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Recent advances in Continuous Compaction Control

Développements récents dans le contrôle de compaction continu

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ABSTRACT: Continuous Compaction Control (CCC) systems are used in connection with dynamic rollers. The basic principle is the assessment of the soil stiffness or compaction respectively based on an evaluation of the motion behaviour of the dynamically excited roller drum. CCC has become the state of the art method for an assessment of the compaction success over the past decades. Since it is a continuous roller- and work-integrated method it is much more efficient compared to spot-like testing methods. However, hitherto the application of CCC systems was limited to vibratory rollers. Therefore, the German roller manufacturer HAMM AG and the Vienna University of Technology launched a research project to investigate the motion behaviour of oscillatory rollers and the aim of developing the first functional CCC system for oscillating rollers. Large-scale in situ tests were performed as well as theoretical investigations, which resulted in a CCC system for oscillating rollers. The study covers the basic principles of CCC systems, a description of the novel CCC value for oscillating rollers, and a validation of the CCC system for oscillating rollers in experimental field tests.

RÉSUMÉ : Les systèmes de contrôle de compaction continu (CCC) sont utilisés pour les compacteurs dynamiques. Le principe général consiste en une analyse de la rigidité du sol ou de sa compacité en se basant sur le comportement du rouleau soumis à une sollicitation dynamique. Au cours des dernières décennies, le CCC s'est avéré être la méthode la plus adaptée pour mettre en évidence que l'objectif de compaction est atteint. Dans la mesure où il s'agit d'une méthode intégrant le rouleau et l'énergie de travail, il est bien plus efficace qu'une méthode de test sur un plot seul. Cependant, le champ d'application du CCC était jusqu'à présent limité au rouleaux vibrants. De ce fait, le fabricant de rouleaux HAMM AG et l'Université Technique de Vienne ont lancé un projet de recherche pour analyser le comportement des rouleaux oscillants, avec l'objectif de développer le premier CCC utilisable pour rouleaux oscillants. Des essais de grande échelle ont été menés en plus d'analyses théoriques, ce qui a mené à un système CCC pour rouleaux oscillants. L'étude couvre les principes de base des systèmes CCC, une description de la valeur ajoutée du nouveau CCC pour les rouleaux oscillants ainsi qu'une validation du système CCC pour les rouleaux oscillants dans des essais expérimentaux sur le terrain.

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 such rollers 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 performance. 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 valuable method to overcome the disadvantages of spot like compaction testing methods.

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.
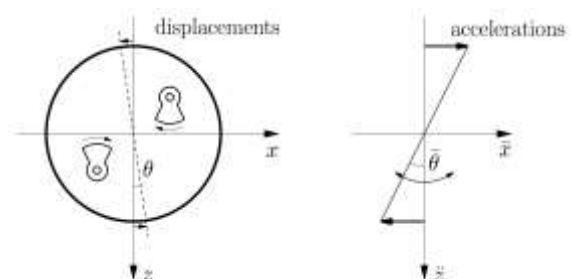

Figure 1. Excitation of an oscillatory drum (Pistrol 2016).

The torsional motion of an oscillatory drum is caused by two opposed rotating eccentric masses, which shafts are mounted eccentrically but point symmetric 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 the 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 (as the name suggests) is a roller integrated compaction measurement method for dynamically excited rollers that allows to measure the compaction performance 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 influencing the motion behaviour of the drum also have an influence on the values of CCC systems. Therefore, the first demand for a CCC system is to keep constant the roller parameters of the compaction process like speed, excitation frequency and excitation amplitude during the CCC measurements. The second requirement for a CCC system is a unit to record the motion behaviour of the drum. This 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 direction.

There are currently three leading CCC systems for vibratory rollers on the market, the Compactometer, 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+ 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 has been used throughout the majority of the tests.

The drum on the front of the roller is a vibrating drum, with 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+ 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. 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 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 within this paper, but can be found in (Pistrol 2016, Pistrol et al. 2015, 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 plane of the gravel pit before filling the first layer. Weak spot 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 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 0.15 m below ground level.

The oscillatory drum of the roller was equipped with four accelerometers with a sensitivity of ±10 g. The accelerometers were mounted on the left and right 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 direction of compaction, the positive vertical accelerations ($\ddot{z}$) were pointing down-wards (see Figure 1). 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 the performed tests (Pistrol 2016, Pistrol et al. 2015). The explanation for this behaviour is the fast forwards-backwards-rotation of the oscillatory drum 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 influences 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 2 for the eleventh pass of the oscillatory roller on lane 2.
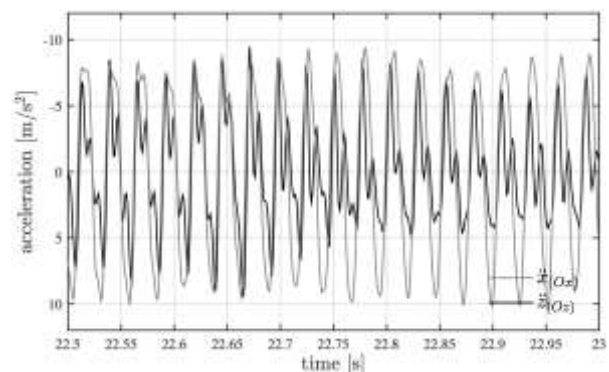

Figure 2. Horizontal ($\ddot{x}$) and vertical ($\ddot{z}$) accelerations in the bearing of the oscillatory roller during the eleventh pass on lane 2 with f = 39 Hz and v = 4km/h (Pistrol 2016).

