Compaction Monitoring Using Intelligent Soil Compactors

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Abstract
The nonlinear vibrations of dynamic soil compactors are taken as the basis for feedback control systems for intelligent compaction. According to the achieved compaction, the parameters of the soil compactor are continuously changed.
The vibratory roller measures permanently the stiffness of the subgrade. In conjunction with GPS-data, this measurement can be used as a QA/QC tool. The stiffness data are directly correlated to plate bearing test.
In practice, the intelligent compaction ensures that the compaction job is completed in a minimum number of passes, the result is monitored and the compaction energy is automatically adjusted while measuring the soil stiffness.

Introduction

Intelligent compaction comprises a vibratory roller with measurement and control technology which selects optimal parameters for the compaction assignment itself. As an operation that is integrated into the working process, compaction is measured in the form of the current stiffness or bearing capacity of the subsoil. In combination with the data from the GPS (Global Positioning System) navigation system, an overview of the compaction work can be visualized, monitored and evaluated for an entire construction site (Continuous Compaction Control, CCC). The individual factors and the way they interact in soil compaction are explained below.

Nonlinear and chaotic vibrations of dynamic compaction machines

Figure 1 shows the simple, non-linear soil-drum model for vibratory rollers and plates; this model is valid subject to the proviso that the excitation frequency is well above the resonance frequency for the frame-suspension elements. In this case, the static weight of the frame may be regarded as a force acting statically on the vibrating mass (Wehrli and Anderegg 1998). More advanced models take account of the horizontal and rotary movements as well as the frame vibrations for vibratory rollers, oscillation rollers and rollers with directed excitations (Kopf 1999).

The model in Figure 1 has been validated many times in practice, not only on tandem rollers for asphalt compaction but also for soil compaction with single-drum vibratory rollers (Anderegg and Kaufmann 2004). After adaptation to the geometry of a directed excitation, the present model can also be used to describe the nonlinear and chaotic vibrations of vibratory plates, trench rollers and rammers (Anderegg and von Felten 2004).

The use of a simple spring-dashpot model is adequate to describe the interaction between the vibrating mass and the elastic subsoil (Wolf 1994); the actual measurement of the spring stiffness k_S can in practice be applied to controlled compactors as a method of continuous compaction control. For earthwork, the stiffness measurement has been validated in practice (Caprez et al. 2003). An example of validation of the stiffness measurement is shown in Figure 5 (left side).

The essential nonlinearity of the soil-drum system arises due to the periodic loss of contact between the vibrating mass of the compactor (which is subject to circular excitation) and the surface below it, as soon as the maximum soil reaction force F_S becomes larger than twice the static weight of the total mass of the machine. In the case of vibratory plates and rammers, this loss of contact is necessary for continued movement (Jönsson 2001).

In analytical terms, the steady-state dynamic behavior of the soil-machine system from figure 1 can be described with the help of the equation of motion according to:

$$F_S = (m_f + m_d)g + m_e r_e \Omega^2 \cos(\Omega t) - m_d \ddot{x} \qquad x_d := x \qquad (1)$$

where F_s = soil-drum-interaction force (kN), m_d = drum mass (kg), m_f = frame mass (kg), x_d = vertical displacement of the drum (m), $m_e r_e$ = eccentric moment of unbalanced mass (kgm), Ω = circular excitation frequency (Hz). The dot notation signifies the differentiation with respect to time.
The soil-drum interaction force can alternatively be written

$$F_S = k_S x_d + c_S \dot{x}_d \quad \text{if} \quad F_S \geq 0\,,\; F_S \equiv 0 \;\text{ else} \qquad (2)$$

where k_S = soil stiffness (N/m), c_S = soil damping (Ns/m).

$$x_d = \sum_i A_i \cos(i\Omega \cdot t - \varphi_i) \qquad x_d := x \qquad (3)$$

where φ_i = phase lag between the generated dynamic force and the part of drum displacement with frequency *if* (°).

