

# In-situ ballast condition assessment by tamping machine integrated measurement system

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The condition of the ballast bed is one of the most important parameters to be determined in order to assure 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. State of the art ballast condition quantification methods all require in-situ ballast 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. The tamping process is the core maintenance activity in ballasted track and it is crucial for 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 a research project presented in this paper. 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. Serving as a confirmation of the ballast condition definitions made based on the in-situ measurements, 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 behaviour under cyclic loading.

## 1. Introduction

Further development in the field of track maintenance indicates a need for condition-based tamping. The in-situ ballast bed condition should be recognized and the difference in approach to tamping new ballast after track renewal and ballast fouled by traffic loads or other ballast fouling sources should be defined. As a result of a joint research project between Plasser & Theurer, Export von Baumaschinen, GmbH, and the Institute of Geotechnics, TU Wien, a semi-analytical model that is able to simulate both ballast conditions is developed and the modelling results are compared to the in-situ measurements conducted with the “Dynamic Tamping Express 09-4X E<sup>3</sup>” tamping machine.

## 2. Existing track condition assessment methods

Breakdown of ballast grains, infiltration of finer particles from the surface, subballast and subgrade as well as sleeper wear are some of the primary causes of ballast bed degradation. The degradation weakens resistance to the vertical (including uplift), lateral and longitudinal forces applied by the sleepers, and



reduces resilient modulus<sup>1</sup> and energy absorption capacity of the ballast bed, making the ballast fouling one of the main reasons for track deterioration. Several track condition assessment methods are known and used throughout the world, and some of them are listed in the following sections.

### 2.1. Level of ballast fouling determination factors

Quantification of ballast fouling or the determination of the in-situ ballast condition is a unique problem in geotechnical engineering. Following quantification methods are proposed as methods to determine the level of ballast fouling [1]:

- Fouling index
- Percentage of fouling
- Percentage void contamination
- Void contaminant index
- Relative ballast fouling ratio
- Ballast breakage index

They are used to determine and classify ballast performance for given traffic loads, speed and track geometry and as such provide an advantage in defining the optimum time for ballast bed cleaning or renewal [1]. However, all of the above listed ballast fouling quantification methods require in-situ ballast sampling followed by laboratory tests determining either the grain size distribution, void ratio, unit weight, dry mass or similar characteristics of a representative ballast sample or the fouling material contained in the sample. A reduction of track availability and additional track closure necessary to determine any of the given ballast fouling level factors make the determination of ballast condition a time-consuming and challenging task.

### 2.2. Non-destructive track condition assessment

Ground penetration radar (GPR) has been increasingly employed for monitoring track conditions due to the fact that it is a non-destructive method that can be used to monitor the track at high speed. GPR is a geophysical measurement system based on electromagnetic waves that are reflected at interfaces between materials of dissimilar dielectric permittivity. The emitted signal enables an assessment of ballast- and substructure condition and moisture content. The difference between different ballast conditions can primarily be noticed due to the moisture trapped in the fouled sections that has a significant influence on the texture of the GPR radagram result [2]. However, GPR test results conducted on actual tracks where the relationship between track condition and the GPR response has not been established usually require additional control by some other available track condition assessment method, causing the need for additional track closure.

