Intelligent tamping - from research to automation

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INTRODUCTION AND PROBLEM STATEMENT

Current practice of track maintenance is based on modern tamping machines that provide a wide range of advanced functions, such as the multiple sleeper tamping mechanism, dynamic track stabilization and combined levelling and lining of the tracks.

Tamping process, the core maintenance activity in ballasted track, is a result of experience and knowledge collected from railway operations worldwide. An extensive basic research conducted in 1983 at Graz University of Technology investigated and determined the optimum tamping frequency (35 Hz) and an oscillation amplitude of the tamping tines (4-5 mm) [1]. However, different global tamping standards driven by local regulations and divergent boundary conditions define a wide spectrum of other tamping parameters such as tamping time, squeezing force, minimum lifting values and number of insertions [2].

State-of-the-art tamping machines operate with a parameter combination previously empirically selected by the machine operator on the spot, which significantly aggravates comparison of conducted tamping work on different locations and in different conditions. Given that an incorrect setting of the tamping parameters leads to sub-optimal ballast bed compaction and shortens the interval between track maintenance activities, the importance of experienced and well-coordinated machine crew becomes even more prominent. Variable tamping parameters and machine settings that are selected by the operator such as the squeezing force and time, frequency modulation during ballast penetration, correction values and tamping depth greatly influence the quality of conducted work.

In addition, only a minority of tamping parameters can be altered in accordance to the ballast condition. Thereby, the process of ballast fouling or attrition is an important aspect to be considered during tamping parameter optimization in a greater scope of developing a fully automated tamping process which would lead to a reduction of workload for the machine operator and to an improvement of quality of conducted track maintenance [3].

AUTOMATION OF THE TAMPING PROCESS

PlasserSmartTamping - THE ASSISTANT

The desired result of the tamping process, extended by lifting and lining, is to restore the defined track geometry. Prior to carrying out the tamping process, the lifting and levelling unit is set in motion. Independent of the tamping technology and tamping machine used, the track must be lifted so that a void is created under the sleeper. Simultaneously, the track is positioned laterally. As a first step towards an automation of the tamping process as a whole, PlasserSmartTamping - The Assistant (Figure 1) is developed in order to support the machine operator in his demanding task. Laser scanning units are used to record the track and its surroundings and digitize them into a 3D model. The usage of artificial intelligence makes it possible for the system to recognize objects in the track and assign them to the correct category. This enables the machine to autonomously distinguish between rails, sleepers and even obstacles such as cables, located in the sleeper bay.

Based on this information the system provides recommended actions for the lifting, levelling and tamping units in "real time" and displays them to the machine operator who can approve or reject recommended actions. As soon as the recommended action is approved, positioning of the lifting, levelling and tamping units is carried out autonomously by the machine [4].

AUTOMATION OF TAMPING PARAMETERS

In the next step towards the development of a fully autonomous tamping process, parameters set during the tamping operation are investigated. Correct assessment and selection of tamping parameters provides a homogeneous, durable and stable track bedding as a result of track tamping. Understanding different soil mechanical and dynamic aspects of track ballast behaviour during tamping is of crucial importance. A comprehensive investigation of the tamping process during regular track maintenance in different ballast conditions was conducted in the scope of a research project initiated by Plasser & Theurer, and carried out in cooperation with the Institute of Geotechnics at TU Wien in 2016 [3]. Main focus of the project was the measurement, recording and analysis of the interaction between the tamping tine and ballast matrix during ballast compaction. Most significant results and conclusions that arose from this research project show that a determination of ballast condition is possible during the tamping process and that the tamping characteristics obtained from measurement conducted in different stages of ballast fouling significantly differ from each other [3].

In the next step, a definition of a desired parameter combination needed to achieve optimum compaction in every ballast condition is necessary. Once fully developed, this system will, for the first time, allow a full automation of the tamping process for lines, switches and crossings, at the same time increasing the quality of conducted track tamping and leading to an autonomously operating tamping machine.