Depending on the operational status, the vibration displacement has one or more frequencies:

permanent drum-ground contact, linear: *i*=1

periodic loss of contact, nonlinear: *i*=1, 2, 3 (“Overtones”)

bouncing/rocking, subharmonic: i=1/2, 1, 3/2, 2, 5/2, 3

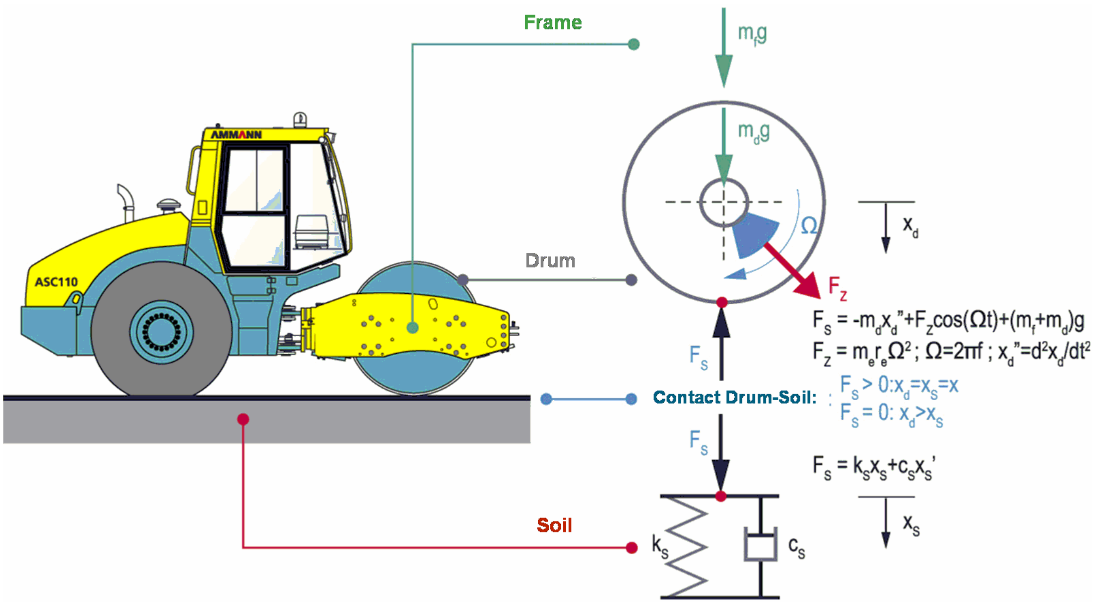

Figure 1. Analytical model of vertical vibration of a single drum roller (circular excitation). This model is also valid for vertical deflection of vibratory plates (directed excitation)

Figure 2 shows an overview of the forms of vibration that occur in practice for various compactors on a well-compacted surface. By using the methods and results of the chaos theory (Thompson and Stewart 2002), (Thomsen 2003) it is possible to arrive at a uniform presentation of the dynamics of dynamic compactors.

The analysis shows that work is carried out with an asphalt roller in 'load' mode (permanently contact between drum and asphalt layer); nonlinearities play a subordinate part and are avoided with controlled rollers. In the case of a single-drum vibratory roller, the surface structure of the compaction material plays a smaller part; the periodic lifting on the boundary with the occurrence of the first subharmonic vibration (so called "bouncing") describes the optimal operating range for soil compaction. The maximum dynamic soil reaction forces occurring in relation to the static axle load k (definition, see Figure 1) range typically from 2.3 to 2.7, and up to 3.0 in some cases. Figure 2 shows the sublinear character of the vibrations using the backbone curve. The first subharmonic vibration with frequency f/2 is part of the incipient period doubling scenario and leads to the first instabilities in the case of vibratory rollers. In practical operation, subharmonic vibrations are avoided by an automatic reduction of the amplitude and a corresponding adaptation of the frequency.

Although the vibratory plate is excited by means of a directed excitation (in contrast to the circular excitation on vibratory rollers), its severely nonlinear movement behavior can also be described by the known resonance curve in the same way as for vibratory rollers.

