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Dynamic simulation and optimisation of plate compactors for subballast compaction during rail track rehabilitation

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ABSTRACT

The sufficient compaction of the formation protective layer (FPL) during track rehabilitation is a crucial process to improve the longevity of railways. Plate compactors are used to ensure sufficient compaction during track-bound rehabilitation works. The most common plate compactor in Austria (Wimmer WBB 530) comprises a frame and a dynamically decoupled, vibrating base plate which includes a rotating mass type of exciter. As the FPL has a thickness of 40 cm (after compaction) ensuring a sufficient compaction presents a challenge to the comparatively light plate compactor. During prior investigations, a mechanical model was developed to determine the motion behaviour of the plate compactor and the interaction between plate compactor and soil during compaction. Additionally, the motion behaviour of the given plate compactor was monitored and analysed during field tests. This paper juxtaposes the simulated motion behaviour and the interaction between plate compactor and soil with data collected during experimental field tests. The investigation shows that the mechanical model can sufficiently replicate the different modes of operation which occur during compaction and can be used for an optimization of the compactor. The measured data corresponds to the simulations. However, the measurements also show that the plate compactor and its periodic loading of the soil highly depends on a careful selection of process parameters.

KEYWORDS

Dynamic Compaction; Plate Compactor; Motion Analysis; Data Processing.

1. INTRODUCTION

Ensuring the correct positioning of railway tracks is crucial for a functioning railway system. The quality of the substructure, which comprises the quality of the ballast as well as the subballast and the subgrade is critical in minimizing track geometry deterioration. Throughout the life cycle of a track formation the quality of the substructure changes and degrades but can be prevented by a formation rehabilitation. Although ballast rehabilitation by tamping (and subsequently ballast compaction) can be achieved more easily, the ballast has less influence on severe track geometry errors compared to the subballast or the subgrade. Tough the rehabilitation of the subballast is much more complex as it requires removing the ballast and the formation protective layer and laying them out again. Depending on the rehabilitation method the track grid may need to be removed as well (Li et al., 2015).

In Austria the AHM 800-R (AHM) is a commonly used track bound formation rehabilitation machine from Plasser & Theurer – Export von Bahnbaumaschinen Gesellschaft m.b.H. (P&T). It enables a rehabilitation without removing the track grid and thus increases the efficiency compared to traditional formation rehabilitation methods (Auer et al., 2008). The AHM is equipped with two excavation chains that operate beneath the lifted track grid. The first excavation chain removes the approximately 30 cm thick layer of ballast. The old ballast is then crushed and mixed with new FPL material. The subgrade excavation chain then removes the existing subgrade and the lower area of the ballast layer and transports the material to the rear of the machine for subsequent disposal.

After excavation, the formation level of excavation is smoothed with a vibrating screed and a geotextile can be installed to minimize mixing of the subgrade with the new FPL layer. The FPL material, which is a mix of quality-assured FPL material and up to 50% of reprocessed ballast material, is then placed on the geotextile with a layer thickness of approximately 50 cm (uncompacted). The FPL material is then compacted resulting in a layer thickness of approximately 40 cm. The compaction is performed using six Wimmer WBB 530 plate compactors in parallel (see Figure 1).

Figure 1. Plate compactor WBB 530 of the AHM 800-R during compaction of the FPL. Source: P&T

Due to the limited workspace beneath the tracks, the plate compactor is restricted in size and weight. The compaction of a 40 cm thick layer of soil presents a challenge for a comparably light plate machine and may cause irregular motion behaviour of the plate compactor and/or an insufficient compaction of the FPL, which could significantly reduce the expected life cycle of the track formation.

Field tests were carried out to analyse the motion behaviour of the plate compactor during FPL compaction to improve the efficiency of the plate compactors and the quality of the compaction. Additionally, the theoretical motion behaviour of the plate compactor under different soil properties and machine parameters was investigated using a mechanical model (Pistrol et al., 2022). This paper juxtaposes the simulated motion behaviour and the interaction between plate compactor and soil with data collected during experimental field tests.

