

Comparison of simulation and field tests of subballast compaction with plate compactors during rail track rehabilitation

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ABSTRACT: The sufficient compaction of the subballast during track rehabilitation is a crucial process to improve the longevity of railways. For track-bound rehabilitation methods, plate compactors are used to ensure sufficient compaction of the subballast layer, as they can operate effectively in confined areas. Formation rehabilitation machines, such as Plasser & Theurer's AHM 800-R, are equipped with six plate compactors to facilitate this process. In Austria, the most used plate compactor, the Wimmer WBB530, consists of a frame and a dynamically decoupled vibrating base plate featuring a rotating mass-type exciter. As a relatively lightweight compaction device, the compaction of a subballast layer of up to 50 cm thickness may present a challenge to the Wimmer WBB530. Ensuring sufficient compaction is therefore a subject of significant interest. Previous investigations included field tests to monitor and analyze the motion behavior of the plate compactor. Additionally, a mechanical model was developed to simulate the motion behavior and analyze the interaction between the plate compactor and the soil during compaction. This paper compares the simulated motion behavior and soil interaction from the mechanical model with the data gathered from experimental field tests. The comparison shows that the model can adequately replicate the motion behavior of the plate compactor for specific process parameters. For these parameters, the model accurately determines the mode of operation during compaction and the interaction between the plate compactor and the soil, corresponding with the measured data. However, the measurements also showed that the plate compactor and its harmonic loading of the soil highly depends on a careful selection of process parameters.

KEYWORDS: Soil dynamics, modelling, motion analysis, plate compactor, subballast compaction.

1 INTRODUCTION

To preserve a well-functioning railway system and guarantee satisfactory railway traffic, it is crucial to minimize geometry deterioration and thus minimize frequent track maintenance. The quality of the subballast greatly affects the longevity of railway tracks as the subballast distributes the load from the tracks to a greater area and protects the natural subgrade from excessive load, which reduces the settlements of the subgrade (Indraratna, Rujikiatkamjorn and Salim, 2023).

As the track formation quality degrades naturally over time it is crucial to maintain it to increase its longevity. A very efficient method for track formation rehabilitation is a track bound rehabilitation machine like the AHM 800-R (AHM) from Plasser & Theurer – Export von Bahnbaumaschinen Gesellschaft m.b.H. (P&T). In track bound formation rehabilitation, the grid is lifted and the ballast as well as the subballast are removed and new layers are placed beneath the lifted track grid. This increases the efficiency of the rehabilitation process (Auer et al., 2008). The AHM is equipped with two excavation chains to remove the ballast and subballast material. The old ballast material is then crushed and processed to be reused as up to 50% of the new subballast material (the other 50% of the material must be certified subballast material). After excavation, a geotextile can be placed on the subgrade to reduce infiltration of the subgrade into the subballast. The new, mixed subballast material is then placed on the subgrade (respectively on the geotextile, if installed) with a layer thickness of approximately 50 cm (uncompacted) which is reduced to approximately 40 cm after compaction.

The compaction of the subballast layer is done by six Wimmer WBB 530 plate compactors working in parallel (see Figure 1). The limited workspace beneath the lifted track grid necessitates a small compaction device. However, the compaction of a 50 cm thick layer may pose a considerable challenge to the comparably lightweight plate compactors. This may result in irregular motion behavior and/or insufficient compaction of the subballast layer. Consequently, this may reduce the expected lifespan of the track formation.

Based on observations during field work P&T started a research project in cooperation with the TU Wien to analyze the motion behavior of the plate compactor, improve its efficiency

and the quality of the compaction. The research project included large scale field tests and a simplified mechanical model of the compactor-soil-interaction. This paper gives a brief overview of the field tests and the mechanical model and compares the results of these two parts of the research project.

As a result of the findings of the first research project P&T and TU Wien started a second research project which aims to develop a new and redesigned plate compactor to improve the subballast compaction even further. In the penultimate section of this paper, the prototype of the redesigned plate compactor is briefly introduced.

