Numerical simulation of dynamic soil compaction with vibratory compaction equipment

Peter Erdmann[1], Dietmar Adam[2]

[1]BOMAG GmbH, Hellerwald, D-56154 Boppard
[2]TU Wien; Institut für Geotechnik; Grundbau, Boden- und Felsmechanik; Karlsplatz 13, A-1040 Wien

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.

1 Dynamic Rollers for soil compaction

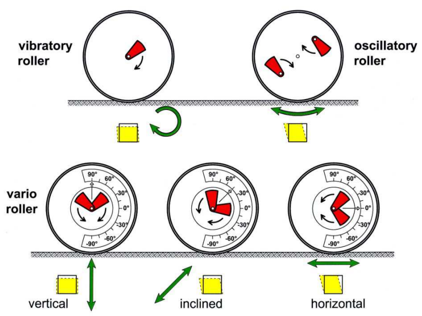
Soil compaction with the help of vibratory compaction machinery, such as vibratory rollers and plates, works due to the static load of the whole machine, combined with dynamic forces. Integrated so-called exciter systems introduce dynamic forces into the compaction tool, which transmits the loads into 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 [1].

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 behavior 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.



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

Fig.1 Description of different exciter systems and operating conditions of a drum of a vibratory roller [2]

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 (**Fig.1**), the company BOMAG produced the first automatically controlled so-called

VARIO CONTROL roller. The Swiss company AMMANN developed the auto-controlled roller ACE in connection with a roller-integrated control system providing dynamic compaction values independent from roller parameters. 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.

2 FEA Simulation of Dynamic Soil Compaction Processes

Finite element models provide numerical calculations of dynamic soil compaction performed by vibratory rollers. For the simulation of soil compaction the FEA code must be capable to solve a so-called contact problem so that it is possible to calculate mechanical effects as impacts, deformations of interfaces, stick and slip, friction and the separation of the independent bodies (soil and compaction tool).

The FEA package MSC.MARC is one of the existing program codes including contact options (**Fig. 2**). Using MSC.MARC the contact between two bodies can be defined by two different methods: the contact between a rigid body, defined by geometric elements and a deformable body consisting of FEA elements or the contact between two deformable bodies. The first possibility is advantageous with respect to the size of the model and for parameter studies. The dynamic behavior of the rigid body must be calculated in a user subroutine. Defining the contact bodies as deformable bodies using elements the dynamic behavior of the bodies is calculated automatically by the code. Model size and solving time increase.

The FEA model presented in this chapter uses an elastic material model. The choice of appropriate material parameters allows a realistic reproduction of the dynamic performance of the soil section.

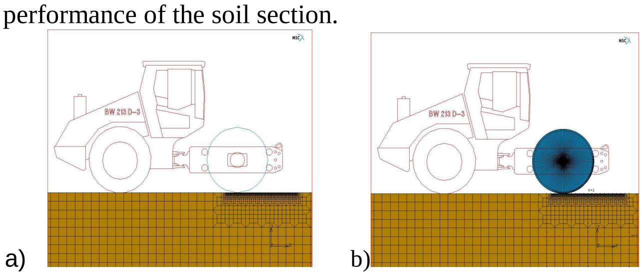


Fig.2 Models in MSC.MARC; a) with rigid drum, b) with deformable drum [2].

2.1 Operation modes of the compaction tool

The vertical excitation of a drum is modeled by applying a vertical sinusoidal force in the center, comparable to a directed exciter in vertical direction. **Fig.3** shows the load-displacement diagram (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 diagrams in **Fig.3** show that the different operation modes of the drum (continuous contact, partial uplift, begin of jumping and double jump) can be calculated using FEA. Irrespective of the definition of the contact bodies (rigid or deformable drum) the results of the FEA simulation calculations are very close to the results of [2] regarding the quality and the quantity of the curves of the different operation modes of the compaction tool.

2.2 Soil behavior during dynamic compaction

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. Regarding the deformations and the stresses of the soil it is possible to get sufficiently accurate estimations concerning compaction effects and compaction depths.