The horizontal accelerations in Figure 2 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 3 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 (Pistrol 2016). An appropriate characterization of the eight-shape can be used to assess the soil stiffness and therefore as a CCC value.
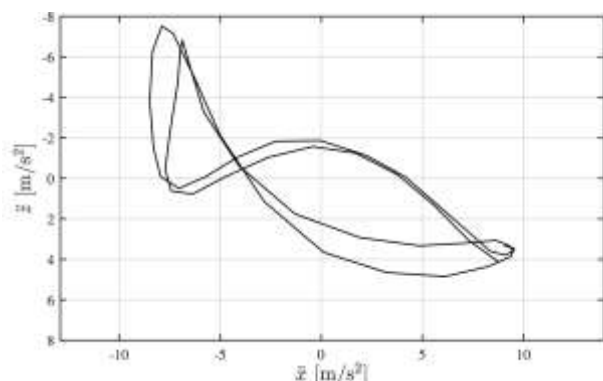
Figure 3. Horizontal ($\ddot{x}$) and vertical ($\ddot{z}$) accelerations in the bearing of the oscillatory roller for two periods of the eleventh pass on lane 2 with f = 39 Hz and v = 4km/h (Pistrol 2016).

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 4). 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 Δm are calculated for a variation of the soil stiffness using a horizontal and vertical cone model according to (Wolf 1994). The Lagrangian equations of motion were derived manually (Pistrol 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 (Pistrol 2016).

In Figure 5 the horizontal ($\ddot{x}_M$) and vertical ($\ddot{z}_M$) accelerations in the drum axis (M in Figure 4) are evaluated for a variation of the dynamic shear modulus G_d of the soil. Figure 5 clearly shows the expansion of the eight-shape with increasing soil stiffness.
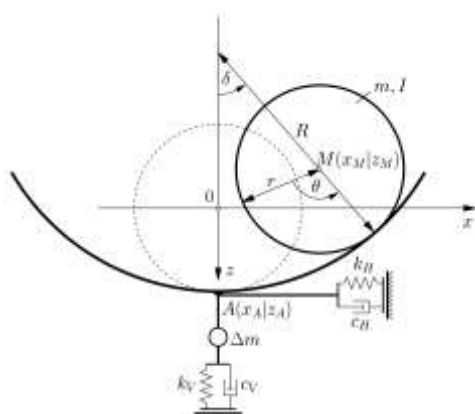

Figure 4. Mechanical model of an oscillatory drum in its own settlement depression (Pistrol 2016).
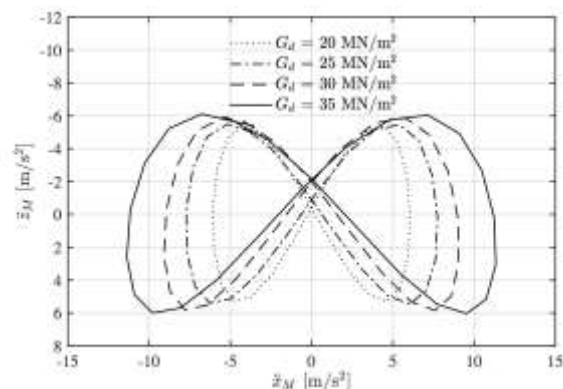

Figure 5. Accelerations ($\ddot{x}_M$ and $\ddot{z}_M$) in the axis (M) of an oscillatory drum according to the mechanical model in Figure 4 for a variation of the soil shear modulus G_d (Pistrol 2016).

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 5. 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 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 had to be developed to approximate the area of the eight-shape with satisfactory accuracy.

Each sampling point in a diagram according to Figure 5 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 the result is the discussed eight-shape (see Figure 6).
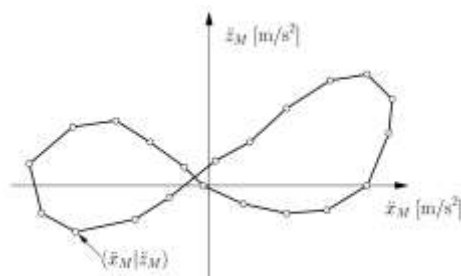

Figure 6. Coordinate pairs ($\ddot{x}_M | \ddot{z}_M$) for one period of excitation connected in chronological order (Pistrol 2016).
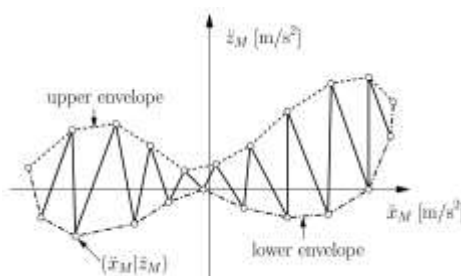

Figure 7. Coordinate pairs ($\ddot{x}_M | \ddot{z}_M$) for one period of excitation connected in accordance with the values of the horizontal accelerations and envelopes for the calculation of the CCC value (Pistrol 2016).

