SEMI-ANALYTICAL APPROACH TO BALLAST BED MODELLING DURING COMPACTION

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ABSTRACT

Throughout the world, the condition of the ballast bed is one of the most important parameters for a safe and economical operation of railway systems. Better knowledge of ballast condition provides an advantage in defining the optimum time for ballast bed cleaning or renewal. Tamping process is the core maintenance activity in ballasted track and it is crucial to the economical service life of the track and essential in restoring the track geometry for safe train operations. During the tamping process, the tamping tines interact with the ballast matrix, transferring the displacement caused by the dynamic excitation to the ballast, compacting it under the sleeper. This interaction is observed and measured in-situ within the framework of this research project. Serving as a mean of comparison and confirmation with the conducted in-situ measurements, a semi-analytical model of the tamping unit – ballast matrix interaction is developed. The tamping unit is presented by a simple system of rods with a dynamic excitation overlapped by a hydraulic cylinder movement modelled with a variable rod length. The ground model is based on a semi-infinite truncated cone for vertical translation, the half space being represented by the Kelvin-Voigt model [5], which consists of a purely elastic spring and a purely viscous damper connected in parallel. The soil model has been extended by an additional plastic spring, modelling the plastic deformation of the ballast matrix, i.e. its compaction under the sleeper. The ballast model described presents a reliable method of modeling non-cohesive soils, and can as such be implemented on other granular materials under dynamic loading.

Keywords: Track Tamping, Track Ballast Compaction, Semi-analytical 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 is 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

The operating principle of a tamping machine i.e. tamping unit (Figure 1) is lifting the track up to the level determined by previous measurements and simultaneously position it laterally. Once the track is in the intended position, the tamping tines penetrate the ballast and the tamping process begins. The squeezing movement begins subsequently and is defined as a closing movement of the tines around the sleeper with the objective of refilling the gap created beneath the sleeper and compacting the ballast. The non-synchronous tamping principle, in which the tamping is performed, described as movement of all tamping tines with the same force, independent of the path, together with directional vibrations, ensures a uniform ballast compaction. [1]

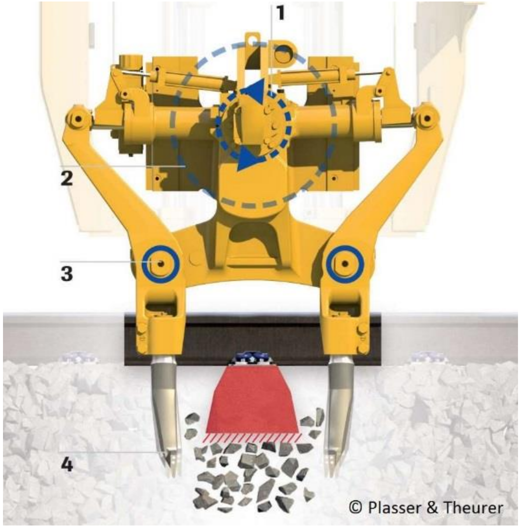

Figure 1. *Tamping unit lowered into work position: (1)Vibration by eccentric shaft, (2)Power reserve from balance weight, (3)Fixed pivot, (4)Stable amplitude*

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 2) in order to describe the interaction of the tamping tines with the ballast. Strain gauges (Figure 2; red) were applied and used to measure the lowering and lateral tine forces. Accelerometers (Figure 2; 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 2; yellow) and elongation measurement at the hydraulic cylinders (Figure 2; green) the tamping process could be fully documented and subdivided [2].

2.1. Experimental results

An initial approach towards successful data analysis implies a newly developed method of dynamic measurement analysis [6], the load-displacement curve i.e. lateral force-oscillation displacement diagram, presenting a single cycle during the tamping process (Figure 3). This presentation 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)