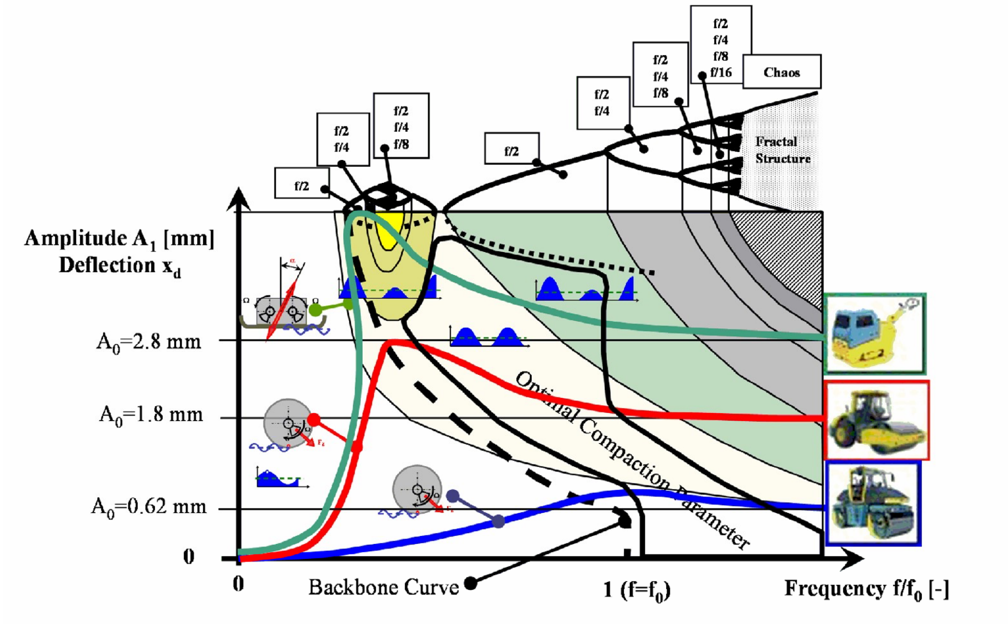

Figure 2. Nonlinear dynamical behaviour of different types of vibratory compaction machines, the soil-drum-interaction-force controls the nonlinearity of the vibrating system

Intelligent Compaction

The objective of automatic control is to achieve optimal entry of power into the ground, depending on the degree of compaction. The parameters of the vibratory roller are automatically adjusted for this purpose on the basis of the measured vibration variables.

Feedback Control System adjusting automatically Amplitude, Frequency and Roller Speed

The measurement of the amplitude A and phase angle φ together with the excitation frequency, the knowledge of the moment of the unbalanced mass and the constant machine parameters allow complete observation of the vibration system. This complete observability is the necessary and adequate condition for complete controllability of the feedback control system, i.e. this is the only possible way of adjusting amplitude and frequency simultaneously. The vibration behavior of the drum-soil system is measured using vertically fitted acceleration sensors. The roller speed is also measured. This data is forwarded to the electronic device where the required variables such as phase angle, soil force and soil stiffness are calculated and the commands to the final controlling elements are generated. When the instructions are executed, the control loop is closed, and the compactor has now become a closed feedback control system which is completely observable and completely controllable.

In the case of a circular vibrator, the mechanical adjustment of amplitude is performed via an eccentric shaft and a tube mounted coaxially in relation to the shaft, each of them producing half of the centrifugal force. The relative position of these two components to one another is continuously adjustable by means of a differential gear so that any desired eccentricity $m_e r_e$ between 0 and the maximum can be obtained. The continuous variation of the frequency is achieved by changing the volume per revolution of the vibropump. The nonlinearity of the drum vibration due to periodic loss of contact from the soil imposes limits on the reasonable use of a vibratory roller, the nonlinearity is controlled by soil-drum interaction force.

The basic idea of a force-based control system is to specify the maximum soil forces $F_S\big|_{\max}$ while simultaneously adjusting the excitation frequency to the measured phase angle φ of the vibration system. The compaction power should be introduced into the soil in such a way that no uncontrollable states of motion (bouncing or rocking) can occur, while optimizing the depth effect of the machine at the same time. As the nonlinearity is force-controlled, this means that the amplitude (and hence the depth effect) of a roller can increase as the vibration frequency decreases.

In addition, the roller speed should be adjusted to the vibration frequency in such a manner that the impact space is between 2 and 4 [cm], the optimum speed is displayed to the roller operator .

Expressed in analytical terms, the machine parameters are controlled according to: the excitation frequency f in such a way that $\varphi=\varphi_{setpoint}$; $140° < \varphi_{setpoint} < 160°$, the eccentric momentum of the unbalanced mass $m_e r_e$ in such a way that $F_S\big|_{\max}$ = target value. Additionally, if subharmonic vibrations occur, $m_e r_e$ is reduced immediately and the roller speed is optimal if the impact space is between 2 and 4 [cm].