TAMPING PROCESS - STATE OF THE ART

Track tamping is used to produce (in the case of new track) or restore (in the case of track maintenance) the defined track position. This complex process starts with lifting the relevant track section, which comprises 1 to 4 sleepers depending on the unit, up to the level determined by previous measurements and dependent on the minimum lifting values, and simultaneously positioning it laterally. Both are done using lifting and levelling units mounted in front of the tamping bank, between the bogies. As the track is lifted in order to be positioned, the contact area between the ballast and the sleeper is dissolved and a void is created [5].

PHASES OF THE SQUEEZING PROCESS

Once the track is in the intended position, the tamping process, consisting of three phases (Figure 2), begins. In the first phase, tamping tines penetrate the ballast on the left and right hand side of each sleeper, reaching the level defined by the nominal tamping depth. This phase is characterized by a higher frequency (approximately 45-48Hz) that temporarily reduces ballast friction angle and thereby aides ballast penetration.

Following the penetration phase, the squeezing movement is initiated, defined as a closing movement of the tamping tines towards the sleeper, instigated by the pre-set squeezing pressure. The squeezing movement is conducted with a frequency of 35Hz and tine oscillation amplitude of 4-5mm, a parameter combination that enables the best compaction effect in combination with the desired ballast elevation [1][6]. Duration of each squeezing movement is given by the squeezing time, pre-set by the machine operator based on several factors such as the in-situ ballast condition, standards, regulations and lifting values, but primarily experience – based. Dependent on the encountered track geometry, correction values and sleeper type, multiple (up to three) tamping processes, ie multiple tamping tine insertions are possible on each sleeper.

During the squeezing movement, the void created under the sleeper (Figure 3) needs to be filled and the ballast matrix compacted in order to create a stable and durable bearing for the track [5]. Total motion of the tamping tines during track tamping incorporates the absolute tine movement driven by the squeezing velocity and the relative tine movement that is dependent on the excitation frequency and amplitude (Figure 4).

Without dynamic excitation, the lowering of tamping bank alone would increase the wear of the tamping bank and the ballast. It would not be sufficient for the tamping tines to penetrate the ballast and reach the necessary position under the sleeper. If the dynamic excitation was only utilized to facilitate the ballast bed penetration but not to perform the squeezing movement, the usual tamping force would not suffice to overcome the passive earth pressure and rearrange the ballast grains to fill the void under the sleeper. On the other hand, increasing the excitation frequency would accelerate the process, but could also lead to ballast bed loosening by dilatation [3].

Figure 1: Tamping machine equipped with PlasserSmartTamping - The Assistant [4].

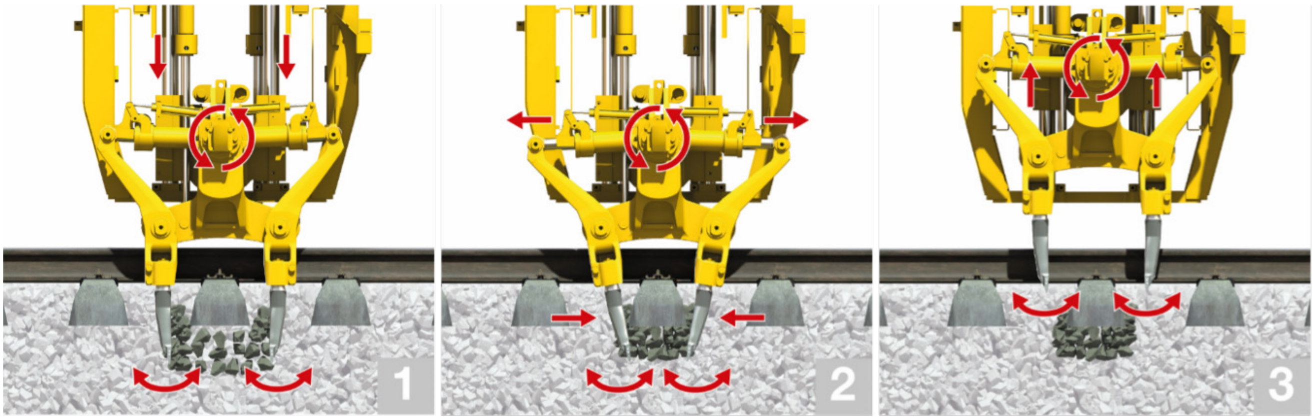

Figure 2: Phases of the tamping process: (1) ballast penetration, (2) squeezing movement, (3) lifting followed by the relocation of the tamping bank [3].