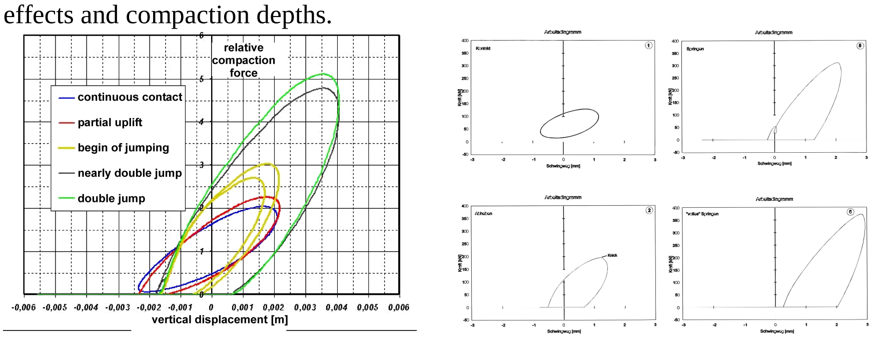


Fig.3 Load-displacement diagram for an increasing compaction with a BOMAG single drum roller BW 213 D-4 (left) compared with semi-analytical calculations [1].

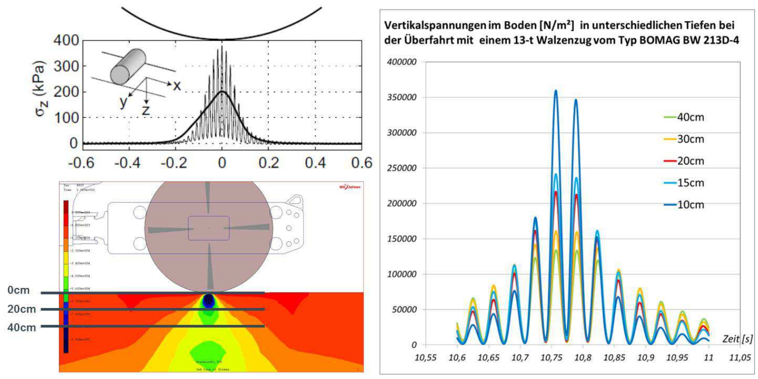


Fig.4 Vertical stresses at one fixed position of the subgrade in different depths during a pass with a 13t single drum roller with vertical dynamic exciter forces of 275 kN; measured values [13] (top on the left) in a depth of 13cm in comparison to calculated graphs for several depths (right)

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 in **Fig.4** the curve progressions and the maximum values are very similar to the measured values of [13] for a 13t single drum roller with a dynamic exciter force of 275 kN:

2.3 2D versus 3D modeling

For simulating dynamic soil compaction with rollers with FEA in many cases it is sufficient to use a 2D model. Applying plain strain elements reduces the degree of freedom in the thickness direction (direction of drum axis), so that the drum-soil-interaction is simulated as being infinite in this direction. The advantages are a smaller number of elements and by this a better solution performance.

For a more detailed and exact simulation of the compaction process it is necessary to create a 3D FEA model with volumetric elements. Effects in the soil at the drum sides, such as the displacement and stress propagations in the soil, and bouncing of the drum with different vertical amplitudes and phase angles can be calculated. This results in a better quality of results, but model complexity and solving time increase significantly. **Fig.5** shows a 2D plain strain model on the left and a 3D volumetric model on the right for the simulation of the drum-soil-interaction. The presented 3D model is a quarter model using two symmetry boundary conditions, which enables the representation of all operating conditions of the drum instead of bouncing.

In the 3D model, the drum is represented by shell elements with the same thickness as the rolled sheet metal in reality. The E-modulus of the drum material can be varied to examine the influence of the drum elasticity. The increase of the E-modulus of steel ($2.1*10^5$ N/mm²) by factor 10^6 provokes an approximately rigid behavior of the drum structure comparable to the drum in the 2D simulation. **Fig.6** shows the results of the calculations with similar parameters for the 2D model and the 3D model with a rigid drum and a realistic elastic drum.

The 3D simulation is more realistic due to the displacement and stress propagations at the sides of the drum (**Fig.6**). In the midplane of the drum (vertical to the drum axis) the 3D model delivers similar stress values and stress propagations as the 2D model. Only small differences in the 3D stress propagation appear between rigid and elastic drum underneath the position of the drum flange plate. The stress values and propagations are dependent on the stiffness of the drum (drum thickness, position of the drum plate).

Regarding the force displacement graphs for the 2D model and the 3D models with rigid and elastic drums, the curves for the 3D models show smaller stiffness due to the effects at the drum sides and the influence of the geometric damping in the 3rd dimension (direction of drum axis). The curve of the elastic 3D drum has the most flat progression, caused by the deformation energy in the drum structure which reduces the energy induced in the subgrade and influences the interaction between drum and soil.