2. THEORETICAL SIMULATION

Pistrol et al. (2022) presented a simplified mechanical model to describe the interaction between the plate compactor and the soil. While various simplifications are made and boundary conditions need to be defined, the model accurately depicts the contact conditions between the two mechanical subsystems (plate compactor and soil). One of the most important simplifications with regard to the equation of motion is the consideration of only vertical motion quantities as the load applied on the soil by the plate compactor is directed in a mostly vertical direction (Pistrol et al., 2022). This simplification has been used in similar investigations for vibratory rollers and showed sufficient accuracy (Adam, 1996; Kopf, 1999). The model can reliably describe three different operation phases: loading, unloading, and loss of contact. Figure 2 shows the simplified mechanical model and its subsystems: soil and plate compactor. The interaction between these two subsystems is described by contact conditions. The plate compactor can be further divided into an upper part (frame) and a lower part (base plate). These parts are connected by rubber buffers which allow for a separate description of those parts (Stefan, 2020).

Equation (1) gives the motion equation of the frame. The force in the rubber buffers as a result of their stiffness and damping properties is summarised in Equation (2) (Pistrol et al., 2022).

$$\left(m_f + m_a\right)\ddot{z}_2 - F_r = \left(m_f + m_a\right) g \tag{1}$$

$$F_r = c_r\left(\dot{z}_1 - \dot{z}_2\right) + k_r\left(z_1 - z_2\right) \tag{2}$$

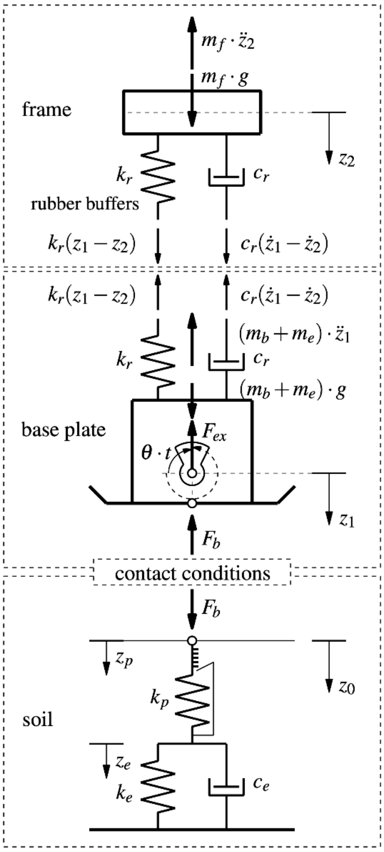

Figure 2. Mechanical model with plate compactor and soil subsystem. The plate compactor is split up in its components frame and base plate (Pistrol et al., 2022).

Equation (3) gives the equation of motion for the base plate. Equation (4) shows the equation to determine the exciter force F_{ex}. Equation (3) can be transformed to determine the soil contact force F_b (see Equation (5)), which defines the interaction between plate compactor and soil as it includes the motion equations of the frame as well as the base plate (Pistrol et al., 2022).

$$\left(m_b + m_e\right)\ddot{z}_1 + F_r + F_{ex} + F_b = \left(m_b + m_e\right) g \tag{3}$$

$$F_{ex} = m_e e \theta^2 \sin(\theta t + \varphi_0) \tag{4}$$

$$F_b = \left(m_b + m_e\right) g - F_r - F_{ex} - \left(m_b + m_e\right)\ddot{z}_1 \tag{5}$$

The soil subsystem is modeled with an elastic-plastic material behavior. The vertical displacement z_0 comprises elastic and plastic components as shown in Equation (6). The elastic behaviour is modeled with a Kelvin-Voigt element, the plastic behaviour with an elastic spring, which is only active during loading (Stefan, 2020). The spring stiffness is based on the cone model by Wolf (1994).

$$z_0 = z_e + z_p \tag{6}$$

The input parameters and variables for the given equations are defined in Table 1. Additionally, Table 1 shows the values of the input parameters used for the simulation for the three chosen time frames in the analysis and comparison.