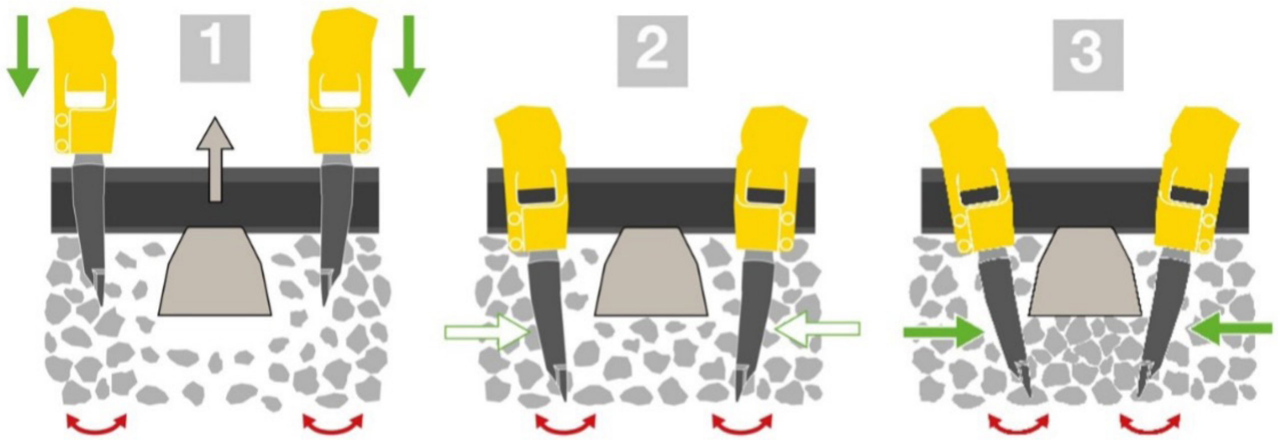

Figure 3: Lifting and creating the void under the sleeper (1), filling the void (2), ballast compaction (3).