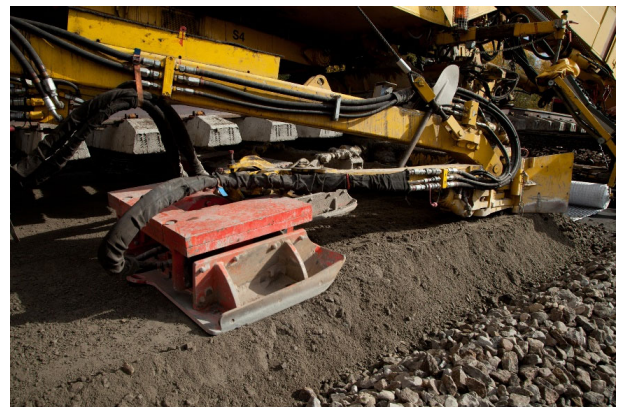


Figure 1. Plate compactor of the AHM 800-R during compaction.

2 FIELD TESTS

The field tests were conducted in a gravel pit located in Fischamend, Austria. The goal of the field tests was to monitor and analyze the motion behavior of the plate compactor. During the field tests, the plate compactor was attached to an excavator using a special mount (see Figure 2). The excavator was pulled along the test lanes to ensure slow and steady movement (equivalent to the travel speed of the AHM of approximately 70 m/h). The subballast material which was used for the test lanes consisted of regular subballast material from certified quarries in Austria. The layer thickness of the test lanes was about 40 cm comparably to the layer thickness of a railway track in Austria.



Figure 2. Plate compactor attached to an excavator (Sigmund, Pistol and Adam, 2023).

During the tests, the plate compactor was equipped with various sensors to track the process parameters and its motion behavior. The base plate was equipped with four MEMS 3D acceleration sensors around the exciter unit (see Figure 3). Additionally, one 3D acceleration sensor was placed on the frame. The imbalance position was monitored using four inductive proximity sensors to track its position during the field tests. Furthermore, the hydraulic cylinder, which applied vertical loads, was attached to a loading cell to monitor the applied force.

The field test program included four reference measurements and eight test runs. During the reference measurements the plate compactor was lifted and oscillated freely. Each test run was then carried out with different process parameters (e.g. variation in vertical loads, exciter frequency, rotational direction of the imbalance etc.).



Figure 3. Base plate equipped with acceleration sensors.

3 SIMULATION

In Pistol et al. (2022) a simplified mechanical model for the plate compactor was presented. The authors show that the model can sufficiently solve the contact problem between plate compactor and soil and is capable of simulating the three phases of operation (loading, unloading and separation). One of the most important simplifications in the model is that only vertical motion quantities (acceleration, velocity, displacement) are considered, as the plate compactor moves mainly in vertical direction and the loading of the soil is applied mostly in vertical direction. This simplification has been used in similar investigations for vibratory rollers and showed sufficient accuracy (Adam, 1996; Kopf, 1999).

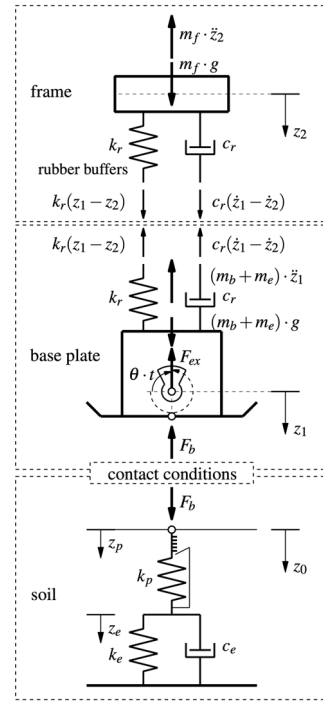


Figure 4. Mechanical model (Pistol et al., 2022).

