Numerical simulation of dynamic soil compaction with vibratory compaction equipment

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Abstract. Roller drums make use of various shapes and their dynamic compaction effect is achieved by different kinds of dynamic excitation systems. The bearing capacity of layered soil constructions can be measured during the soil compaction process. The finite element method has been applied for dynamic analyses using elastic models. For the realistic simulation of the dynamic compaction process it is necessary to integrate an inelastic material law for cyclic loads. Compaction with dynamic rollers takes place in different operating modes, which could be proven by the numerical simulations and the influence on continuously recorded control data could be clearly detected.

Keywords: Soil compaction, Numerical Simulation; Continuous Compaction Control; Hypoplasticity

1 DYNAMIC ROLLERS FOR SOIL COMPACTION

Soil compaction with the help of vibratory compaction machinery, such as vibratory rollers and plates, works due to the static load of the whole machine, combined with dynamic forces. Integrated so-called exciter systems introduce dynamic forces into the compaction tool, which transmits the loads into the subgrade.

Today, different kinds of exciter systems, such as adjustable or non-adjustable circular exciters, adjustable or non-adjustable directed exciters and oscillatory exciters, are implemented in vibratory rollers and their use results in different compaction effects in the subgrade. The dynamically excited drum delivers a rapid succession of impacts to the underlying surface from where the compressive and shear waves are transmitted through the material to set the particles in motion. This eliminates the internal friction periodically and facilitates the rearrangement of the particles into positions in combination with the static load which results in a low void ratio and a high density.

The drum of a vibratory roller is excited by a rotating eccentric mass, which is attached to a shaft on the drum axis (Fig. 1). The rotating mass sets the drum in a circular translatory motion, i.e. the direction of the resulting force is corresponding with the position of the eccentric weight. Compaction is achieved mainly by transmitted compression waves in combination with the effective static drum load. Thus, the maximum resulting compaction force is intended to be almost vertical and in fact it is inclined only by a little.

Due to the interaction with the response of the soil the vibration of the roller drum changes the amplitude and shape. Numerous studies have revealed that the drum of a vibratory roller operates in different conditions depending on roller and soil parameters. Five operating conditions specified in Fig. 1 can occur; defining criteria is the contact condition between drum and soil and the drum motion cycle as a multiple of the excitation cycle (Adam 1996, Kopf 1999).

Continuous contact only occurs when the soil stiffness is very low, i.e. in case of low compacted or soft layers, or the drum amplitude is very small. Partial uplift and double jump are the most frequent operating conditions. The difference between these two operating conditions consists of the number of excitation cycles; consequently, the motion behaviour of the drum repeats itself. With further
increasing soil stiffness the vertical translation of drum axis is heterodyned with a rotation and the drum starts the so-called rocking. Very high soil stiffness in combination with disadvantageous roller parameters can cause chaotic motion of the drum. In this operating mode the roller cannot be controlled.

In a so-called VARIO roller two counter-rotating exciter masses, which are concentrically attached to shafts in the axis of the drum, produce a directed vibration. The direction of excitation can be adjusted by turning the complete exciter unit (Fig. 1). If the exciter direction is (almost) vertical or inclined, the compaction effect of a VARIO roller can be compared with that of a vibratory roller. However, if the exciter direction is horizontal, VARIO rollers operate like an oscillatory roller, although the motion behavior of the drum is different. The shear deformation of soil is caused by a horizontally translatory motion, whereas the drum of an oscillatory roller operates torsionally. Thus, a VARIO roller can be used both for dynamic compression compaction (like a vibratory roller), for dynamic shear compaction (like an oscillatory roller), as well as any combination of both.

Based on the findings related to the ways of operating of different dynamic rollers, the company BOMAG produced the first automatically controlled so-called VARIO CONTROL roller. Exemplary, the direction of excitation (vibrations can be directed infinitely from the vertical to the horizontal direction) is controlled automatically in VARIO CONTROL rollers by using defined control criteria, which allow an optimized compaction process.