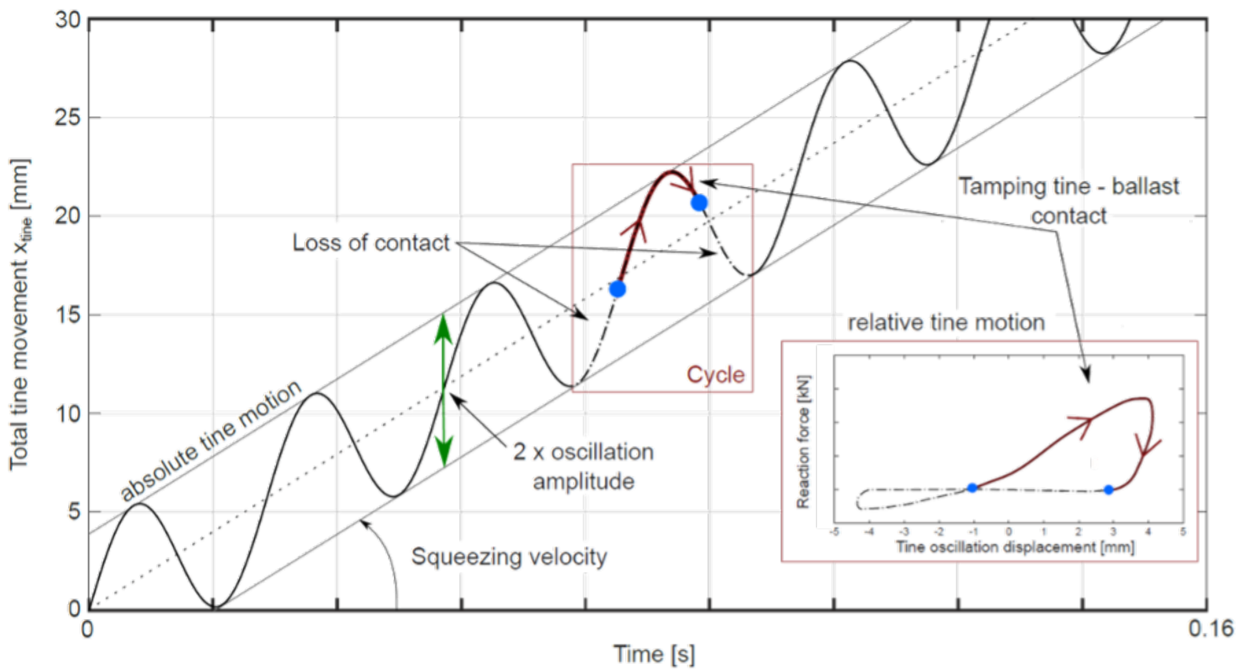

Figure 4: Total tine motion – a combination of squeezing motion and tine oscillation [3].

Once the void under the sleeper has been filled, relative tine movement, ie tine oscillations initiate further ballast compaction in this area [5]. During compaction, a periodic pulsating load is transferred from the tines to the ballast matrix, allowing a rearrangement of ballast grains into a denser configuration [3]. In order to achieve a durable and stable bearing for the sleeper, the highest possible compaction should be achieved, thus reducing settlements that could be induced by following traffic loads. However, the implemented compaction energy should only be utilized to rearrange the grains which make up the ballast matrix, without initiating/accelerating the ballast fouling process, ie changing the ballast matrix grain-size distribution. Following a successful compaction, the tamping tines are simultaneously opened and pulled out of the ballast, as the last phase of the tamping process is initiated. The lifting phase (Figure 2) is characterized by the closing of hydraulic cylinder and loss of contact between the tamping tines and the ballast.

EXPERIMENTAL APPROACH

MEASURING SYSTEM

The cornerstone of a full tamping process automation is the autonomous identification of ballast condition to which the tamping parameters could be adapted. As a necessary foundation for the development of this condition-based tamping process, information about the track substructure and the ballast condition need to be determined and related to a customized parameter combination. In order to make the on-the-spot condition determination possible, the machine has to be able to differentiate between different degrees of ballast bed fouling. For this purpose, a specially developed measurement system was implemented directly to the Plasser & Theurer tamping bank of a four-sleeper track tamping machine Dynamic Tamping Express 09-4X E^3 as well as to a single sleeper track and turnout tamping machine Unimat 09-4x4/4s E^3 (Figure 5) [7].

The sensor set-up (Figure 5b) consists of strain gauges that are used to measure the penetration resistance and reaction forces at the tamping tine plate. Angle encoders and accelerometers placed on the tamping arm allow a precise calculation of both the absolute and relative tamping tine motion. In conjunction with pressure sensors, the tamping process could be fully documented and subdivided into the respective operating phases – ballast penetration, squeezing movement and tamping bank lifting and / or relocation to the next sleeper [4][7].

Data collected by the sensors mounted on several Plasser & Theurer tamping bank provided approximately 600,000 data points per sleeper and made a detailed analysis of the tamping tine movement and interaction with the ballast matrix possible. As mentioned before and shown in Figure 4, total tine motion can be subdivided into an absolute and a relative one. The latter can be presented in the form of a load-displacement diagram (Figure 6), showing each individual tamping tine oscillation, ie each cycle with its three constituent phases (loading-unloading-withdraw) as well as the following tamping characteristics:

- oscillation amplitude ie displacement
- maximal reaction force per cycle
- ballast matrix response during loading and unloading
- energy transferred into the ballast (red area underneath the load-displacement curve)
- points of tamping tine-ballast begin and loss of contact

After the measurement data was analysed, several irrefutable differences were recognized among the derived tamping characteristics on different measurement locations. Relevant differences between ballast conditions are found for the following tamping characteristics: maximal reaction force per cycle, energy per cycle and the ballast matrix response during loading. The measured differences can be attributed to the condition of the ballast bed, ie to the differences in ballast matrix reaction to the interaction with the tamping tine. This knowledge provided experimental verification of the influence of ballast fouling on its behaviour during compaction and once again emphasized the importance of ballast condition in the process of automation of the tamping process.

