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Soil dynamic behavior of track ballast - experimental and semi-analytical verification

Comportement dynamique du sol du ballast de voie - vérification expérimentale et semi-analytique

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ABSTRACT: 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. Tine oscillations during tamping trigger the reposition of the ballast grains in the search of denser ballast matrix packing, thus providing a compacted ballast bed by increasing its bulk density. Tamping tines interact with the ballast matrix, transferring displacements caused by the dynamic excitation to the ballast, compacting it under the sleeper. Lateral forces and compaction energy, together with the loading and unloading response of the ballast matrix during compaction are used to determine the ballast condition in-situ. Serving as a mean of comparison with the conducted in-situ measurements and confirmation of the ballast condition definitions made, a semi-analytical model of the tamping unit – ballast matrix interaction has been developed. The mechanical model is used to simulate different ballast conditions in order to optimize the ballast life cycle and improve the understanding of ballast behavior under cyclic loading.

RÉSUMÉ : Le processus de bourrage est l'activité principale de maintenance des voies ballastées et il est crucial pour la durée de vie économique de la voie et essentiel pour restaurer la géométrie de la voie pour des opérations ferroviaires sûres. Les oscillations des dents lors du bourrage déclenchent le repositionnement des grains de ballast à la recherche d'un garnissage matriciel de ballast plus dense, fournissant ainsi un lit de ballast compacté en augmentant sa densité apparente. Les dents de bourrage interagissent avec la matrice de ballast, transférant les déplacements provoqués par l'excitation dynamique au ballast, le compactant sous la traverse. Les forces latérales et l'énergie de compactage, ainsi que la réponse de chargement et de déchargement de la matrice de ballast pendant le compactage sont utilisées pour déterminer l'état du ballast in situ. Servant de moyen de comparaison avec les mesures in-situ réalisées et de confirmation des définitions des conditions de ballast effectuées, un modèle semi-analytique de l'interaction unité de bourrage - matrice de ballast a été développé. Le modèle mécanique est utilisé pour simuler différentes conditions de ballast afin d'optimiser le cycle de vie du ballast et d'améliorer la compréhension du comportement du ballast sous charge cyclique.

KEYWORDS: track tamping, ballast compaction, ballast bed condition, mechanical model

1 INTRODUCTION

An important step towards further improvement of the state-of-the-art track tamping process is to combine the significant technological progress made over the last decades with geotechnical knowledge, focusing on track ballast behavior and characteristics as well as on the tamping machine – ballast interaction. Technology-enabled improvement in the field of track tamping alone is insufficient and cannot be utilized fully unless an in-depth understanding of the soil dynamic behavior of track ballast during tamping as well as of ballast bed condition is available. Geotechnical, experimental and modelling aspects of track tamping and ballast behavior have been considered in the scope of this research project and are described in the following chapters.

2 GEOTECHNICAL ASPECTS

Non-cohesive coarse-grained soils are compacted primarily by overcoming grain-to-grain friction, usually as a result of short-term dynamic effects such as roller or vibratory compaction, track tamping or dynamic track stabilization. Result of successful compaction is observed in the increase of bulk density and decrease of the void ratio in the affected area. In-situ determination of non-cohesive soil bulk density is a very challenging task. Continuous compaction control (CCC) methods have been developed for several dynamic soil compaction methods, i.e. oscillating rollers. Operating principle of track maintenance machines, however, dictates that the optimum final compaction has to be achieved after a single machine employment – this can only be achieved if the process is condition-based and the tamping parameters such as tamping time, pressure and number of insertions can be adapted to the ballast bed condition encountered in-situ (Barbir 2022).

Ballast bed condition changes over time due to several factors:

- breakdown of ballast particles due to mechanical traffic loading forces
- particle infiltration from the surface (coal or iron ore, dust, dirt)
- sleeper wear
- infiltration from the sub-ballast and the subgrade

Independent of the source, all of the above-mentioned changes of the ballast bed, usually described by the technical term ballast contamination, wear or ballast fouling, influence its soil mechanical properties. Following the progress of ballast fouling, the ballast bed bearing capacity, as well as its ability to withstand significant compressive stresses reduces, mainly as a result of reduced friction between the grains, causing irregular settlements and deviations from the nominal track geometry.

Several ballast bed condition assessment methods are known and used throughout the world. All of them, however, require in-situ sampling followed by laboratory tests, reducing track availability and making additional track closure necessary, thus making the determination of ballast condition a time-consuming and challenging task. Apart from the practical reasons, existing ballast bed condition determination methods only give a selective overview of the condition of the ballast bed, even if they do provide detailed information about the ballast matrix. Some of the existing methods or factors determining the level of ballast fouling are the fouling index, percentage of fouling, percentage void contamination, void contaminant index, relative ballast fouling ratio and ballast breakage index (Barbir 2022). Apart from the listed, an additional approach is to determine the ballast bed condition based on the Ground-penetrating radar (GPR) measurements. Given that it is a non-destructive method of surveying the superstructure at comparatively high speeds, it is increasingly used to monitor track condition. The difference between different ballast conditions is primarily due to moisture trapped in dirty sections. One of the major advantages of the GPR is that it provides information on the condition of the ballast bed continuously rather than at selected measurement points. However, a great deal of effort and experience is subsequently required to interpret the data correctly.