Table 1. Parameters and variables of the mechanical model and values for the time frames 1 to 3

Variable	Description	Unit	Frame 1	Frame 2	Frame 3
c_e	Soil dashpot coefficient (Kelvin-Voigt)	N/ms	2.3e5	3.1e5	2.1e5
c_r	Rubber buffer dashpot coefficient	Ns/m	15000	15000	15000
e	Eccentricity of eccentric mass	m	0.032	0.032	0.032
f	Excitation frequency	Hz	51	54	35
g	Gravitational acceleration	m/s^2	9.81	9.81	9.81
k_e	Soil spring stiffness (Kelvin-Voigt)	N/m	5.7e7	1.0e8	4.9e7
k_p	Soil spring stiffness for plastic deformation	N/m	3.2e8	5.8e8	2.8e8
k_r	Rubber buffer spring stiffness	N/m	2e6	2e6	2e6
m_b	Mass of base plate	kg	295	295	295
m_e	Eccentric mass	kg	20	20	20
m_f	Mass of frame	kg	385	385	385
F_b	Soil contact force	N			
F_{ex}	Excitation force	N			
F_r	Force in the rubber buffers	N			
t	Time	s			
z_0	Vertical displacement of soil	m			
z_1	Vertical displacement of base plate	m			
$\dot{z}_1$	Vertical velocity of base plate	m/s			
$\ddot{z}_1$	Vertical acceleration of base plate	m/s^2			
z_2	Vertical displacement of frame	m			
$\dot{z}_2$	Vertical velocity of frame	m/s			
$\ddot{z}_2$	Vertical acceleration of frame	m/s^2			
z_e	Elastic deformation of soil	m			
z_p	Plastic deformation of soil	m			
θ	Circular frequency of excitation	rad/s			
φ_0	Phase shift	rad			

3. FIELD TESTS

The field tests were conducted in a gravel pit located in Fischamend, Austria. A plate compactor was attached to an excavator by a special mount (see Figure 3 (a)) which allowed to apply vertical loads onto the plate compactor. The excavator was pulled along the test lanes (see Figure 3 (b)) to ensure a slow and constant speed equivalent to the travel speed of the AHM during formation rehabilitation (approximately 70 m/h). The test lanes consisted of regular FPL material with a layer thickness of about 40 cm. The series of field tests consisted of four reference measurements, in which the plate compactor was lifted and oscillated freely in the air and eight test runs with various machine configurations (Sigmund et al., 2023).

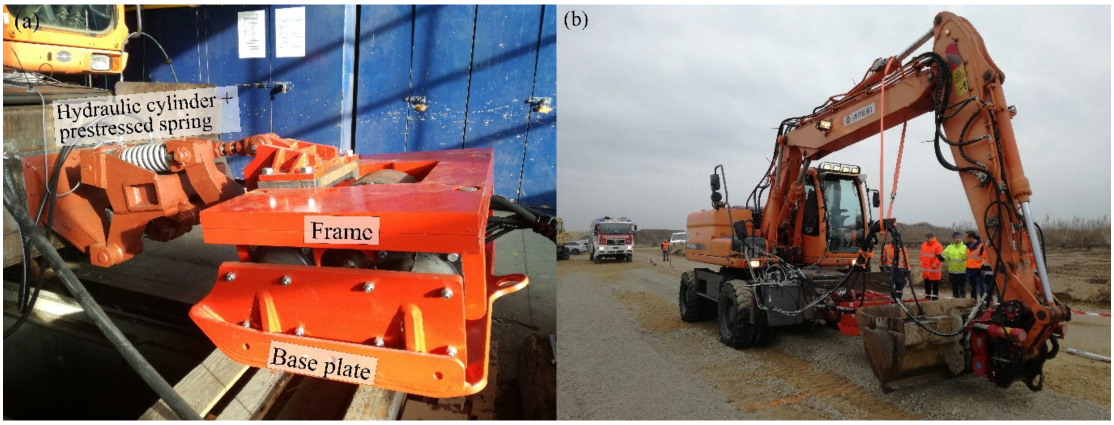

Figure 3. (a) Mounted plate compactor. (b) Excavator equipped with plate compactor is pulled along the test lanes during field test. (Sigmund et al., 2023)

The plate compactor was equipped with five MEMS 3D accelerometers; four were mounted on the base plate around the exciter unit to record the movement of the plate and one was attached to the frame to determine the influence of the plate's movement on the frame. Additionally, the exciter unit was equipped with four inductive proximity sensors to track the position of the unbalance during the field tests. In addition to the accelerometers and position sensors, a loading cell was used to monitor the force applied by the hydraulic cylinder.