Figure 4 shows a scheme of the mechanical model. The model consists of two subsystems, the soil and the plate compactor, which are connected through contact conditions. The plate compactor subsystem can be further divided into frame and baseplate. Frame and baseplate are connected by rubber buffers for vibration decoupling which are modeled using a Kelvin-Voigt Element. The distinction between the frame and the baseplate allows separate descriptions of the motion equations for each part (Pistol et al., 2022).

The motion equation of the frame can be described by the following Equation (1). The force in the rubber buffers F_r (which acts between frame and base plate) can be determined by summarizing damping and stiffness properties (see Equation (2)). All symbols used in Equations (1) to (6) are listed and described in Table 1.

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

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

The motion equation of the base plate is given in Equation (3). The exciter force F_{ex} can be determined using Equation (4). To apply the load of the plate compactor onto the soil and determine the interaction between the two subsystems, Equation (3) needs to be solved for the soil contact force F_b . Equation (5) shows the transformed motion equation of the base plate which can be solved by using F_r from Equation (2) and F_{ex} from Equation (4).

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

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

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

The soil subsystem is modeled with elastic-plastic material behavior. The (vertical) displacement z_0 comprises elastic and plastic components as shown in Equation (6). The elastic behavior is modeled with a Kelvin-Voigt element, while the plastic behavior is modeled with an elastic spring, which is only active during loading (Pistol et al., 2022). The parameters of the Kelvin-Voigt element are derived from the cone model proposed by Wolf (1994).

$$z_0 = z_e + z_p \quad (6)$$

The contact conditions between the two subsystems are dependent on the soil contact force F_b and define the interaction between plate compactor and soil. Three different phases of operation are defined through boundary conditions: loading, unloading and separation. Loading is characterized by an increase of the soil contact force F_b , unloading by a decrease of the soil contact force F_b and separation is defined by a soil contact force F_b equal to 0.

Table 1. Parameters and their symbols from the mechanical model.

| Parameter | Symbol | Unit |
|---|--------------|------------------|
| Soil dashpot coefficient (Kelvin-Voigt) | c_c | N/ms |
| Rubber buffer dashpot coefficient | c_r | Ns/m |
| Eccentricity of eccentric mass | e | m |
| Excitation frequency | f | Hz |
| Gravitational acceleration | g | m/s ² |
| Soil spring stiffness (Kelvin-Voigt) | k_c | N/m |
| Soil spring stiffness (plastic deformation) | k_p | N/m |
| Rubber buffer spring stiffness | k_r | N/m |
| Mass of base plate | m_b | kg |
| Eccentric mass | m_c | kg |
| Mass of frame | m_f | kg |
| Soil contact force | F_b | N |
| Excitation force | F_{ex} | N |
| Force in the rubber buffers | F_r | N |
| Time | t | s |
| Vertical displacement of soil | z_0 | m |
| Vertical displacement of base plate | z_1 | m |
| Vertical velocity of base plate | \dot{z}_1 | m/s |
| Vertical acceleration of base plate | \ddot{z}_1 | m/s ² |
| Vertical displacement of frame | z_2 | m |
| Vertical velocity of frame | \dot{z}_2 | m/s |
| Vertical acceleration of frame | \ddot{z}_2 | m/s ² |
| Elastic deformation of soil | z_e | m |
| Plastic deformation of soil | z_p | m |
| Circular frequency of excitation | θ | rad/s |
| Phase shift | φ_0 | rad |

4 RESULTS AND COMPARISON

The analysis of the data collected during the field tests indicates that the hydraulic pressure of the excavator was not sufficient to supply both, the vertical loads applied by the hydraulic cylinder and the exciter frequency, equally. Therefore, high vertical loads could only be applied during phases of lower frequencies and vice versa.

Furthermore, the field test data indicates that the motion behavior and mode of operation of the plate compactor is highly dependent on the process parameters. The mode of operation is especially influenced by the applied vertical loads and the exciter frequency. The data shows that the soil contact force was very low during sections with low vertical loads. After applying a certain vertical load, the data indicates a substantial increase in soil contact force. This can be attributed to a suboptimal mounting construction, which lifted the plate compactor off the ground in case of insufficient vertical loads.