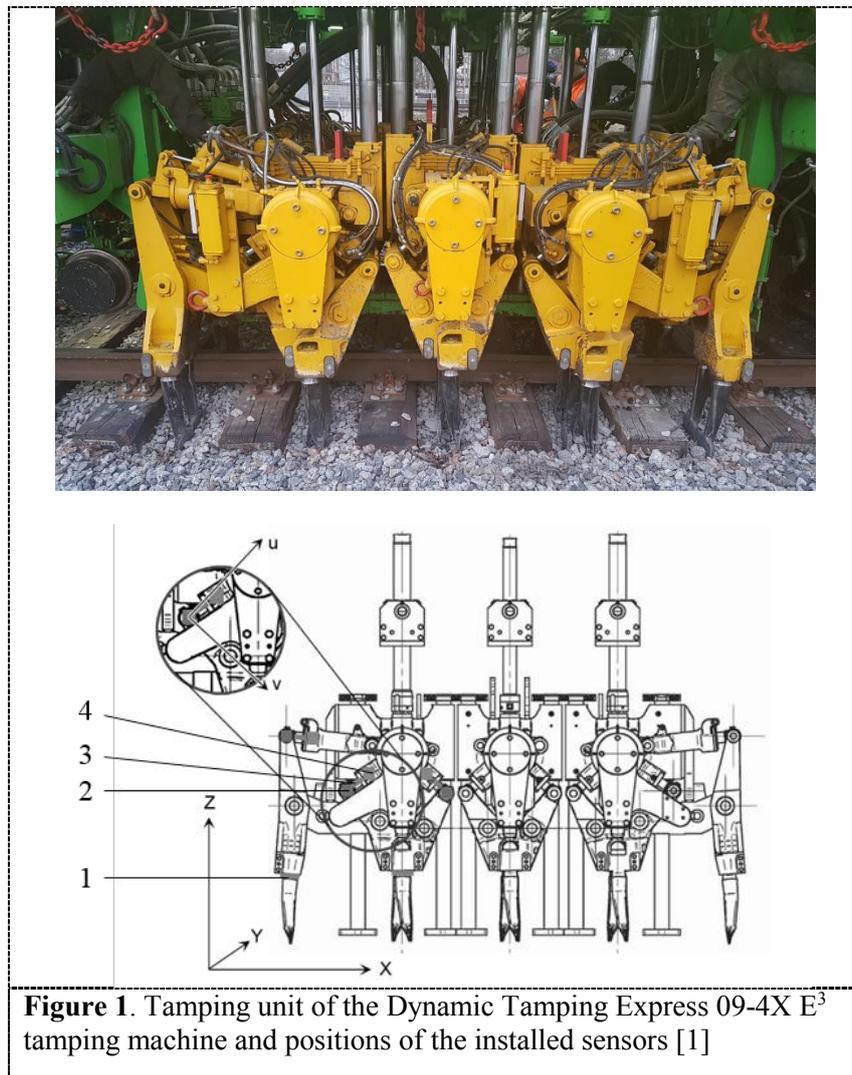
## 3. Tamping machine integrated measurement system

Within the framework of this research project an effort has been made to enable ballast condition assessment in-situ by the tamping machine during regular track maintenance. Adapting responsible tamping parameters to the ballast condition would increase the efficiency of the maintenance work and optimize the ballast life cycle.

A tamping machine utilized for the described measurements was equipped with strain gauges (Figure 1; 1) that are applied and used to measure the lowering and lateral tine forces. Accelerometers (Figure 1; 2) 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; 4) and elongation measurement at the hydraulic cylinders (Figure 1; 3) the tamping process could be fully documented and subdivided (Figure 3).

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<sup>1</sup> ratio of repeatedly applied deviator stress to the recoverable axial strain during unloading

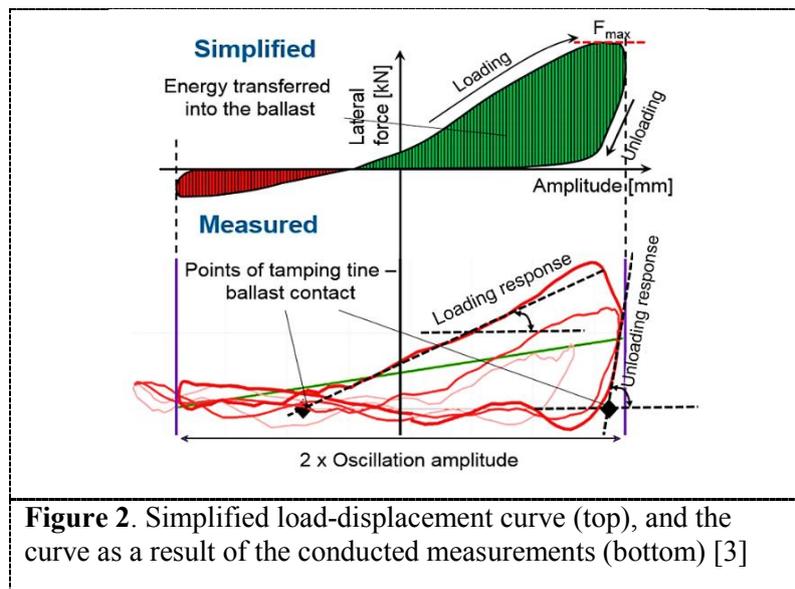


**Figure 1.** Tamping unit of the Dynamic Tamping Express 09-4X E<sup>3</sup> tamping machine and positions of the installed sensors [1]