The roller-integrated continuous compaction control (CCC) represents a significant improvement and is based on the measurement of the dynamic interaction between dynamic rollers and soil (Adam 1996 and Erdmann et al. 2006). The motion behaviour of different dynamically excited roller drums changes in dependence of the soil response. This fact is used to determine the stiffness of the ground. Accordingly, the drum of the dynamic roller is used as a measuring tool; its motion behaviour is recorded, analysed in a processor unit, where a dynamic compaction value is calculated, and visualized on a display device. Furthermore, an auxiliary sensor determines the location of the roller or the localization is GPS-based. Control data is already available during the compaction process and all over the compacted area (Fig. 2 left picture).

Four recording systems are available for vibratory rollers, VARIO rollers and ACE rollers with vertical or any inclined excitation direction (except horizontal direction). All systems consist of a sensor containing one or two accelerometers attached to the bearing of the roller drum. The sensor continuously records the acceleration of the drum. The time history of the acceleration signal is analysed to determine dynamic compaction values. A more detailed overview and description of the different CCC systems can be found in (Kopf and Erdmann 2005).

The gradient of the force displacement curve of the dynamic interaction between drum and subgrade (see Fig. 2), determined by processing the measured acceleration data, is the basis for the CCC value \( E_{\text{ vib}} \), combined with an analytical approach of Lundberg for the contact between cylindrical bodies (more details in Kopf and Erdmann 2005). The diagram for \( E_{\text{ vib}} \) in Fig. 2 shows that a steeply rising force-displacement curve results in a higher \( E_{\text{ vib}} \) value as well as a flat gradient results in a lower \( E_{\text{ vib}} \) value.

![Figure 1. Description of different exciter systems and operating conditions of a drum of a vibratory roller (Erdmann et al. 2006)](image)
Finite element models provide numerical calculations of dynamic soil compaction performed by vibratory rollers. The FEA code must be capable to solve a so-called contact problem to calculate mechanical effects as impacts, deformations of interfaces, friction and the behaviour of the independent bodies (soil and compaction tool). The FEA model presented in this chapter uses an elastic material model which allows a realistic reproduction of the dynamic performance of the soil section. The presented model has also been used for other soil compaction problems as for example vibratory plates (Erdmann 2009a, Erdmann 2009b, Erdmann 2010).

2.1 Operation modes of the compaction tool and soil behaviour during dynamic compaction

The vertical excitation of a drum is modelled by applying a vertical sinusoidal force in the centre, comparable to a directed exciter in vertical direction. Fig. 3 (left) shows the load-displacement curves (soil contact force related to the static load versus the vertical displacement amplitude) for an increasing stiffness of the subgrade, reproducing an increasing compaction status of the soil during the compaction process. The presented simulation model is not able to reproduce the increase of density and stiffness of the subgrade during compaction due to the applied elastic material model, which does not take into account plastic deformation. Nevertheless, the variation of the soil stiffness enables the simulation of the different modes of the drum, which occur during the compaction process. The results of FEA simulation are similar to measurements (Kröber 1988) and other simulations (Adam 1996).

Focusing on one position in the subgrade during a pass of the roller shows graphs with dynamically swelling stresses as well as accelerations and displacements in the subgrade, depending on the static and dynamic forces, the distance and the driving speed of the roller. The stresses reach the maximum values in the moment of passing over. The increasing and decreasing stress values at the observation points are generated by the periodically dynamic stress propagations (pressure bulbs) induced by the moving roller. Regarding the simulation results for the subgrade in Fig. 3 the curve progressions and the maximum values are very similar to the measured values of (Mooney and Rinehart 2009) for a 13t single drum roller with a dynamic exciter force of 275 kN:

Figure 3. FEA results for the dynamic behaviour of the drum and in the subgrade
2.2 3D simulation with drum parameter variation and influence on the CCC value

A 3D FEA model allows the examination of the influence of the drum stiffness and elasticity on the gradient of the force-displacement curve and hereby the $E_{ vib}$ value as well. All parameters of the simulation model, such as soil parameters and roller parameters were the same for all calculations with the exception of the thickness of the FEA shell elements of the drum. The variation of the drum thickness results in a different deformation of the drum due to the interaction with the subgrade. The elastic deformation increases when the shell thickness is being decreased (see Fig. 4 plots on the bottom left), and the corresponding gradient of the force-displacement curve flattens (Fig. 4 graph), so that a reduction of the $E_{ vib}$ value appears. The stress propagations in the subgrade (Fig. 4 plots on the right) differ by varying the drum stiffness. The depth effect decreases and the impact of the position of the stiff drum head plate increases by reducing the drum shell thickness.