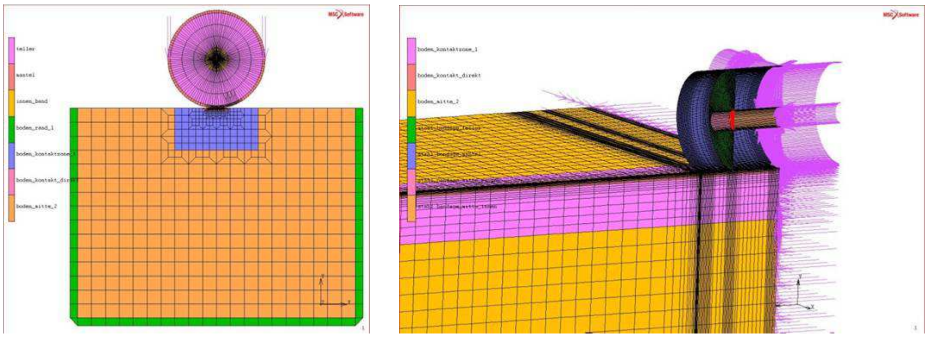


Fig.5 2D and 3D Model with MSC.MARC.

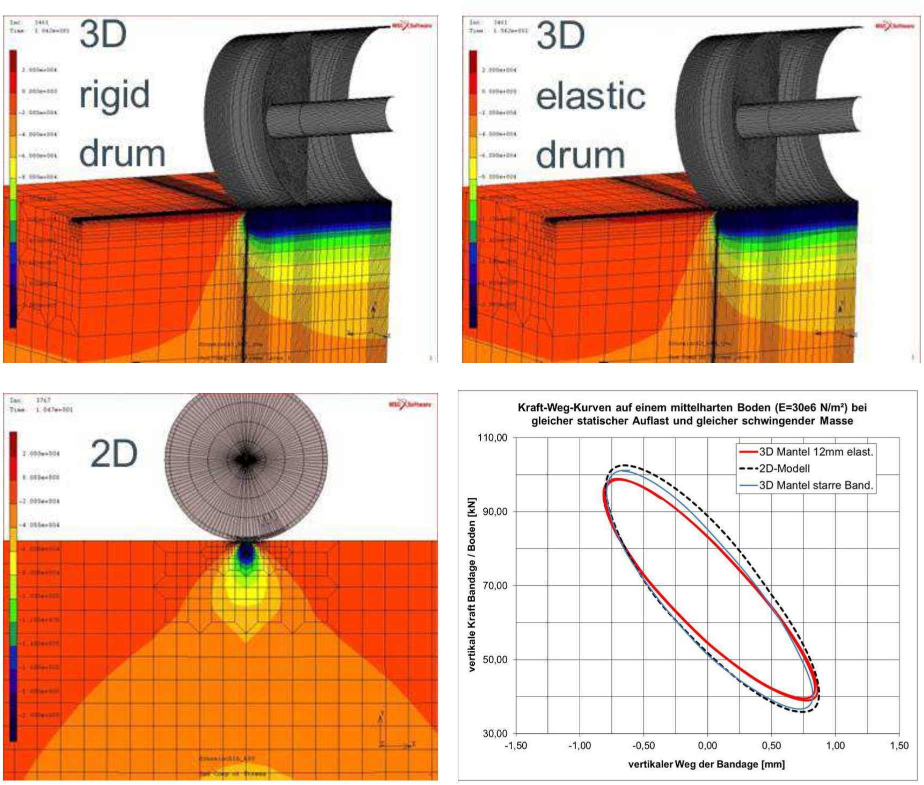


Fig.6 Results of 2D and 3D models.

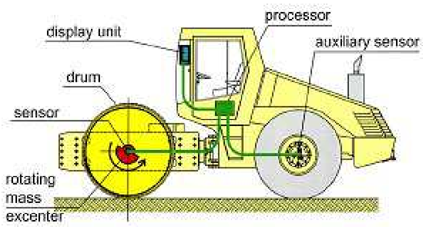
3 Integrated Continuous Compaction Control Methods (CCC)

3.1 General description

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 [1][2]. The motion behavior 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 behavior is recorded, analyzed 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. 7** 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 analyzed to determine dynamic compaction values.

