Compaction energy as an indicator for ballast quality

Olja BARBIR[1], Bernhard ANTONY[2], Fritz KOPF[3], Johannes PISTROL[4], Dietmar ADAM[5], Florian AUER[6]

[1,4,5]TU Wien, Institut für Geotechnik, Vienna, Austria
[2,6]Plasser & Theurer, Export von Bahnbaumaschinen, Gesellschaft m.b.H. Vienna, Austria
[3]FCP - Fritsch, Chiari & Partner ZT GmbH, Vienna, Austria
Corresponding Author: Olja Barbir (olja.barbir@tuwien.ac.at)

Abstract

The tamping process is the core maintenance activity in ballasted track. It is crucial to the economical service life of the track and essential in restoring track geometry for safe train operations. Over the history of railways, the process advanced from manual to mechanical work and the working parameters were optimised based on empirical observations. Nowadays, the tamping process is the result of experience and knowledge from railway operations worldwide. The current practice of track maintenance is entirely based on modern tamping machines that provide a wide range of advanced functions, such as the 4-sleeper-tamping mechanism, dynamic track stabilisation and combined levelling and lining of the tracks. The purpose of this research is to determine and optimise the relevant parameters for successful ballast compaction and to ensure durability of the track geometry after tamping. Conducted investigation is based on in-situ measurements followed by a parameter study based on the semi-analytical mechanical model of the tamping unit-ballast matrix interaction. In the scope of this research project, a comprehensive study of different ballast conditions is carried out in order to improve ballast serviceability and track life cycle performance.

Keywords: track tamping, track ballast compaction, semi-analytical ballast modelling

1. Introduction

During the tamping process, the tamping tines interact with the ballast matrix, transferring the displacement caused by the dynamic excitation overlapped with the extension in the hydraulic cylinder to the ballast, compacting it under the sleeper. This interaction was observed and measured in-situ in several locations in Austria. Conclusions regarding differences in response and resistance to compaction of both new and fouled ballast material are made and presented in this paper.

2. Experimental approach and primary results

Within the framework of a joint research project of Plasser & Theurer, Export von Baumaschinen, GmbH, and the Institute of Geotechnics, TU Wien, the „Dynamic Tamping Express 09-4X E³" tamping machine was equipped with a number of strategically positioned sensors (Figure 1) in order to describe the interaction of the tamping tines with the ballast. Strain gauges (Figure 1; red) were applied and used to measure the lowering and lateral tine forces. Accelerometers (Figure 1; blue) placed on the upper point of the tamping arm allowed a precise calculation of the tine oscillation amplitude in a local coordinate system. In conjunction with the pressure (Figure 1; yellow) and elongation measurement at the hydraulic cylinders (Figure 1; green) the tamping process could be fully documented and subdivided.

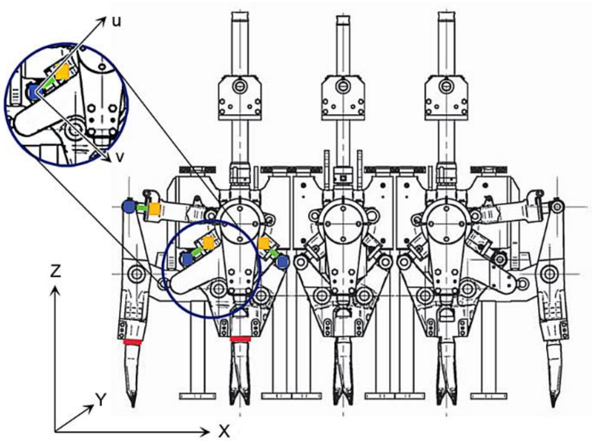

Fig. 1: Position of the measuring units [1]

Based on the measurements described an initial approach towards successful data analysis was chosen in form of a load-displacement curve i.e. lateral force-oscillation displacement diagram, presenting a single cycle during the tamping process (Figure 2). This newly developed method of dynamic measurement analysis [6] allows an insight into seven tamping parameters essential for a successful data evaluation:

- oscillation amplitude (1)
- maximal lateral force (2)
- ballast matrix stiffness/response during loading (3) and unloading (4)
- energy transferred into the ballast (area under the curve) (5)
- points of tamping tine - ballast contact - begin (6) and loss of contact (7)