3 FEA SIMULATIONS OF COMPACTION PROCESSES WITH HYPOPLASTICITY

Hypoplasticity is a material model for granular materials developed at the University of Karlsruhe in the 1970s (Kolymbas 1978). Since the first approaches the hypoplastic law was improved for a more realistic reproduction of the reality (Herle 1997, Herle and Niemunis 1997). The implementation in a FEA model was realized for the code ABAQUS by the material user subroutine UMAT. The hypoplastic law with intergranular strain (Herle and Niemunis 1997) enables the calculation of dynamic cyclic problems such as vibratory roller compaction (Kelm 2004) taking into account the elastic deformations between the grains. A later extension was done by Niemunis (Niemunis 2002) at the University of Bochum for cohesive materials, which is also of interest for soil compaction calculations.

Hypoplasticity is a constitutive law of a rate type, a relation which associates strain rate with stress rate. The nonlinear behaviour of the hypoplastic law is modeled by the stress dependence of the stiffness.

Before starting complex simulation calculations for rollers, the implementation of the hypoplastic law in MSC.MARC has been validated by the simulation of element tests (Erdmann et al. 2006).

In the following chapter results of a study on compaction simulations with dynamic excited rollers, which drive with a constant speed, are presented. All boundary conditions and subgrade and machine parameters have been kept constant in all simulations with the exception of the dynamic excitement.
Thus results of a static roller without dynamic excitement, a roller with a vertically directed exciter system and an oscillation roller can be compared. The parameters of the applied hypoplasticity with intergranular strain as material law for the subgrade have been chosen according to the parameters of Schlabendorf Sand, presented for example in Herle 1997, Herle and Niemunis 1997 or Kelm 2004. The simulation models are configured for an 8t single drum roller. The roller parameters are listed in Table 1.

Table 2. Roller Parameters.

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<td>1,5</td>
<td>1720</td>
<td>2700</td>
<td>150</td>
<td>30</td>
<td>140 (2 shafts dist. 0.9m)</td>
<td>30</td>
<td>4</td>
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An overview on representative simulation results is given in Table 2, where contour plots of the vertical displacements, the void ratios in the soil and the vertical stresses in the subgrade are shown for the three different models.

Comparing the vertical displacements, the graphs show that the roller with the vertical exciter system produces the maximum settlement in the soil, followed by the oscillation roller, where the vertical settlements are generated by induced shear stresses.

Table 2. Results of FEA soil compaction processes with different rollers using hypoplasticity

<table>
<thead>
<tr>
<th>Vertical Displacement [m]</th>
<th>Static Roller</th>
<th>Roller with Vertical Exciter</th>
<th>Roller with Oscillation Exciter</th>
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<td>void ratio</td>
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<td>Vertical stresses [MN/m²]</td>
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In each of the three simulations the drum provokes a material loosening in the top layer of the subgrade, a phenomenon that commonly appears in non-cohesive soils or in materials with a closely graded granulometric distribution. An overview on representative simulation results is given in Table 4, where contour plots of the vertical displacement, the void ratio in the soil and the vertical stresses in the subgrade are shown for the three different models.

Regarding the vertical stresses in the soil, the vertically excited drum induces the highest vertical stresses into the subgrade whereas the static and the oscillation drum produce approximately similar
stress values and propagations (pressure bulbs). Simulation calculations with elastic soil material behaviour provide comparable stress results concerning the amounts and propagations, but the point of load incidence in the contact area between drum and subgrade is different. Whereas the pressure bulb is located nearly right below the drum axis, the one in simulations with plastic soil deformations occurs in front of the vertical drum centre plane due to the bow wave in front of the contact area between drum and soil.

CONCLUSIONS

The FEA model with elastic material properties describes excellently the dynamic performance of a compaction tool. It is very helpful for interpretations of compaction phenomena in the soil. Existing CCC systems have been simulated with the MSC.MARC model providing accordance to practical experiments and to the results of semi-analytical models. Many different situations of soil compaction can be simulated to show the effects in the soil. An appropriate material law including plastic deformations and dynamic cyclic loads is necessary for compaction simulation. The hypoplastic law for soil simulates the phenomena in the soil during a compaction process with sufficient accuracy, as presented for vibratory rollers with different exciter systems on a sand material.

REFERENCES


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