MECHANICAL MODEL

In order to investigate the influence of ballast bed condition on the quality and durability of the conducted track tamping, a semi-analytical mechanical model of the tamping tine - ballast matrix interaction during the squeezing movement was developed. The model depicts both relative and absolute motion of the tamping tine and consists of two fundamental parts: tamping bank and ballast matrix model (Figure 7). The tamping bank is modelled as a simple system of rods with a dynamic excitation overlapped by a hydraulic cylinder movement modelled by a variable rod length.

The tamping bank model depicts the geometry of the Dynamic Tamping Express 09-4X E^3 tamping bank and can be easily altered to another bank geometry. The ballast matrix model consists of three components and can be used to simulate elastic and plastic ballast matrix deformation as well as ballast grain motion during loss of contact between the tine and the matrix. Dynamic shear modulus, Poisson's ratio and ballast density are used to describe ballast properties. Special attention is given to the tamping tine – ballast

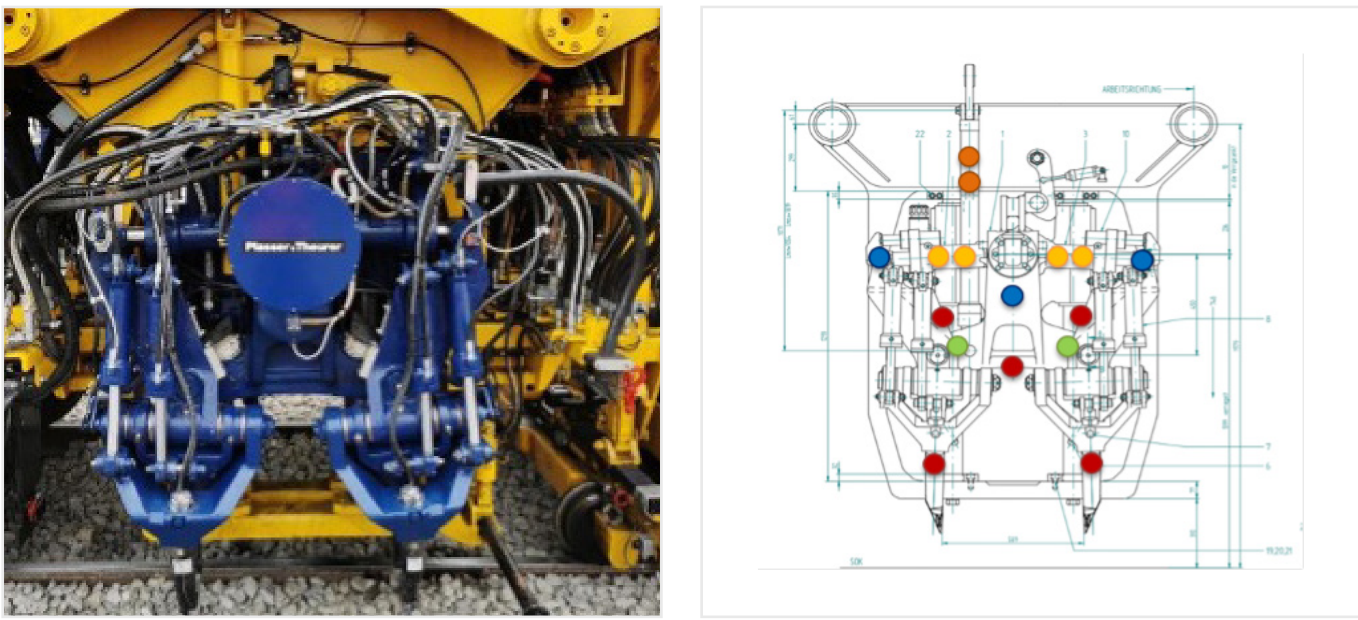

Figure 5: Tamping bank of the universal tamping machine Unimat 09-4x4/4s E3 (a left); Position of the installed sensors – strain gauges (red), angle encoders (green), accelerometers (blue) and pressure sensors (orange) (b right).

matrix model contact conditions, providing the possibility to simulate both continuous contact and the loss of contact between the two model parts, (in detail in [3] and [7]). Following the development of a stable algorithm the model was calibrated using the results from in-situ collected data and is able to simulate different encountered ballast bed conditions. In the next step, the model is used to conduct parameter studies in order to determine the influence of selected tamping parameters and parameter combinations on the quality of performed track tamping that are, in further consequence, going to be adapted to the ballast condition [3].