4. ANALYSIS AND COMPARISON

The movement of the unbalance and the exciter frequency were determined from the data collected by the exciter units' proximity sensors. The results show that the hydraulic pressure of the excavator's engine was not sufficient to support both, a high exciter frequency and a high vertical load on the plate compactor. Therefore, high vertical loads could only be applied during phases of lower frequencies and vice versa.

The data analysis from the field tests indicates that the plate compactor's mode of operation changes with varying conditions. The applied vertical load and the exciter frequency are the main influencing factors on the plate compactor's behaviour. The data indicates that the soil contact force of the plate compactor was very low during phases of low vertical loads. This can be attributed to a suboptimal mount construction that lifted the plate compactor off the ground without sufficient vertical loads. However, after applying a certain vertical load, the data shows a significant increase of the soil contact force. However, low vertical loads cause the plate compactor's motion behaviour to be indistinctive. As the load increases, the motion behaviour becomes more periodic and distinctive. (Sigmund, 2021).

For the comparison between field tests and simulation, three time frames are selected from the field test data that show a periodic and distinctive motion behaviour. The parameter sets of the time frames differ in exciter frequency and vertical load. The exciter frequency from the field data was then used for simulating the motion behaviour of the given time frame. Figures 4 to 6 show the comparison between the field test data and the simulation. Figure 4 to 6 (a) (left) compares the exciter force and the soil contact force of the given time frame. The lower graph compares the exciter force F_{ex} of simulation and field data and shows the difference (delta) to verify the frequency input of the model. The upper graph shows the soil contact force F_{b} of simulation and field data. Figure 4 to 6 (b) (right) show the orbital (vertical over horizontal) displacement of the plate compactor for the respective time frame. The red and green lines indicate the movement of the front and rear sensor. The movement of the centre is determined by weighting the displacements of the front and rear sensors according to the distance from the sensors to the centre. The grey lines connect time-equivalent points at the front and rear. As the distance between the sensors is not shown true to scale, the rotation of the base plate at any given time is significantly inflated.

During time frame 1 the plate compactor shows a distinctive, periodic motion behaviour (see Figure 4 (b)). Due to the unbalanced design of the plate compactor, the base plate starts to tilt during compaction. Depending on the rotation direction of the unbalance, the front end shows significantly larger amplitudes compared to the rear end. The lower graph of Figure 4 (a) shows that the alignment of the exciter forces F_{ex} of model and field tests works sufficiently as the delta is negligible. The upper graph shows that the model as well as the field test data registered a 'spike' in the soil contact force F_{b} every other exciter period. Thus, after a high intensity impact the base plate loses contact and lifts off the ground for one full period before hitting the soil surface again. This mode of operation is referred to as 'double jump' in dynamic roller compaction (Adam, 1996). The difference in time at which the impact occurs can be explained by the slight rotation of the base plate during the field tests, resulting in an earlier contact initialisation between plate compactor and soil or with the load application point of the soil contact force deviating from the centre of the plate compactor, which can also cause a time discrepancy.