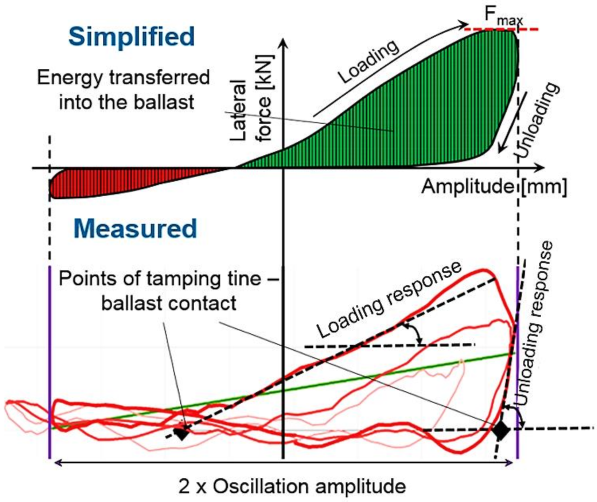

Fig. 2: Simplified load – displacement curve (above), and the curve as a result of the conducted measurements (below) [1]

The tamping process subdivision (Figure 3) enables the determination of energy consumption per category, with a particular emphasis on the squeezing movement described as the closing movement of the tines around the sleeper that contributes mainly to ballast compaction.
The operation of the Dynamic Tamping Express 09-4X E³ was monitored at different locations in Austria by means of the measuring system described above, resulting in an extensive series of collected measurement data.

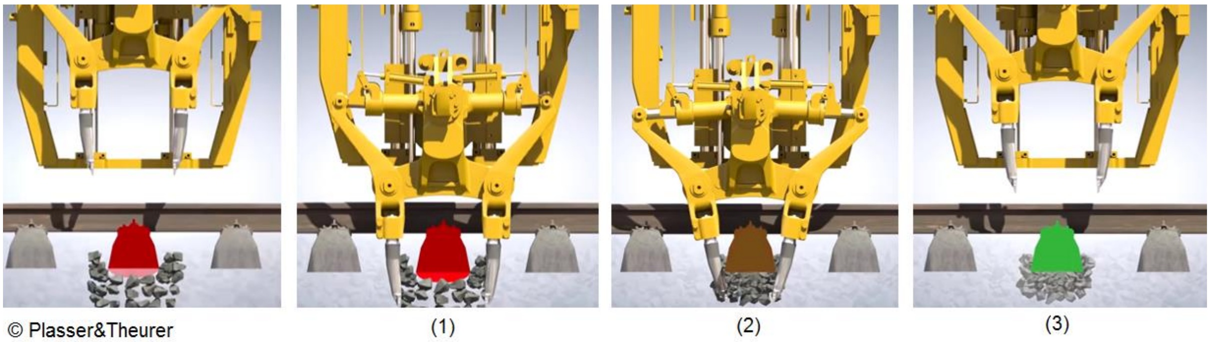

Fig. 3: Tamping process subdivision: (1) ballast penetration, (2) squeezing movement, (3) lifting followed by the relocation of the tamping unit [2]

Depending on the observed part of the tamping process the load-displacement curve can take several different shapes. During initial contact, while penetrating the ballast, the diagram displays a typical elliptical shape, caused by the unsymmetrical shape of the tine. During the course of a squeezing movement, the tamping tines compact the ballast beneath the sleeper, forming a typical curve, as can be seen in Figure 2. The eccentricity of the curve is attributed to the squeezing velocity, where the negative part of the curve would decrease with the increase of velocity. However, the velocity has to be kept under certain limits for the tamping tine to remain in contact with the ballast for the time required for the transfer of energy (minimal required impulse duration - 0.8 to 1.2 seconds) [3].

3. Semi-analytical approach (tamping ballast interaction model)

Apart from the in-situ measurements a semi-analytical mechanical model (Figure 4) of the tamping unit – ballast matrix interaction has been developed. The mechanical model consists of two fundamental parts:

- Tamping unit
- Ballast matrix model

3.1 Tamping unit

The tamping unit is modelled as a simple system of rods with a dynamic excitation overlapped by a hydraulic cylinder movement modelled with a variable rod length. It is additionally extended with a friction element, incorporated into the upper part of the tamping arm (Figure 4).
The model is based on the exact geometry of the Dynamic Tamping Express 09 4X E³ [2].