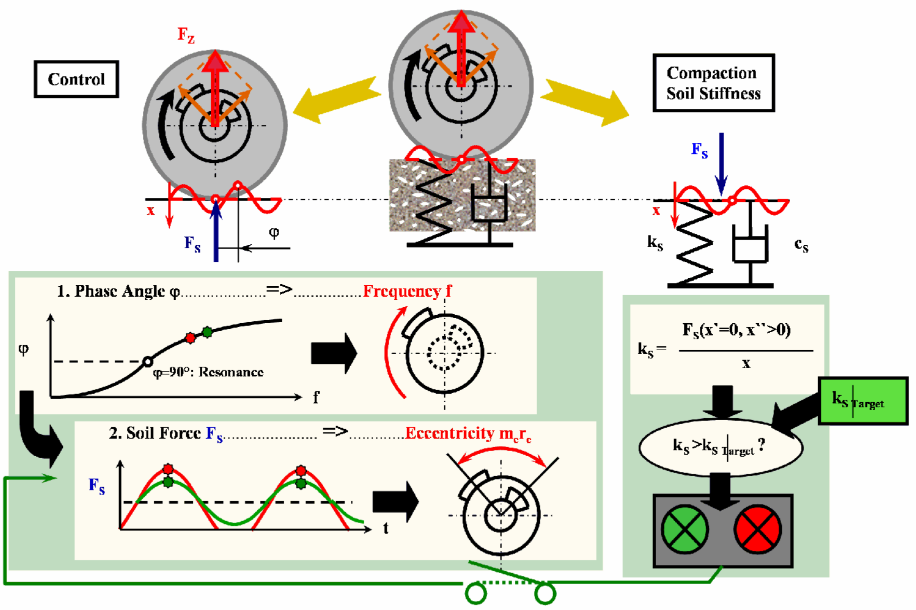

Figure 3. Principle of the automatic control of amplitude and frequency and the measurement of soil stiffness during the compaction process using “Ammann Compaction Expert” ACE

Figure 3 shows the basic algorithms implemented in the control circuit of an intelligent roller (ACE). In addition to the controlled parameters of a single-drum vibratory roller, Figure 4 shows the effect of automatic control in practice. On the first roller pass, the machine operates at the lowest frequencies and maximum amplitude, and the depth effect of the compaction work is maximized. On the following passes, the excitation frequency increases automatically as the bearing capacity of the surface rises, and the amplitude regulates itself towards lower values. The compaction power is increasingly transmitted into the layers near the surface. The last roller pass is used to close the surface at maximum frequency and low amplitude.

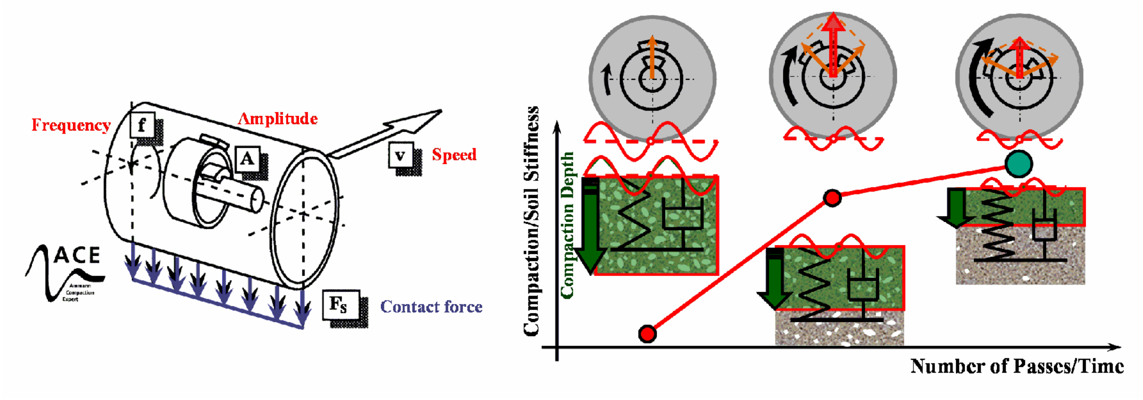

Figure 4. Ammann Compaction Expert ACE: automatic control of amplitude and frequency

GPS-based Continuous Compaction Control displays the Compaction process

If we link the work-integrated bearing capacity measurement of "intelligent rollers" with the information on position and time supplied by the GPS system, the compaction process can be recorded and presented in graphic form. The machine operator is able to use the graphic visualization of the compaction process to assess the compaction achieved, the number of roller passes, the increase in compaction and other information, so as to optimize his work accordingly. Moreover, digital construction plans can be read in, and the working procedure and the compaction result can be recorded and evaluated on them. Figure 5 shows a compaction result comprising the soil stiffness attained and the number of roller passes. The original construction plan was available in digital form and was read in prior to starting work.