Significantly more precise and reliable results could be achieved if the condition of the ballast bed could be determined on-the-spot, i.e. directly during track tamping by tamping machine itself, making further automation of the tamping process by developing a *Smart tamping tool*, possible. Adapting decisive tamping parameters to the ballast condition would increase the efficiency of the maintenance work and optimize the ballast life cycle.

3 EXPERIMENTAL APPROACH

A measurement system implemented directly to the tamping unit is developed especially for the purpose of in-situ ballast condition determination. A tamping machine utilized for the described measurements was equipped with strain gauges (Figure 1; red) that are 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 is divided into separate phases.

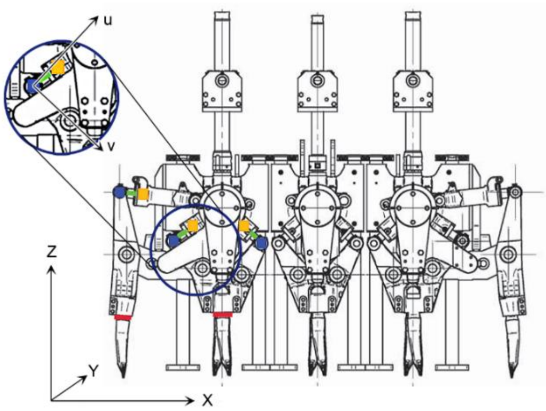

Figure 1: Position of the installed sensors: strain gauges (red), accelerometers (blue) pressure measurement (yellow) and elongation measurement at the hydraulic cylinders (green) (Barbir & Antony 2020)

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). Every cycle can be further subdivided into the loading (tamping tine movement in the squeezing direction) unloading (tamping tine movement opposite of the squeezing direction) and withdraw (contactless) phases. This newly developed method of dynamic measurement analysis (Plasser Theurer 2017) allows an insight into tamping characteristics essential for a successful data evaluation:

- oscillation amplitude
- maximal reaction force per cycle
- ballast matrix response during loading and unloading
- energy transferred into the ballast
- points of tamping tine-ballast begin and loss of contact

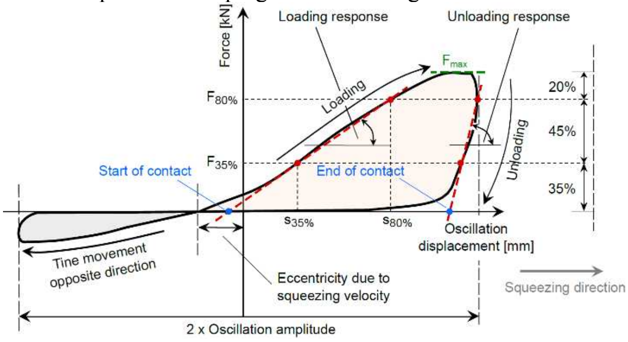

Figure 2: Simplified load-displacement curve (Barbir, 2021)

The tamping process is divided into three operating phases: ballast penetration (a), squeezing movement (b) and tamping unit lifting and/or relocation to the next sleeper (c), as shown in Figure 3. Tamping machine operation during regular track maintenance was monitored at different locations in Austria by means of the measuring system described, resulting in an extensive series of collected measurement data. Considering the extent of the collected and analyzed data, a development of a stable and reliable algorithm for data analysis was necessary. All of the data sets assembled during the measurements were analyzed both graphically and statistically.

It was, for the first time, proven by measurement that a periodic loss with a subsequent gain of contact between the tamping tine and the ballast matrix, occurs. In contrast to static compaction, periodic contact loss and contact gain allow a rearrangement of ballast grains in the contactless phase, resulting in a denser bedding achieved by lower acting tamping forces.

Based on the evaluation of selected measurement data, decisive tamping characteristics are defined for the following ballast bed conditions:

- clean ballast, tamping conducted following track renewal,
- fouled ballast with high fines content, tamping in the scope of during track maintenance.

Relevant differences between the above ballast conditions are found for the following four tamping characteristics:

1. Maximal reaction force per cycle
2. Energy per loading point
3. Ballast matrix response during loading
4. Ballast matrix response during unloading (shape of the load-displacement diagram)

Significantly higher tamping force, energy and loading response are measured in fouled ballast condition. In addition, the shape of the diagram in the unloading phase clearly indicates the changes of the ballast condition, influenced by an increase of proportion of fines with the progress of ballast fouling, which increases the resistance to further compaction.