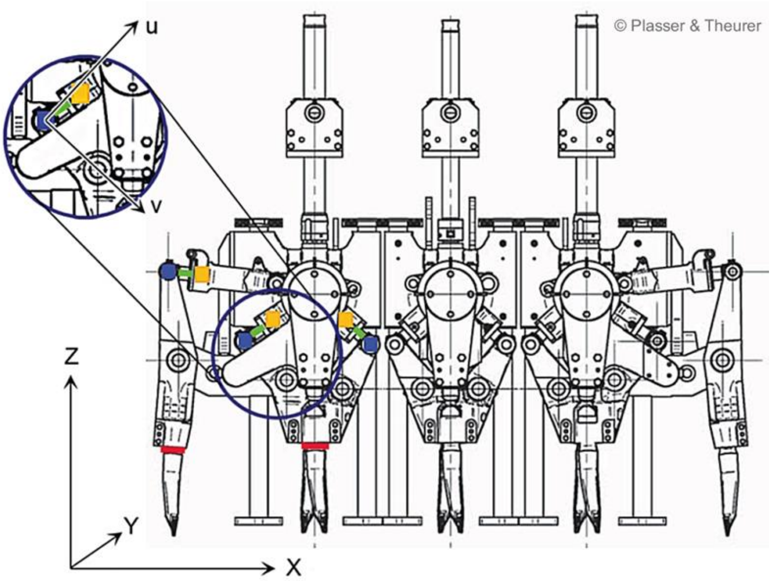

Figure 2*. Position of the measuring units[2]*

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 3. 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)[7].

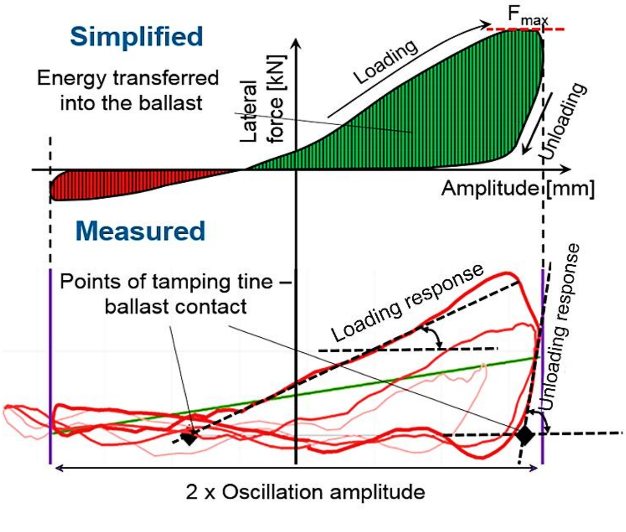

Figure 3*. Simplified load – displacement curve (above), and the curve as a result of the conducted measurements (below)[1]*

3. TAMPING UNIT - BALLAST MATRIX INTERACTION

A semi-analytical mechanical model of the tamping tine - ballast interaction during the squeezing movement is developed and is used as a tool for future development of a condition based tamping process. The mechanical model consist of two fundamental parts – the tamping unit and the soil or the ballast matrix model, focusing especially on the interaction between two parts, and on the tamping tine - soil contact conditions. The calculations are done using Matlab R2017b.

The calculation of all state variables is time dependent, based on the selected sampling rate and time step. Due to the semi-analytical calculation, a vector is calculated for each state variable, portraying their development throughout the squeezing process modeled. The simulation time of 1 second is selected based on the state-of-the-art tamping machine characteristics, working with a squeezing time ranging from 0.8 to 1.2 seconds.

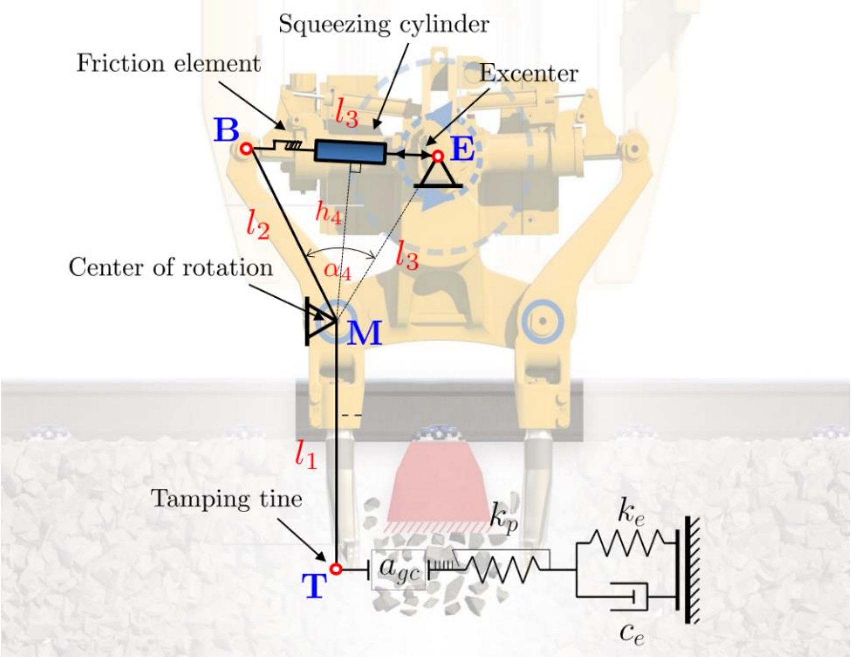

Figure 4. Mechanical model of the tamping unit – ballast matrix interaction[2]

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 E^3" [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, half space of an idealized homogeneous soil is represented by a purely elastic spring and a purely viscous damper connected in parallel
- 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.