The chart on the right in **Fig. 7** gives a review of the recording systems of CCC. All defined CCC-values have proven suitable for roller-integrated checking of the actual compaction state. A more detailed overview and description of the different CCC systems can be found in [14].



CCC-system	CCC-value	definition of CCC-value
Compactometer	**CMV** [ ]	acceleration amplitude ratio (first harmonic div. by excitation frequency amplitude) – *frequency domain*
Terrameter	**OMEGA** [Nm]	energy transferred to soil (considering soil contact force displacement relationship of 2 excitation cycles) – *time domain*
Terrameter	**E_{vib}** [MN/m²]	dynamic elasticity modulus of soil beneath drum (inclination of soil contact force displacement relationship during loading) – *time domain*
ACE	**k_B** [N/m]	spring stiffness of soil beneath drum (derived from soil contact force displacement relationship at maximum drum deflection) – *time domain*

Fig.7 Vibratory roller with integrated CCC system and currently available CCC systems

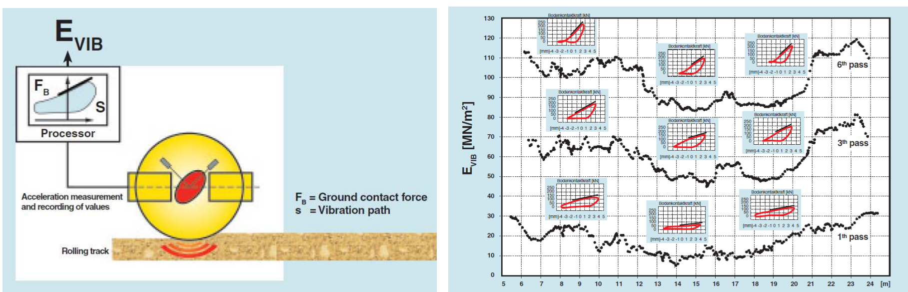


Fig.8 Dynamic stiffness E_{vib} determined with the VARIOCONTROL system on silty gravel

The gradient of the force displacement curve of the dynamic interaction between drum and subgrade (see **Fig.8**), determined by processing the measured acceleration data, is the basis for the CCC value E_{vib}, combined with an analytical approach of Lundberg for the contact between cylindrical bodies (more details in [11]). The diagram for E_{vib} in **Fig.8** shows that a steeply rising force-displacement curve results in a higher E_{vib} value as well as a flat gradient results in a lower E_{vib} value.

3.2 3D simulation with drum parameter variation

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.9** plots on the bottom left), and the corresponding gradient of the force-displacement curve flattens (**Fig.9** graph), so that a reduction of the E_{vib} value appears. The stress propagations in the subgrade (**Fig.9** 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.

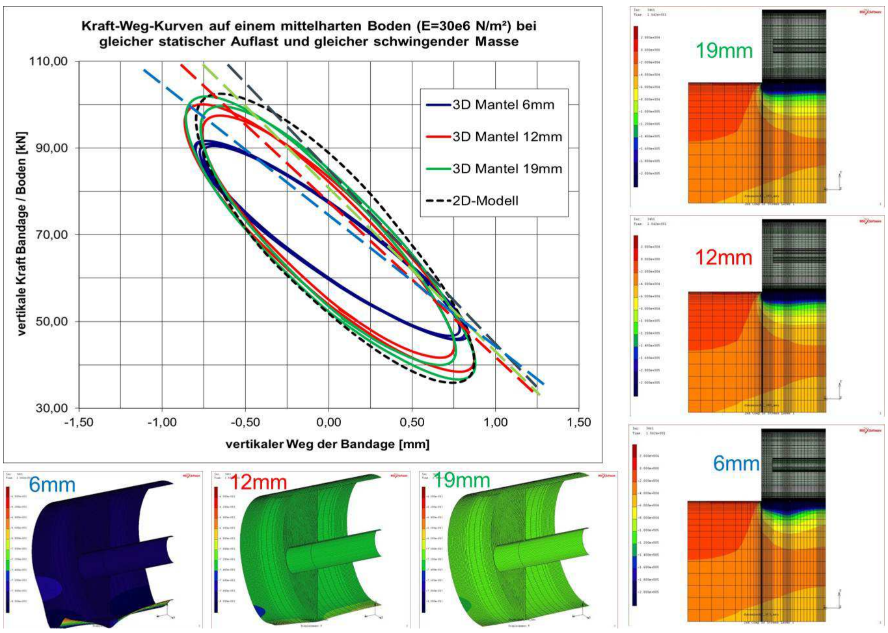


Fig.9 Results with FEA for a parameter study on the influence of the drum stiffness on the dynamic behavior of the compaction tool