After surpassing this point, low vertical loads cause an indistinctive motion behavior of the plate compactor. As the vertical load increases, the motion behavior becomes more periodic and distinctive (Sigmund, 2021).

For a comparison between the simulation and the field test data, two different time frames were selected. Time frame 1 shows a section with medium vertical loads, while time frame 2 shows a section with high vertical loads, thus much lower exciter frequency and a change of the rotational direction of the unbalance. Table 2 summarizes the parameter values of both time frames.

Table 2. Parameter values for the selected time frames.

| Parameter | Unit | Time Frame 1 | Time Frame 2 |
|-----------|------------------|--------------|--------------|
| c_c | N/ms | 2.3e5 | 2.1e5 |
| c_r | Ns/m | 15000 | 15000 |
| e | m | 0.032 | 0.032 |
| f | Hz | 51 | 35 |
| g | m/s ² | 9.81 | 9.81 |
| k_c | N/m | 5.7e7 | 4.9e7 |
| k_p | N/m | 3.2e8 | 2.8e8 |
| k_r | N/m | 2e6 | 2e6 |
| m_b | kg | 295 | 295 |
| m_c | kg | 20 | 20 |
| m_f | kg | 385 | 385 |

The field test data indicates that during both time frames the plate compactor shows a distinctive, periodic motion behavior, which is displayed in the orbital displacement of the plate compactor in the Figure 5. During time frame 1 (Figure 5 (a)) the front of the plate compactor shows significantly larger amplitudes compared to the rear. This can be attributed to the imbalanced design of the plate compactor and the rotational direction of a single imbalance. The different amplitudes between the front and the rear lead to tilting of the base plate. The gray lines in Figure 5 represent the tilting of the base plate, although they have been exaggerated due to the distance between the front and rear. Due to the change of the rotational direction during time frame 2 (Figure 5 (b)), the front amplitudes in this time frame are much larger compared to the rear amplitudes. This results in an even larger tilt angle of the base plate.

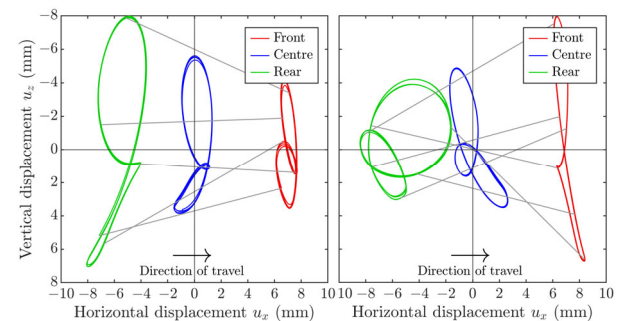


Figure 5. Orbital displacement for: (a) time frame 1; (b) time frame 2.

Figure 6 compares the soil contact force F_b between the measured field test data and the simulation. The gray line displays the exciter force F_{ex} which is aligned between both data sets. The simulation 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 with the soil and lifts off the ground for one full exciter 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 (between field data and simulation) at which the impact occurs can be explained by the slight tilting of the base plate during the field tests, resulting in an earlier contact initialization with the soil.

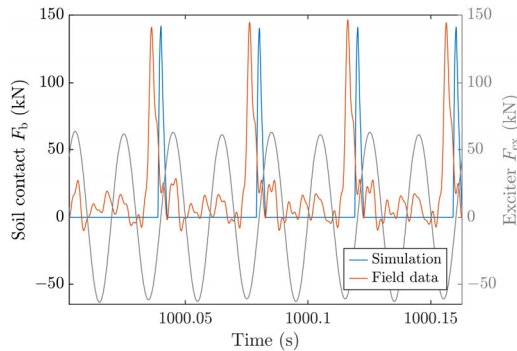


Figure 6. Comparison of the soil contact force F_b for time frame 1.