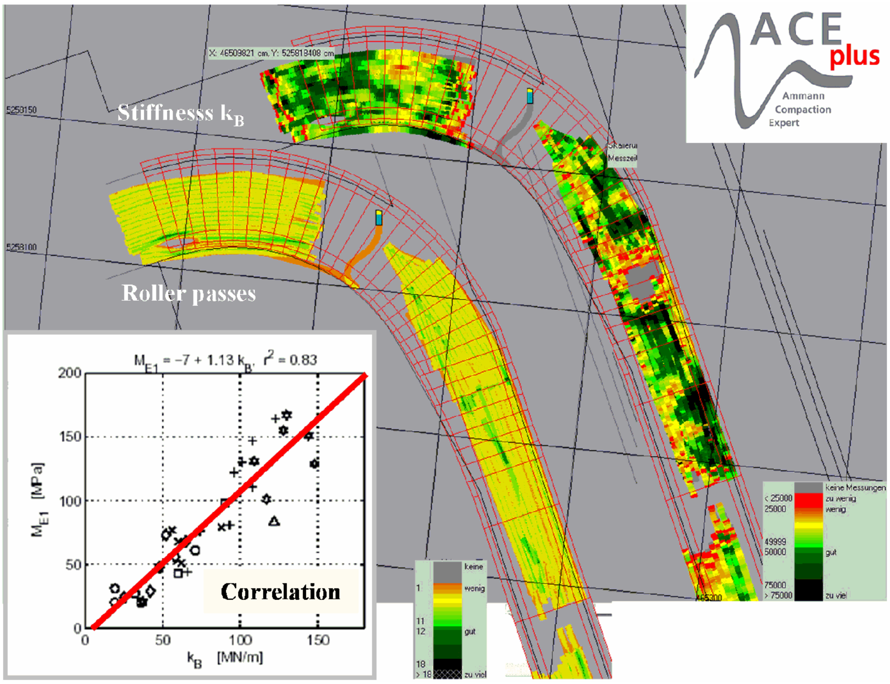

Figure 5. ACE_{plus}:Continuous Compaction Control using differential GPS technology. The soil stiffness measurement is directly correlated to the data of plate bearing test

The navigation device used is the Differential GPS System with an accuracy of 2-4 cm. In addition to the GPS receiver on the roller, a reference station on site is used for the correction signals that enable an accuracy of 2-4 cm for the roller position. These signals are sent to the roller by radio.

The plate-bearing tests that were conducted were also registered together with the current GPS position. Following the compaction work, this allowed a simple correlation of the plate-bearing results with the respective values measured by the intelligent roller.

Conclusions

Intelligent compaction in the earthwork sector enables a defined compaction job to be carried out in a very short time and in a verifiable manner. Linking the soil stiffness measured during controlled compaction to the data from the GPS system allows graphic visualization of the current process so as to provide the machine operator with a simple and very effective aid to work.

Automatic control of the amplitude and frequency ensure attainment of the optimal performance for the respective compaction status of the soil. The indication of impact spacing allows the driver to keep to the correct roller speed. The basis for control is formed by the nonlinear and chaotic vibrations of the soil-drum system. The nonlinearity of the system is created by the one-sided boundary condition between the drum and the surface below it: if the contact forces are sufficiently high, the machine starts to lift from the soil periodically and nonlinearity develops.

The measurement of soil stiffness which is taken in parallel with the control of the roller allows verification of the compaction attained while work is in progress. In combination with a GPS system, this provides the roller operator with a simple visual aid showing him the compaction attained, number of roller passes, size of the construction site and other important indicators for his work.

The recorded data can be used for Continuous Compaction Control (CCC) and they supply an informative overview of compaction for an entire construction site. The data are compatible and can be exchanged with those from graders or dozers.

An automatically controlled roller combined with GPS-aided recording of the bearing capacity values provides an ideal basis for compaction monitoring on construction sites.

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