4 Hypoplasticity

4.1 General aspects

Hypoplasticity is a material model for granular materials developed at the University of Karlsruhe in the 1970s [12]. Since the first approaches the hypoplastic law was improved for a more realistic reproduction of the reality [9][10]. The implementation in a FEA model was realized for the code ABAQUS by the material user subroutine UMAT. The hypoplastic law with intergranular strain [10] enables the calculation of dynamic cyclic problems such as vibratory roller compaction [11] taking into account the elastic deformations between the grains. A later extension was done by Niemunis [15] 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 behavior of the hypoplastic law is modeled by the stress dependence of the stiffness.

$$\boxed{\overset{\circ}{\mathbf{T}} = \mathbf{h}(\mathbf{T}, \mathbf{D}, e)} \qquad (1)$$

with: - T : objective stress rate
- h : tensor function
- D : strain rate
- e : void ratio

4.2 Implementation in MSC.MARC and results of element tests

Before starting complicated and extensive soil compaction calculations with FEA including the hypoplastic material law it is necessary to calibrate and validate the hypoplastic law integrated in MSC.MARC. In the literature [11] results of simulations with hypoplasticity of the so-called element tests are presented in comparison to practical tests.

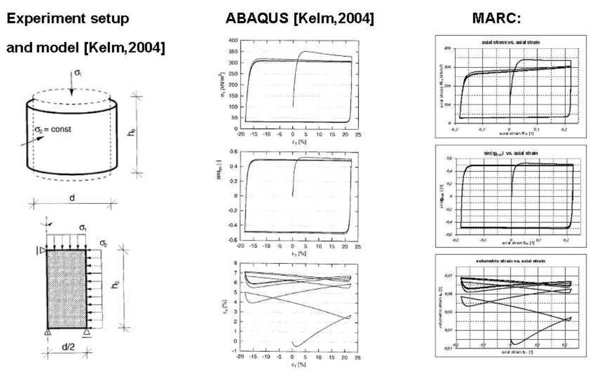


Fig.10 Static cyclic triaxial test – results with MSC.MARC vs. ABAQUS results [11]

The graphs in **Fig.10** show the results of the static cyclic triaxial test calculated with ABAQUS in comparison with the MSC.MARC results. The diagrams for the different variables are very similar regarding the ABAQUS and MSC.MARC results.

5 FEA Simulations of compaction processes with hypoplasticity

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.

Table 2. Parameters for hypoplasticity with intergranular strain

Critical friction angle φ_c [°]	Granular hardness h_s [MPA]	Exponent n	Critical void ratio at ps=0 e_{c0}	Min. void ratio at ps=0 e_{d0}	Max. void ratio at isotropic compression e_{i0}
32,5	1600	0,19	0,85	0,44	1,00

Exponent α	Exponent β	Intergranular strain R	Multiplier m_R	Multiplier m_T	Parameter β_r	Parameter χ	Initial void Ratio e_0
0,25	1,00	$1*10^{-4}$	5,0	2,0	0,5	6,0	

The parameters of the applied hypoplasticity with intergranular strain as material law for the subgrade are listed in **Table 2**, according to the parameters of Schlabendorf Sand, presented for example in [9][10] [11] [15]. The simulation models are configured for an 8t single drum roller. The roller parameters are listed in **Table 3**.

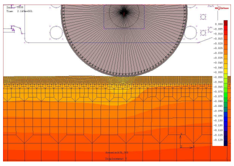
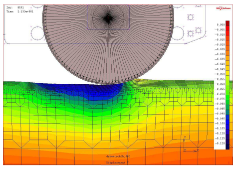
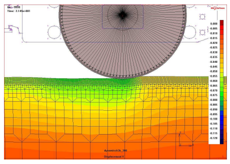
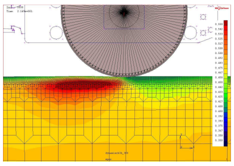
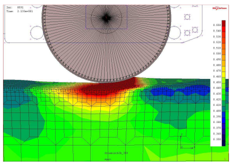
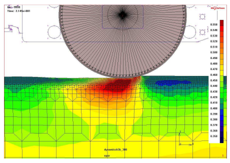
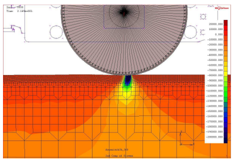
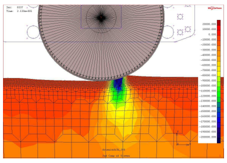
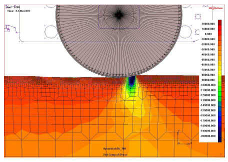
Table 3. Roller Parameters.