3.2 Ballast matrix model

The ballast matrix model used to show ballast compaction under the sleeper is made up of three components (Figure 4):

- Kelvin-Voigt model - elastic deformation of the ballast matrix
- Plastic spring - plastic deformation of the ballast matrix
- Gap-closing acceleration

During the tamping process, the motion of the tamping tine is imposed on the ballast, thereby inducing deformation of the matrix. The elastic share of this deformation is modelled by a semi-infinite truncated cone for horizontal translation, where the half space of an idealised homogeneous soil is represented by the Kelvin-Voigt model [4], [7]. The model consists of a purely elastic spring and a purely viscous damper connected in parallel. The stiffness of the spring k_e and the dashpot coefficient c_e for the translational cone in vertical motion rotated by 90 degrees to model the tine motion can be calculated with the following set of equations for compressible soils:

$$k_e = \frac{G \cdot b_0}{1-\nu}\left[3{,}1 \cdot \left(\frac{a_0}{b_b}\right)^{0{,}75} - 1{,}6\right]$$

$$c_e = 4 \cdot \sqrt{2\rho \cdot G \frac{1-\nu}{1-2\nu}} \cdot a_0 b_0$$

This approach ensures that ballast properties are described by two soil parameters customarily used in soil dynamics: shear modulus G and Poisson´s ratio ν, as well as the soil density ρ. The responsive stiffness of the ballast matrix is also dependent on the contact area of the tine with the matrix, described by half of the length and width of the tamping tine area a_0 and b_0.The soil model has been extended by an additional plastic spring with the constant spring stiffness k_p (Figure 4), modelling the plastic deformation of the ballast matrix, i.e. its compaction under the sleeper. In case of loss of contact a gap appears between the tamping tine and the ballast matrix. Ballast stones strive to fill this void, causing the tine to come in contact with the ballast matrix sooner in the following cycle. The influence of the ballast stone movement during the loss of contact is calculated as the gap-closing acceleration a_{gc} (Figure 4) [2].

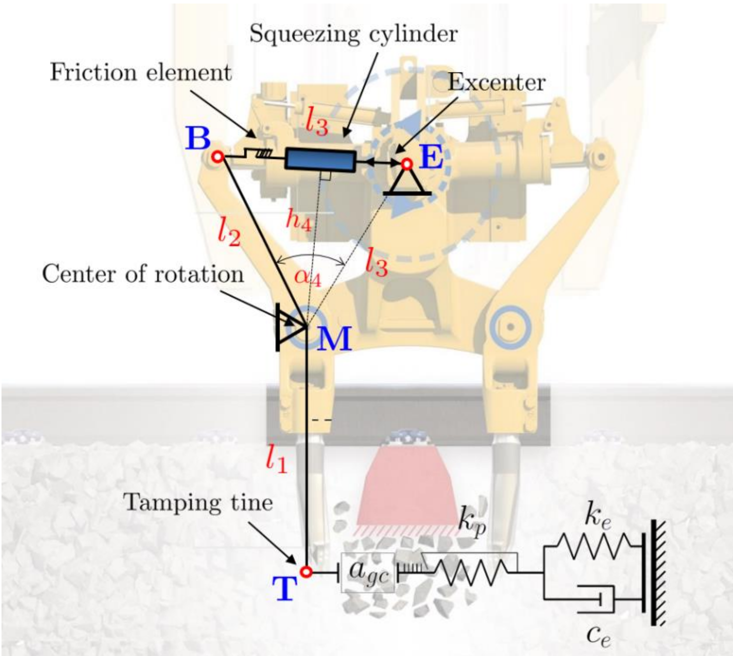

Fig. 4: Mechanical model of the tamping unit lowered into work position and of the ballast matrix with its three components [2]

Serving as a means of confirmation and comparison with the conducted in-situ measurements, the model also allows the development of a condition-based tamping process.

4. Results

Based on an extensive series of measurements, a detailed graphical and statistical analysis of the in-situ collected data was carried out and compared to the semi-analytical approach. In order to gain insight into the entire squeezing process or to see how the energy of compaction and the ballast stiffness change during the squeezing movement, every single cycle, i.e. load-displacement curve was plotted and stacked behind one another, forming the so-called waterfall diagrams (Figure 5). These show the apparent distinction in the shape of the load-displacement curve in different ballast conditions, as well as the progress of ballast matrix compaction. As the ballast compaction progresses, the required lateral force as well as the steepness of every following curve increase, indicating an increase of the ballast matrix stiffness. Additionally, average energy per cycle values are examined, showing a significant increase of energy towards the end of a squeezing movement. This implies successful ballast compaction under the sleeper.