FILLING PROCESS MONITORING

As a next step in the development of a fully automated tamping system, the squeezing movement and its constituent phases, void filling and ballast compaction, were additionally investigated. As mentioned before, filling the voids created during lifting is the basis for producing a precise and durable track layer. Only if the area under the sleeper, which is subjected to regular traffic loads, is filled and compacted successfully, can the desired track geometry can be maintained. Therefore, a monitoring system designed to survey the filling process was developed in order to further improve the quality of the tamping work [5].

This system, developed by Plasser & Theurer, is based on the change in resistance when the void under the sleeper is filled with ballast. Before the void is filled, ballast grains encounter less resistance during their motion, resulting in comparatively higher squeezing velocity, depending on the set squeezing force. As soon as the void is filled, the ballast grain range of motion is reduced and the resistance increases, resulting in a decrease of squeezing velocity (Figure 8) [5]. This ensures an automatic adaptation to the track and ballast conditions in-situ and at the same time prevents ballast fouling that would be initiated by attrition at higher force values.

Figure 8 shows an example of a tamping process with high lifting values creating a lager void under the sleeper. Low resistance at the beginning of the squeezing movement leads to a higher squeezing velocity that starts to decrease as soon as the void is filled. In Figure 9, measured data showing both incomplete and complete void filling is plotted. It can be clearly distinguished between the two cases based on the curve slope – as soon as the filling is completed the slope decreases (Figure 9b) while the curve showing incomplete filling (Figure 9a) runs almost linear during the entire squeezing movement.

Similar to several other tamping parameters, there are a number of guidelines and recommendations such as minimum squeezing time and number of insertions that should be taken into consideration in order to insure a complete void filling and a stable, durable sleeper bearing. These guidelines, although they provide good results, are mostly driven by local regulations and are largely based on experience, meaning that they cannot guarantee optimum void filling under any conditions. For this reason, Plasser & Theurer developed a filling monitoring system that can alert the machine operator of incomplete void filling for each individual tamping arm immediately after tamping [5]. This is achieved by showing the operator the

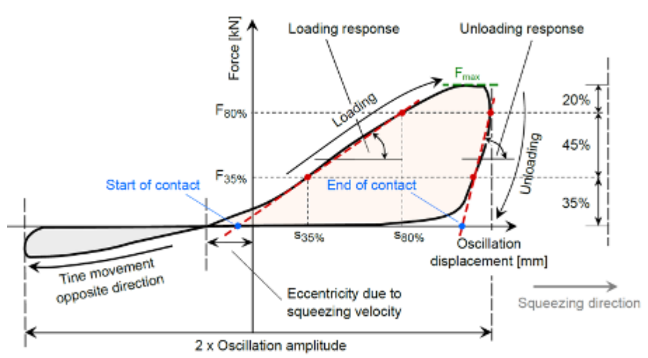

Figure 6: Simplified load-displacement diagram [3].

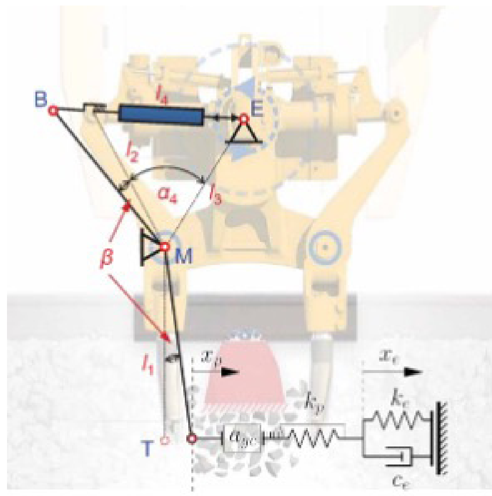

Figure 7: Mechanical model of the tamping bank and the ballast matrix during squeezing movement [3].