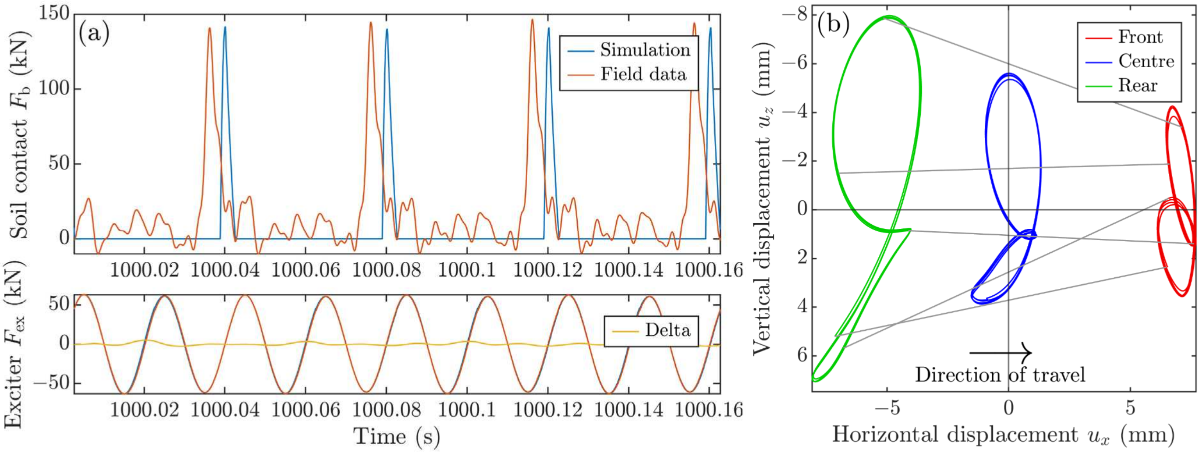

Figure 4. Time frame 1: (a) Comparison of soil contact force F_b and exciter force F_{ex} from simulation and field tests. (b) Orbital movement of the plate compactor from field tests (inflated rotation).

Figure 5 shows time frame 2. The delta of the exciter forces remains negligible. Similar to time frame 1 (Figure 4), the plate compactor shows a periodic motion behaviour (see Figure 5 (b)) but the higher frequency leads to a lower vertical load in this section which results in a slightly different movement of the front end for each exciter period. This time frame was selected from a second compaction run on a test lane. Therefore, an increased soil stiffness is expected compared to the first test run. The increased soil stiffness leads to an increased soil contact force, which is replicated in the mechanical model by an adjustment of the soil parameters, as shown in Figure 5 (a).

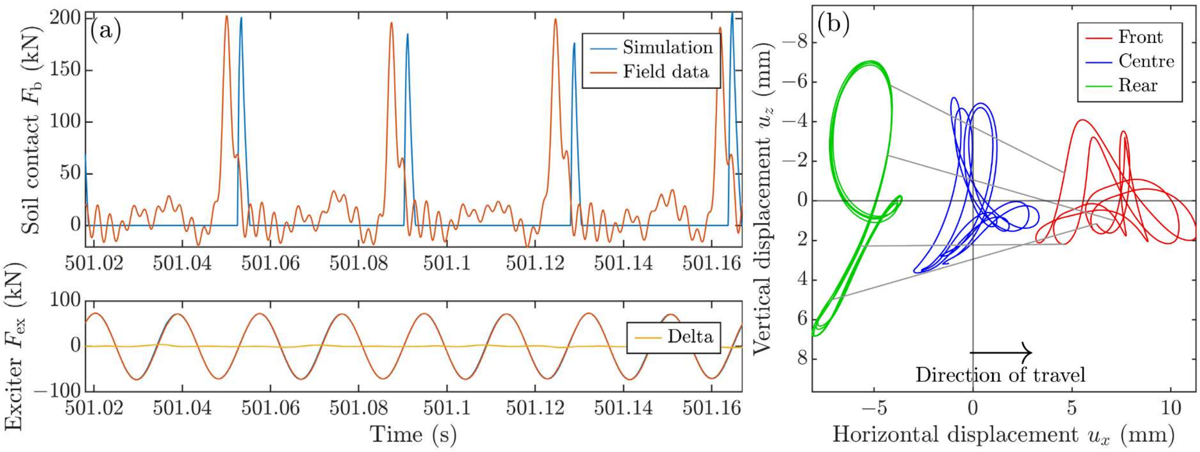

Figure 5. Time frame 2: (a) Comparison of soil contact force F_b and exciter force F_{ex} from simulation and field tests. (b) Orbital movement of the plate compactor from field tests (inflated rotation).