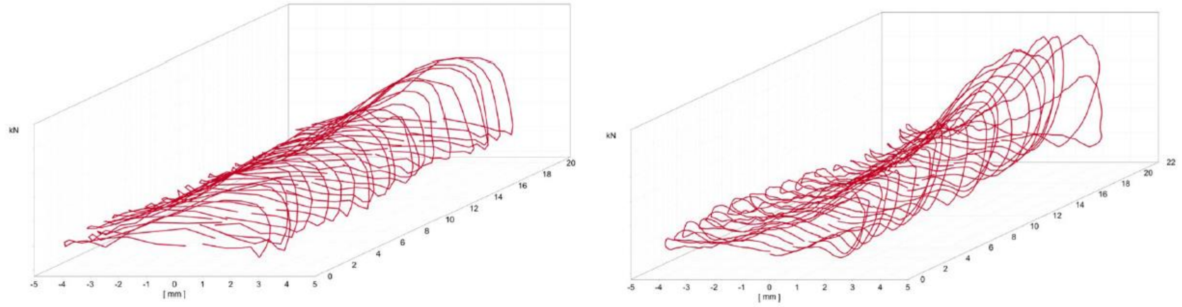

Fig. 5: Waterfall diagram showing stacked consecutive load–displacement curves for new (left) and fouled (right) ballast conditions

4.1. Tamping parameter comparison

Following data analysis of the selected in-situ measurements first reference values can be established for the two edge cases of the track condition:

- Track reconstruction / new ballast conditions
- Track maintenance / fouled ballast conditions

The highest level of divergence can be noted for the following four tamping parameters: maximum force, energy per squeezing movement and loading and unloading response of the ballast matrix. (Table 1).

Table 1: Parameter comparison of the two ballast conditions

Tamping force	[kN]	New < Fouled
Energy per squeezing movement	[J/s]	New < Fouled
Loading response	[MN/m]	New < Fouled
Unloading response	[MN/m]	(-) New (+) Fouled

A significant difference can also be noted in the shape of the load-displacement curves (Figure 6), confirming a clearly higher tamping force in fouled ballast condition, as well as a difference in the response of the ballast matrix in different conditions. This can be explained by a higher level of smaller gain-sized particles in fouled ballast, making it more resistant to compaction. The negative unloading response of the ballast matrix in new ballast conditions can be attributed to the elasticity of the new ballast, allowing the tamping tine to continue its motion during compaction even after the maximal force has been reached.

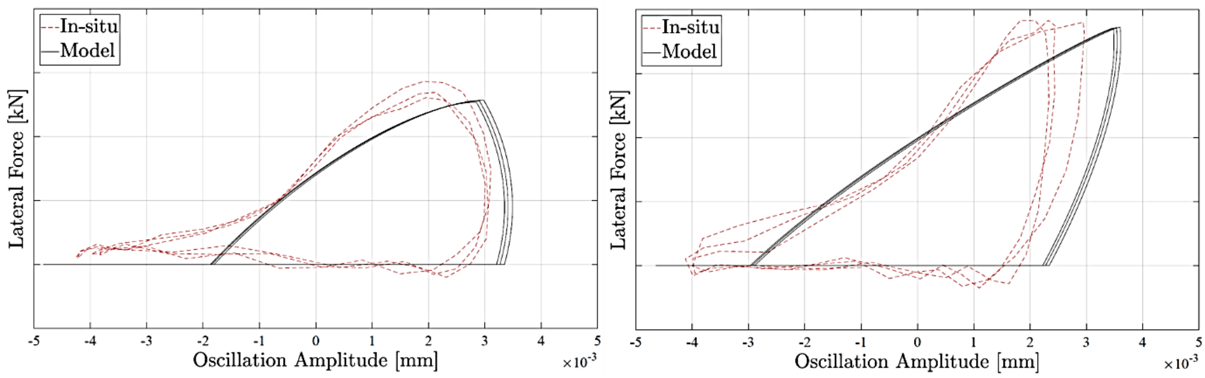

Fig. 6: Load-displacement curves of the two selected in-situ measurements compared to the semi-analytical approach (new ballast (left), fouled ballast (right)) [2]

Using the mechanical model described, load-displacement curves of two selected in-situ measurements with new and fouled ballast conditions are compared to the curves obtained employing the semi-analytical approach (Figure 6). A high level of correlation between the two approaches can be observed, confirming the reliability of the developed model. The same model is used to display both ballast conditions, and the ballast fouling process is presented as a decrease of the ballast elasticity. In the semi-analytical approach, this phenomenon is modelled as an increase of the elastic spring stiffness in the Kelvin-Voigt model that progresses with the fouling of the material, making it less elastic and more resistant to compaction.

5. Conclusions

The outlined parameter deviation (Table 1) not only clearly indicates the ballast condition at every location, but can also be used as a tool in the development of a condition-based tamping process, where the condition of the ballast is "recognised" by the tamping machine and the machine parameters are modified accordingly to increase the quality of the whole track system while reducing costs by extending maintenance cycles. The mechanical model developed can depict both edge cases of the ballast condition as well as the progression of ballast fouling. It is used as a reliable tool for a parameter study as well as a determination of the tamping parameters that should be adapted according to the condition of the ballast material at any given location.

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