satisfactory accuracy.

Each sampling point in a diagram according to Figure 6 is defined by a horizontal ( $\ddot{x}_M$ ) and

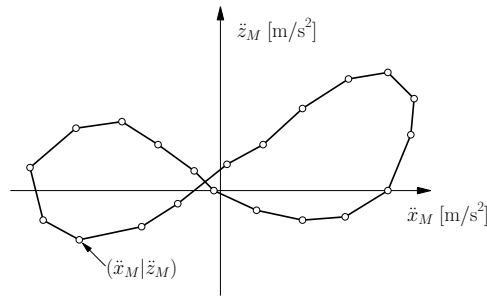


Figure 7: Coordinate pairs  $(\ddot{x}_M | \ddot{z}_M)$  for one period of excitation connected in chronological order [1]

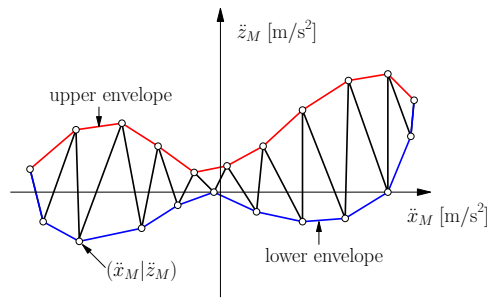


Figure 8: Coordinate pairs  $(\ddot{x}_M | \ddot{z}_M)$  for one period of excitation connected according to the values of the horizontal accelerations and envelopes for the calculation of the CCC value [1]

a vertical ( $\ddot{z}_M$ ) acceleration. When all sampling points of one period of excitation are connected chronologically, the result is the discussed eight shape (see Figure 7).

However, the coordinate pairs can also be sorted and connected according to the values of the horizontal accelerations. The result is a vibration (see Figure 8). Furthermore, the upper and lower envelopes are calculated by identifying and connecting local maximum and minimum points of the vibration (see Figure 8). 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 has the theoretical unit of  $m^2/s^4$ .

## 4 CCC in Experimental Field Tests

The CCC value for oscillating rollers, as described in subsection 3.2, was evaluated for the experimental field tests discussed in section 2. For the calculation of the CCC values a time frame of 1,024 sampling points was chosen, which equals approximately 1 CCC value for each second.

In Figure 9 the curves 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 2). When the CCC curves for the various passes are compared, an increase of the level of the CCC values can be observed. Figure 9 shows a significant increase within the first four passes on lane 2 and another smaller increase during

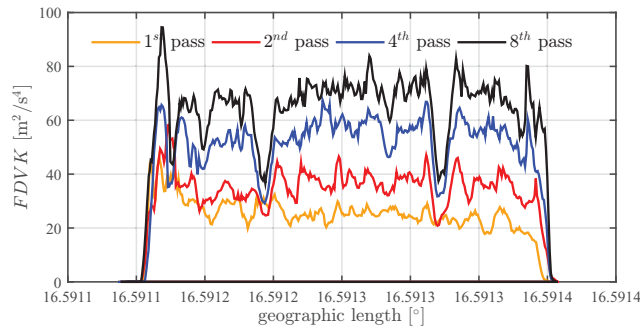


Figure 9: Curves of the calculated CCC values of the passes 1, 2, 4 and 8 on layer 2 of lane 2 of the test field [1]

the passes 5 to 8. This accords to the general experience, that the first passes of a roller on uncompacted soil gain the largest increase in soil stiffness. When the soil gets closer to its state of maximum compaction, the increases in soil stiffness become asymptotically smaller with each pass of the roller.

The artificial weak spots under lane 2 (see Figure 2) can not be located in the measurement curve of the first pass on the uncompacted soil. However, their location becomes clearer with every pass of the roller. Weak spot 2 was buried in a depth of only 30 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 after the first pass. Although weak spot 1 was buried in a depth of 70 cm beneath ground level of lane 2, it is still clearly visible in the CCC curves in Figure 9.

The presented CCC value for oscillating rollers is properly reflecting the increase in soil stiffness with increasing number of roller passes. Also the linear elastic weak spots in a depth of 30 cm and 70 cm respectively could be localized. Moreover, an excellent accordance of the CCC values with the results of dynamic load plate tests was found and is discussed in [1].

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