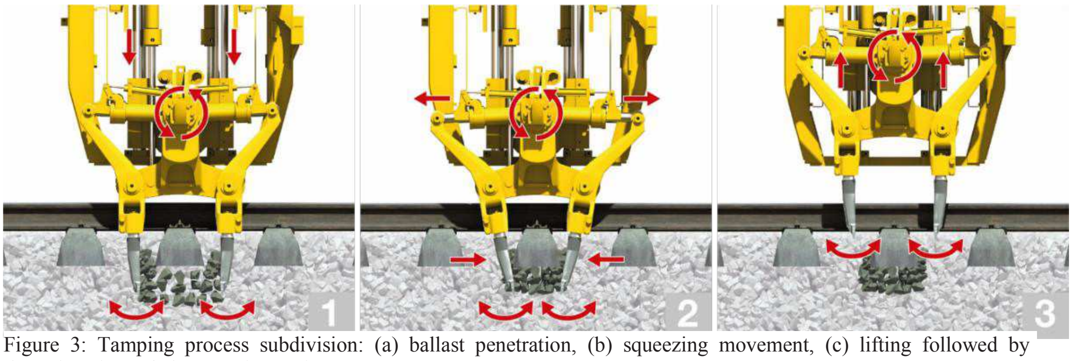

Figure 3: Tamping process subdivision: (a) ballast penetration, (b) squeezing movement, (c) lifting followed by the relocation of the tamping unit

4 SEMI-ANALYTICAL MODEL OF THE TAMPING UNIT-BALLAST MATRIX INTERACTION

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

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 tamping unit utilized to conduct the measurement described in the previous chapter.

The ballast matrix enclosed by the tines during compaction is based on a semi-infinite truncated cone for horizontal translation (Wolf 1994), half space of an idealized homogeneous soil being represented by the Kelvin-Voigt model, which consists of a purely elastic spring k_e and a purely viscous damper c_e connected in parallel. Using the cone model allows the ballast matrix to be described using its soil mechanical properties – shear modulus, density and Poisson's ratio.

The soil model is extended by an additional "plastic" spring, k_p 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 grains strive to fill this void, causing the tine to reinitiate contact with the ballast matrix sooner in the following cycle. The influence of the ballast grain movement during the loss of contact is calculated as the "gap-closing acceleration" a_{gc}.

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 (Barbir 2022):

- Loading – tamping tine in contact with the ballast matrix, both elastic and the plastic segments of the model are active (compressed).
- Unloading – backward movement of the tamping tine, still in contact with the ballast matrix. The elastic spring stretches back, modelling the elasticity of 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. In order to enable the modelling of motion of ballast stones during this phase of the cycle, an acceleration of the ballast stones during loss of contact, i.e. during withdrawal a_{gc} (Figure 4) is calculated.

Based on the in-situ measurements, "model-updating" was conducted – tamping and ballast matrix parameters were modified in order to simulate ballast behavior observed during the field measurements. Load-displacement diagrams as well as tamping characteristics described in the previous chapter were successfully reproduced by the model. In order to conduct a model verification, an effort was made to simulate different ballast fouling stages by using the semi-analytical approach. One of the most important steps forward in the model development was recognizing the elastic spring constant k_e as a parameter that can be varied to achieve the desired effect.

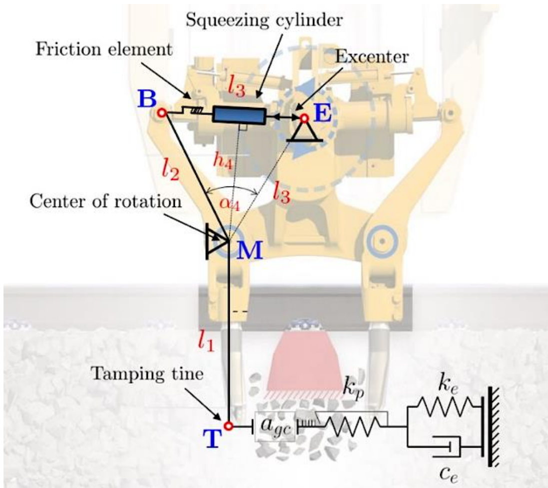

Figure 4: Mechanical model of the tamping unit-ballast matrix interaction (Barbir 2022)

Finding that fouled ballast reacts more elastically under dynamic loading in comparison to clean ballast in which ballast fluidization can occur also reflected in impressive progress in enhancement of the mechanical model.