The comparison between the soil contact force F_b of field tests and simulation of time frame 2 is displayed in Figure 7. Even though the field test data still indicates a distinctive and periodic motion behavior over two exciter periods, the simulation does not show the same periodicity, as the simulation indicates a periodic behavior over one exciter period. However, the mode of operation from the field tests is not classified as ‘double jump’ but rather as a transition from ‘partial uplift’ to ‘double jump’ (Adam, 1996). Additionally, the tilting of the base plate is more pronounced in this time frame, resulting in a double impact on the soil. The two peaks in the field test data’s soil contact force also indicate this behavior. With the given process parameters, the simulation cannot reproduce this mode of operation. The exciter frequency and thus the amplitude of the exciter force are relatively low. Therefore, the mode of operation of the simulation does not transition from ‘partial uplift’ to ‘double jump’ regardless of the soil stiffness. Increasing the frequency changes the simulation’s mode of operation to match the mode of operation from the field test data. This indicates that the transition zones between the modes of operation vary slightly between field tests and simulation. Additionally, due to its simplification, the mechanical model is unable to account for the tilting and double impact of the base plate.

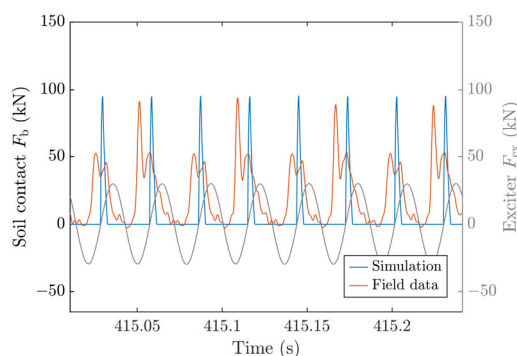


Figure 7. Comparison of the soil contact force F_b for time frame 2.

5 PLATE COMPACTOR REDESIGN

The findings from the experimental field tests and the simulation provided deeper insights into the motion behavior of the plate compactor. Based on these findings, a new research project has been started to develop a prototype of a new plate compactor. Figure 8 shows the prototype both without (left) and with (right) additional ballast. For research purposes the size and weight of the prototype has been increased, as both the size

of the base plate as well as the vibrating mass of the plate compactor play a critical role in compaction quality. Moreover, the prototype features a newly developed exciter unit composed of six imbalances (respectively three directional oscillators), designed to enhance compaction energy. This enables different configurations for amplitude and frequency during field tests (Barbir, 2025).

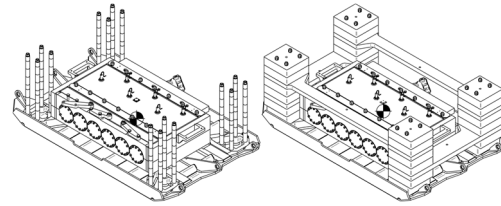


Figure 8. Prototype of the new plate compactor without/with ballast (Barbir, 2025).

6 CONCLUSION AND OUTLOOK

The motion behavior of a plate compactor of type WBB 530 was investigated in field tests during the compaction of a layer of subballast material. Furthermore, a simplified mechanical model of the compaction process was developed. This paper compared the interaction between the plate compactor and the soil regarding the results of a simulation and experimental data. The simulation reliably reproduces the characteristic motion behavior of the plate compactor. However, the transition zones between the distinct modes of operation, which are contingent on various process parameters, show slight discrepancies between the simulation and the field tests. Furthermore, the mechanical model is not suitable for reproducing the indistinctive motion behavior observed during some test runs of the field tests. Based on the findings from the field tests, a redesign of the plate compactor was initiated. The new prototype features a redesigned exciter unit and modifications to the size and mass of the plate compactor. The redesign of the plate compactor aims to increase the compaction quality and efficiency of subballast compaction. Additionally, the new plate compactor will be equipped with the necessary instrumentation for the future development of a continuous compaction control.

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