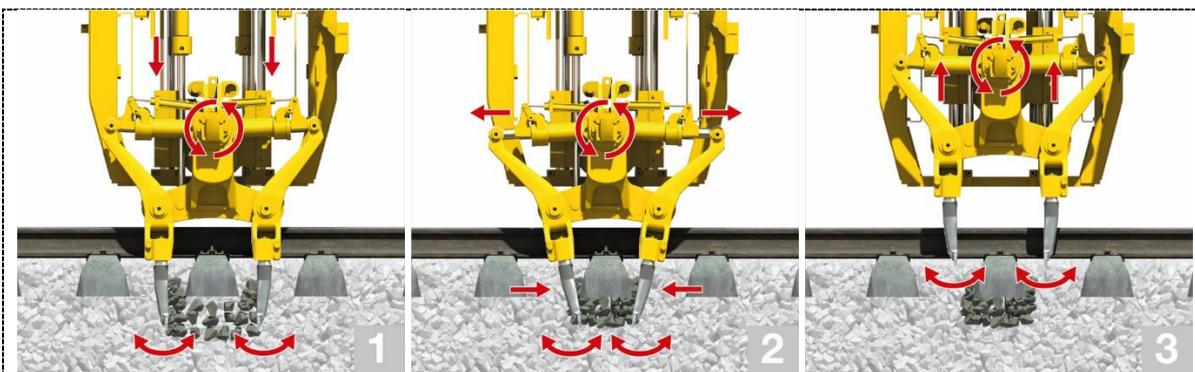
Based on the measurements described, an initial approach towards successful data analysis was chosen in form of a load-displacement curve i.e. lateral force-oscillation displacement diagram, presenting a single cycle or every tamping tine oscillation with an 4-5 mm amplitude during the tamping process (Figure 2). This newly developed method of dynamic measurement analysis [4] 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)

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 [3].



The operation of the Dynamic Tamping Express 09-4X E<sup>3</sup> was monitored at different locations in Austria by means of the measuring system described above, resulting in an extensive series of collected measurement data. 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. Over 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 [3] (minimal required impulse duration of 0.8 to 1.2 seconds) [5].



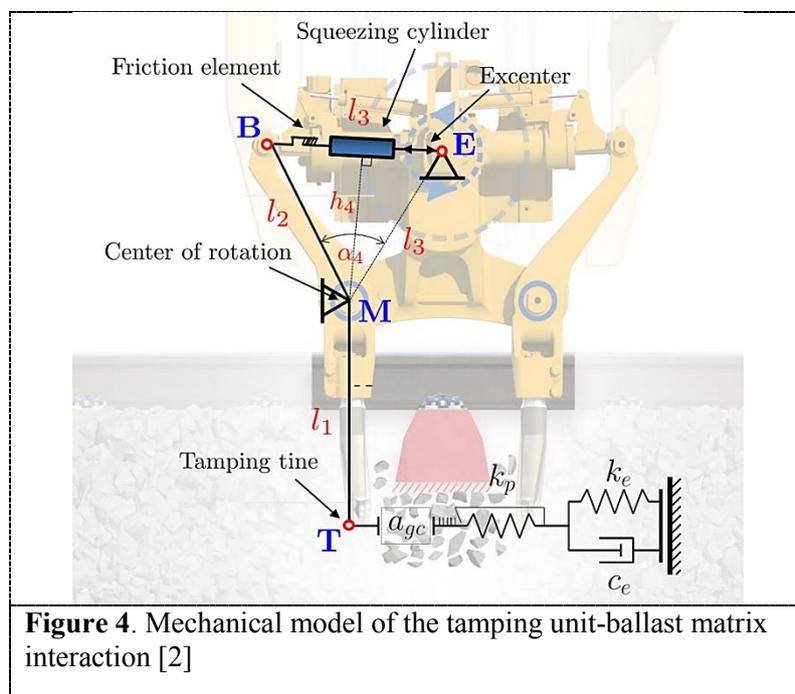
**Figure 3.** Tamping process subdivision: (1) ballast penetration, (2) squeezing movement, (3) lifting followed by the relocation of the tamping unit [2]