5 RESULTS

Analysis of in-situ measurements indicated distinct differences between different track conditions and allowed first reference values to be established. Moreover, a significant difference is observed in the shape of the load-displacement curves (Figure 5), confirming a clearly increased tamping force in fouled ballast conditions, as well as a difference in the response of the ballast matrix in different ballast bed conditions. Using the mechanical model described, load-displacement curves of selected in-situ measurements with clean and fouled ballast conditions are compared to the curves obtained employing the semi-analytical approach (Figure 5). 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 simulated by an increase of the elastic spring stiffness in the Kelvin-Voigt model that progresses with the fouling of the material, making it more resistant to compaction.

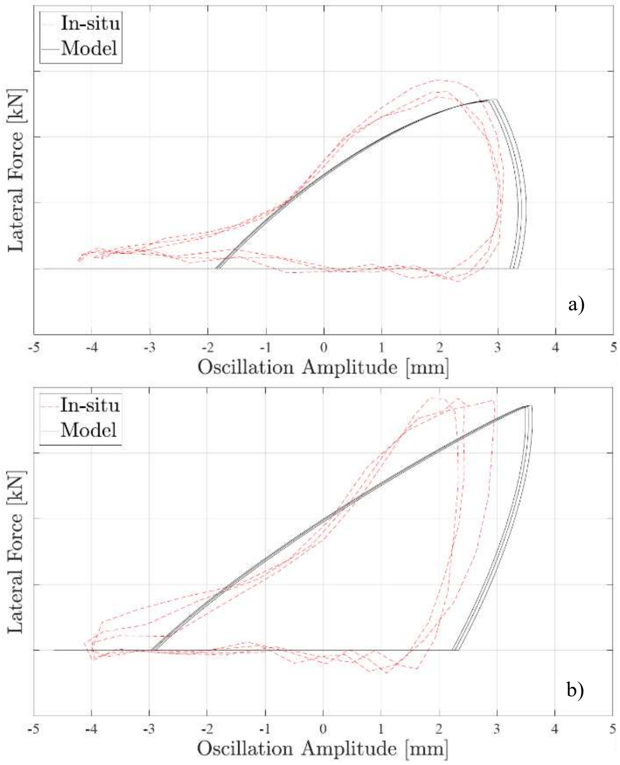

Figure 5: Load-displacement curves of the two selected in-situ measurements (dashed red lines) compared to the semi-analytical approach (black lines): a) tamping in clean and b) tamping in fouled ballast conditions. (Barbir 2022)

6 NUMERICAL MODELING

In addition to the described in-situ measurements and mechanical modelling, numerical simulations using the Discrete element method (DEM) (Figure 6) are conducted using the measurements for model calibration and parameter definition. Studies on the influence of tamping parameters such as tamping frequency as well as vibration amplitude during tamping are of particular interest. First results show that in addition to the vibration frequency, the vibration amplitude also has a significant influence on the compaction result (in detail in Omerovic et al. 2021).

Numerical simulations offer a novel and intuitive approach to the complex deformation behavior of granular materials such as track ballast and will be indispensable for efficient product development processes in track construction in the near future. For example, the efficiency of different aggregates, different tamping tine shapes, as well as variations of side plate kinematics can be compared and systematically developed.

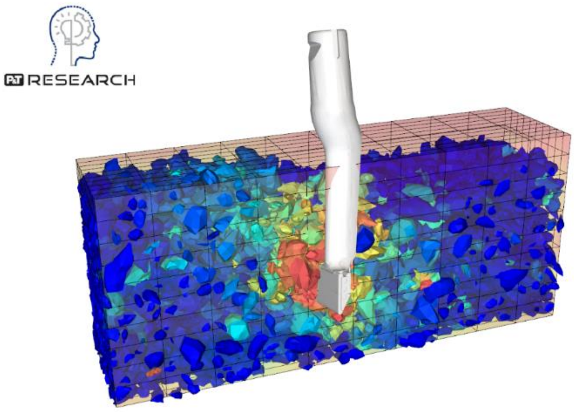

Figure 6: DEM simulation of the squeezing process (absolute displacement velocity of single particle grains marked in color, red color marking the highest velocity (in detail in Omerovic et al. 2021))

7 CONCLUSIONS AND OUTLOOK

Determination of the ballast bed condition was taken into consideration as one of the most important criterion in tamping parameter selection. The developed semi-analytical model enables modeling both edge cases of the ballast condition as well as the progression of ballast fouling. This serves as a first step in the development of a *Smart tamping tool,* the tamping machine transformed from a track maintenance tool into a measuring device that is able to determine an optimal tamping parameter combination for every ballast condition, thus increasing the quality of the whole track system while reducing costs by extending maintenance cycles.

Following the basic research described in this paper, tamping machines in Europe in 2018, Japan in 2021 and the US in 2021 have been equipped with similar measurement systems that enable a detailed monitoring and analysis of the entire tamping process down to each single tamping tine/tool oscillation. This will further sharpen the ballast condition definition and condition determination possibilities.

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