However, the coordinate pairs can also be sorted and connected according to the values of the horizontal accelerations. The result is a vibration of the coordinate pairs

along the x-axis (see Figure 7). Furthermore, the upper and lower envelopes can be calculated by identifying and connecting local maximum and minimum values of the vibration (see Figure 7). 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 considered, which equals approximately one CCC value for each second.

The curves of the calculated CCC values are shown in Figure 8 for the passes 1, 2, 4, and 8 on layer 2 of lane 2 of the test field. When the CCC curves for the various passes are compared an increase of the level of the CCC values can be observed. Figure 8 shows a significant increase within the first four passes on lane 2 and another smaller increase during 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 increase in soil stiffness becomes asymptotically smaller with each pass of the roller.

The artificial weak spots under lane 2 cannot be located in the measurement curve of the first pass on the non-compacted soil. However, their location becomes clearer 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 after the first pass. Although weak spot 1 was buried in a depth of 55 cm below ground level of lane 2, it is still clearly visible in the CCC curves in Figure 8.

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 could be localized.
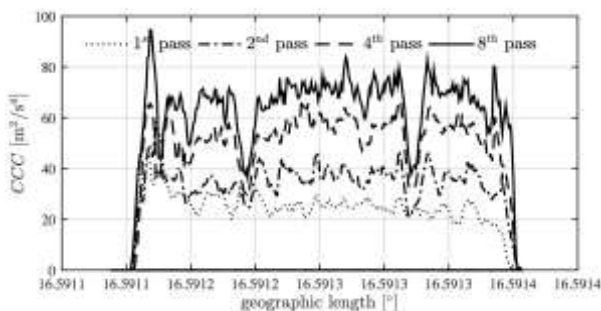

Figure 8. Curves of the calculated CCC values of the passes 1, 2, 4, and 8 on layer 2 of lane 2 of the test field (Pistrol 2016).

4 .1 *Comparison of the CCC values with conventional testing methods*

At least one dynamic load plate test was performed after each pass of the roller to determine the dynamic deformation modulus E_{vd}. The results of these spot tests are compared to the mean CCC values of various roller passes in Figure 9. This type of correlation is also used for the calibration of standard CCC systems for vibrating rollers. Figure 9 shows several CCC values and corresponding results of the dynamic load plate tests for all test runs on the test field, a highly compacted subgrade and on cohesive soils. All depicted test results were obtained from test runs using the standard parameters of the HAMM HD+ 90 VO roller (frequency f = 39 Hz, roller speed v = 4 km/h).

An excellent correlation (coefficient of correlation r_K = 0.998) can be observed for similar soil types like on the test field and the highly compacted subgrade. However, Figure 9 also illustrates the need for the limitation of a calibration to one type of soil and constant machine parameters. The characteristics of cohesive soils differ significantly from those of non-cohesive soils. Therefore, the CCC readings on cohesive soils show a different level of CCC values.
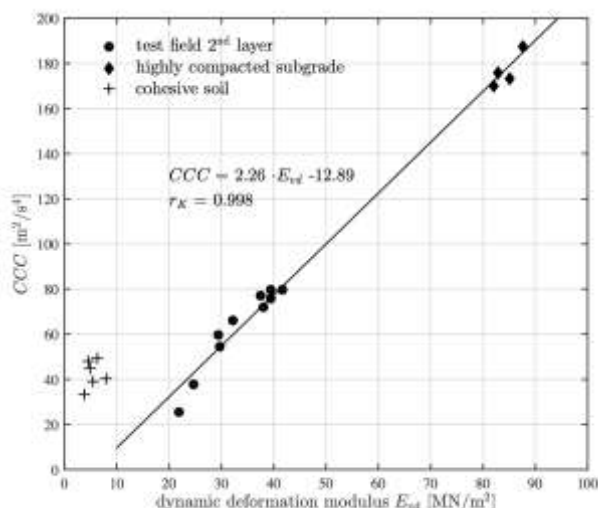

Figure 9. Correlation between the dynamic deformation modulus E_{vd} and the CCC values for oscillating rollers (Pistrol 2016).

2 CONCLUSION

In the presented study, the basic principles of oscillatory roller compaction and CCC systems were discussed. Large-scale in situ tests were performed as well as theoretical investigations, which resulted in a CCC system for oscillating rollers. The novel CCC value for oscillating rollers was described in detail and tested in experimental field test. The CCC results were also compared to a conventional testing method, the dynamic load plate test.

2 ACKNOWLEDGEMENTS

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