#### 4. Semi-analytical model of the tamping unit-ballast matrix interaction

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 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 “Dynamic Tamping Express 09 4X E<sup>3</sup>” [3]. The ballast matrix enclosed by the tines during compaction is based on a semi-infinite truncated cone for horizontal translation [6][7], 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 (Figure 4). 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:

$$k_e = \frac{G \cdot b_0}{1-\nu} \left[ 3,1 \cdot \left( \frac{a_0}{b_b} \right)^{0,75} - 1,6 \right] \text{ [N / m]} \quad c_e = 4 \cdot \sqrt{2\rho \cdot G \frac{1-\nu}{1-2\nu}} \cdot a_0 b_0 \text{ [Ns / m]}$$



This approach ensures that ballast properties are described by two soil parameters customarily used in soil dynamics: shear modulus  $G$  and Poisson’s ratio  $\nu$ , as well as the soil density  $\rho$  [3].

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”  $a_{gc}$  [1].

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 [1]:

- 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 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 ballast grains motion 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 [1].

## 5. Comparison of tamping parameters

Analysis of in-situ measurements indicated distinct differences between the following two edge cases of the track condition and allowed first reference values to be established:

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

The highest level of divergence can be noted for the following four tamping parameters (Table 1):

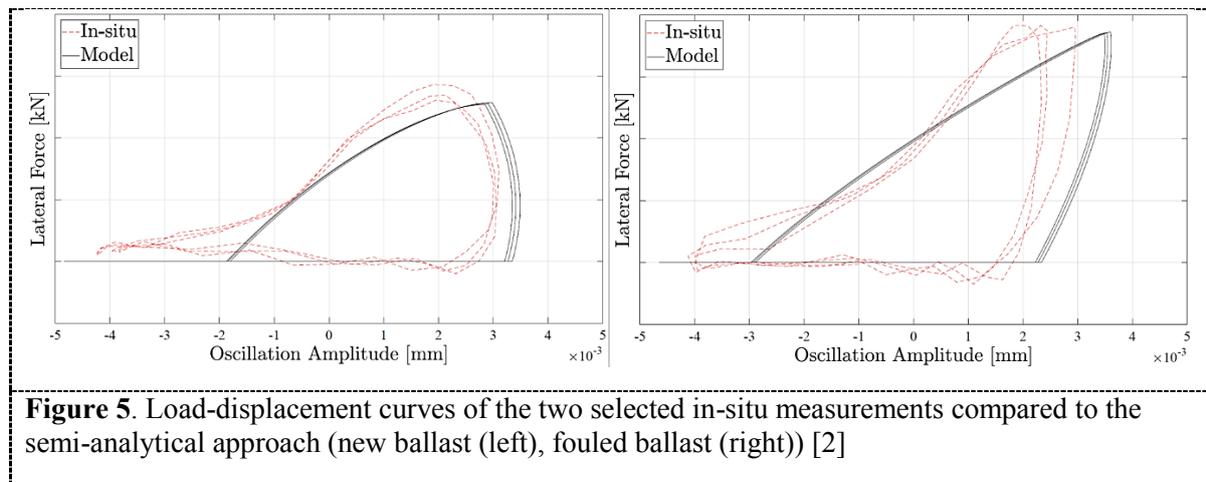
**Table 1.** Parameter comparison of the two ballast conditions

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

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. 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 [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 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 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 [3].

## 6. Conclusion

The developed semi-analytical model enables modeling both edge cases of the ballast condition as well as the progression of ballast fouling, serving as a means to determine an optimal tamping parameter combination for every ballast condition. The optimal combination of tamping parameters is determined as a result of an extensive parameter study performed with the semi-analytical model. The tamping machine itself can not only be used as a reliable track condition assessment tool for every level of ballast fouling but it can adapt the parameters to the condition encountered in-situ, increasing the quality of the whole track system while reducing costs by extending maintenance cycles. This novel approach to track maintenance would also reduce the duration of track closure and eliminate the need for additional track condition determination methods by creating a possibility for continuous ballast compaction and track condition control.



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