.	Static mass (frame) [kg]	Dynamic Drum mass [kg]	Vertical Exciter force [kN]	Vertical exciter frequency [Hz]	Oscillation Exciter force [kN]	Oscillation Exciter Frequency [Hz]	Driving Speed [km/h]
1,5	1720	2700	150	30	140 2 shafts distance900mm	30	4

An overview on representative simulation results is given in **Table 4**, 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 oszillation roller, where the vertical settlements are generated by induced shear stresses.

Table 4. Results of FEA soil compaction processes with different rollers using hypoplasticity

Text	Static Roller	Roller with Vertical Exciter	Roller with Oscillation Exciter
Vertical Displacement [m]			
Void ratio			
Vertical stresses [MN/m²]			

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 behavior 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 center plane due to the bow wave in front of the contact area between drum and soil.

6 References

1. Adam D: Flächendeckende Dynamische Verdichtungskontrolle (FDVK) mit Vibrationswalzen. Dissertation. Technische Universität Wien, 1996.
2. Erdmann P, Adam D, Kopf F: Finite element analyzes of dynamic compaction techniques and integrated control methods. NUMGE 1996 Graz, Austria: 197-204, 1996.
3. Erdmann P: Simulation von Verdichtungsvorgängen in Böden mit Hilfe der Finite-Elemente-Methode. 1st Commercial Vehicle Technology Symposium Kaiserslautern, Germany: 319-329, 2010.
4. Erdmann P: : Simulation von Verdichtungsvorgängen in Böden mit Hilfe der Finite-Elemente-Methode. 7. Österreichische Geotechniktagung,: 353-368, 2009.
5. Erdmann P: Compaction simulation of road building materials using EDEM. Usermeeting DEM Solutions, Edinburgh, Scotland, 2009
6. Kopf F: Flächendeckende Dynamische Verdichtungskontrolle (FDVK) bei der Verdichtung von Böden durch dynamische Walzen mit unterschiedlichen Anregungsarten. Dissertation, Technische Universität Wien, 1999.
7. Kröber W.: Untersuchung der dynamischen Vorgänge bei der Vibrationsverdichtung von Böden. Dissertation, Technischen Universität München, 1988.
8. Erdmann P: Einsatz von MSC.MARC zur Simulation von Problemstellungen in der Bodenverdichtung. Beitrag zum MSC.MARC-Technologietag. München, 2002..
9. Herle I: Hypoplastizität und Granulometrie einfacher Korngerüste. Dissertation. Universität Karlsruhe, 1997.
10. Herle, I, Niemunis A: A hypoplastic model for cohesionless soils with elastic strain range. Mechanics of cohesive-frictional materials Vol.2: 279-229, 1997.
11. Kelm M: Nummerische Simulation der Verdichtung rolliger Böden mittels Vibrationswalzen. Dissertation, TU Hamburg-Harburg, 2004.
12. Kolymbas D: Ein nichtlinerares viskoplastisches Stoffgesetz für Böden. Dissertation, Universität Karlsruhe, 1978.
13. Mooney MA, Rinehart RV: InnnSitu Soil Response to Vibratory Loading and Its Relationship to Roller-Measured Soil Stiffness. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, August 2009.
14. Kopf F, Erdmann P: Numerische Untersuchungen der Flächendeckenden Dynamischen Verdichtungskontrolle. Österreichische Ingenieur- und Architekten-Zeitschrift (ÖIAZ), 150.Jahrgang, Heft 4-5, S.126-143, 2005.
15. Niemunis, A: Extended hypoplastic models for soils. Habilitation, Universität Bochum, 2002.
16. Floss R: Compaction Technology in Earthwork, Highway and Transportation Engineering. Specialist book of BOMAG GmbH & Co. OHG, Germany, 1st edition 2001 Published by BOMAG GmbH & Co. OHG, 2001.