Time frame 3 shows a contrasting image to time frames 1 and 2. The unbalance's rotational direction changed, causing the front end to show larger displacement amplitudes compared to the rear end. The plate compactor's motion behaviour remains distinct and periodic over two exciter periods (as shown in Figure 6 (b)). However, in this case the mode of operation is not classified as 'double jump' but rather as a transition from 'loss of contact' to 'double jump' (Adam, 1996). Figure 6 (a) shows alternating impacts of low and high intensity. Additionally, the rotation of the plate compactor is more pronounced, resulting in a double impact on the soil. The two peaks of the field data's soil contact force also indicate this behaviour. With the given process parameters, the mechanical model cannot reproduce this mode of operation. The exciter frequency and thus the amplitude of the exciter force are relatively low. Therefore, the mechanical model does not transition from 'loss of contact' to 'double jump' regardless of the soil stiffness. Increasing the frequency changes the mode of operation to match the field data's mode of operation. This indicates that the transition areas between the modes of operation differ slightly between field tests and simulation. Additionally, due to its simplification, the mechanical model is unable to account for the rotation and double impact of the base plate.

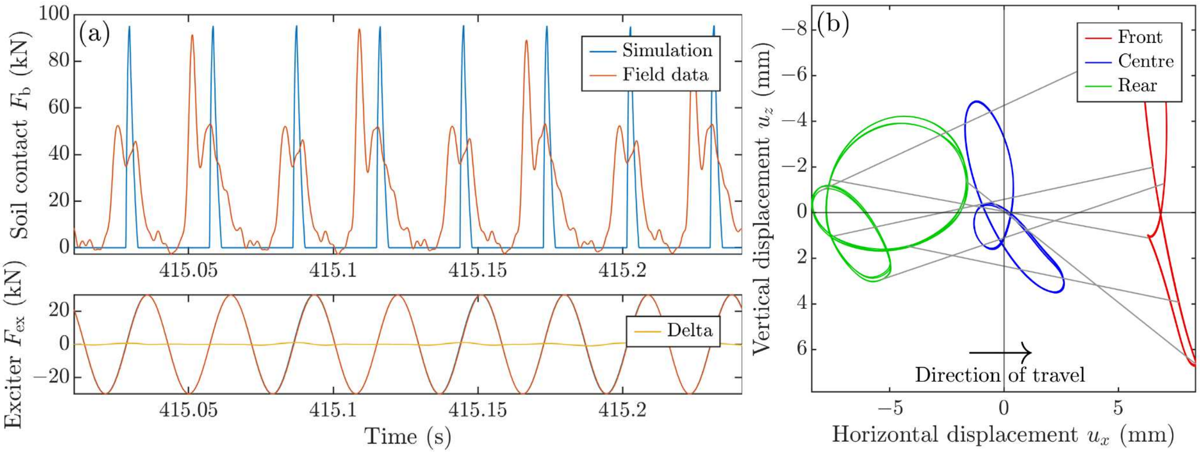

Figure 6. Time frame 3: (a) Comparison of soil contact force F_b and exciter force F_{ex} from simulation and field tests. (b) Orbital movement of the plate compactor from field tests (inflated rotation).

5. CONCLUSION

In this paper, the motion behaviour of a plate compactor of type WBB 530 was investigated during the compaction of a formation protective layer. The interaction between the plate compactor and the soil is compared to the results of a simplified mechanical model. The experimental data was collected during field tests. The study shows that, under certain conditions, the mechanical model can reliably reproduce the motion behaviour of the plate compactor. The model can also replicate the higher soil contact forces that occur during a second compaction pass over an already compacted test lane by increasing the soil stiffness. However, the transition areas between the different modes of operation, which depend on various process parameters, differ slightly between the mechanical model and the field tests. Moreover, the mechanical model is not suitable for reproducing the indistinctive motion behaviour observed during the field tests. The field data also shows that the test setup, including the plate compactor mount, should be improved to collect reliable data for a wider range of process parameters. Additional validation of the mechanical model with more distinctive measurement data could provide more information about the motion behaviour of the plate compactor that potentially enables an optimization of the compaction equipment.

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