3.3. Mechanical model operating phases

The semi-analytical approach is able to model both the displacement and force-controlled motion of the tamping unit, as well as all three operating phases of one cycle during the squeezing process:

- Loading – tamping tine in contact with the ballast matrix, both elastic and the plastic segments of the model are activate (compressed).
- Unloading – backward movement of the tamping tine, still in contact with the ballast matrix. The elastic spring stretches back, modelling the elasticity od the ballast matrix, while the plastic spring remains „locked“, modelling the remaining plastic deformation of the matrix, i.e. ballast compaction under the sleeper.
- Withdraw – tamping tine loses contact with the ballast matrix and reaches back before the next cycle begins. Following the loss of contact between the tamping tine during its backwards movement and the ballast matrix, a vertical ballast wall forms between the two model components. In order to enable the modelling of ballast grains motion during this phase of the cycle, an acceleration of the ballast stones during loss of contact i.e. during withdraw a_{gc} (Figure 4) is calculated. Implementation of the "gap closing acceleration" enables calculation of the exact ballast matrix position before the tamping tine reaches it again and the next cycle begins.

This approach grants a possibility to model all of the different ballast conditions and phenomena measured in-situ, ranging from new and clean to the fouled ballast bed conditions, as well as a verification of the in-situ measured load-displacement curves.

4. RESULT 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 between the two edge cases 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), as well as in the shape of the load-displacement curves (Figure 5).

Correlation between the in-situ and the semi-analytical approach can be observed, confirming the reliability of the developed model (Figure 5). 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.

***Table 1**. Parameter comparison of the two ballast conditions[1]*

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

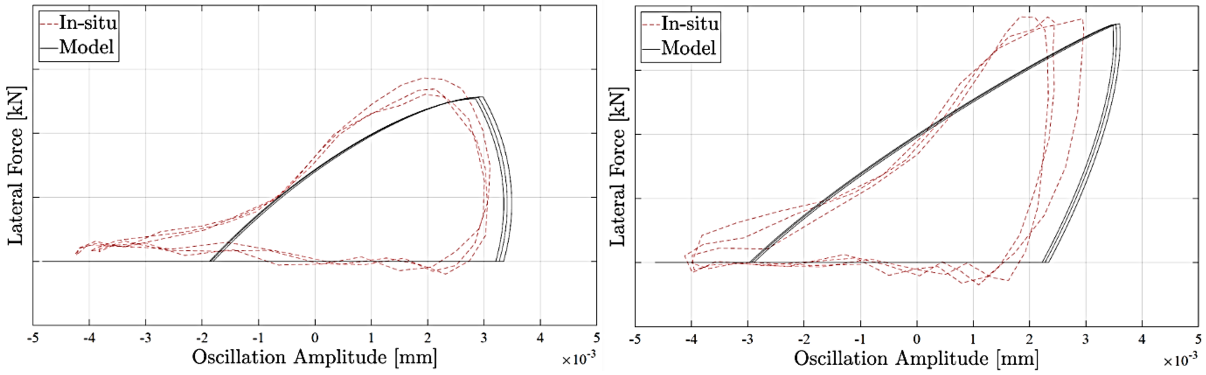

Figure 5*. Load-displacement curves of the two selected in-situ measurements compared to the semi-analytical approach (new ballast (left), fouled ballast (right))[1]*

CONCLUSION

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 s determination of the tamping parameters that should be adapted according to the condition of the ballast material at a given location (condition-based tamping). Tamping process adjusted to the in-situ ballast condition would increase the probability to achieve the optimum ballast compaction. Better knowledge of ballast condition provides the infrastructure manager the additional advantage of defining the optimum time for ballast bed cleaning or renewal, in addition to the increase of quality of the whole track system while reducing costs by extending maintenance cycles.

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