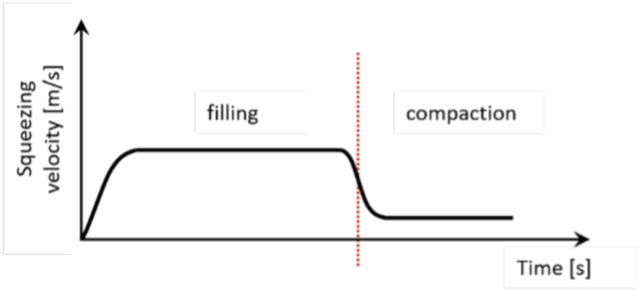

Figure 8: Schematic representation of the squeezing velocity during the filling and compaction process [5].

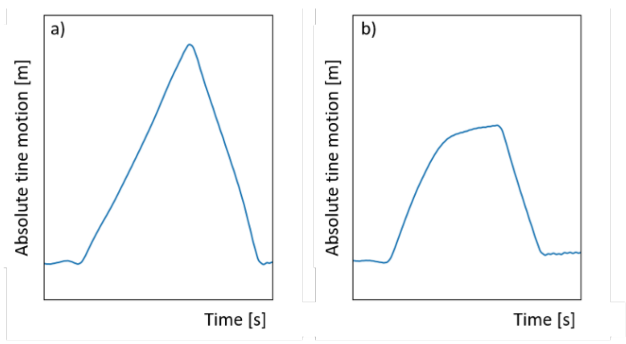

Figure 9: Measured squeezing displacement (absolute tine motion) with (a) incomplete and (b) complete void filling. Both curves were recorded with the same working parameters (tamping pressure, squeezing time, penetration depth, lifting values and sleeper type) [5].

squeezing velocity and the ballast resistance reached at the end of the squeezing movement. Ballast resistance is calculated as a ballast resistance coefficient $\gamma_{\_ballast}$ from the force $F_{\_end}$ and the squeezing velocity $v_{\_end}$, using the following equation:

$$\gamma_{ballast} = \frac{F_{end}}{v_{end}}$$

$F_{\_end}$ describes the force at the tamping tine calculated using the pressure in the squeezing cylinder. The squeezing velocity $v_{\_end}$ is calculated as follows:

$$v_{End} = \frac{\Delta x_{End}}{\Delta t_{End}}$$

where $\Delta t_{\_End}$ is given by last 0.1 s before the maximal tine displacement is reached and $\Delta x_{\_End}$ the distance travelled by the tamping tine during $\Delta t_{\_End}$. Based on this information, the machine operator can now initiate an additional insertion on a sleeper in case of incomplete filling. For the implementation of this monitoring system, several measured values must be continuously recorded and analyzedanalysed. For this purpose, additional sensors are installed to the tamping bank (in detail in [5]) and the system has been in use by customers for the first time.

In addition to the squeezing velocity, the system also shows the operator the tamping depth and squeezing force. With this information, it is now possible to detect and react to incomplete void filing directly during tamping thus avoiding individual defects and further improving the durability of the track position.

THE TAMPING PROCESS PROTOCOL

An important step towards a completely transparent process recording has been made by the development of the tamping protocol (Figure 10), recording all tamping process aspects and parameters that are considered quality-relevant. It shows data recorded during track tamping, tamping bank positioning and setting of machine parameters. From the infrastructure manager point of view this system enables a new type of verification documentation. The system has a modular structure - the basic version comprises the control of lifting and levelinglevelling units and it can be extended to control the tamping bank.

OUTLOOK AND CONTRIBUTION TO FURTHER DEVELOPMENT

Complexity of the track system together with an increasing demand on track quality and durability, environmental influences and loads during regular operation ensure continuous challenges and demand for further development of the state-of–the-art tamping machines that must be designed and operated to deliver optimum results under all operating conditions.

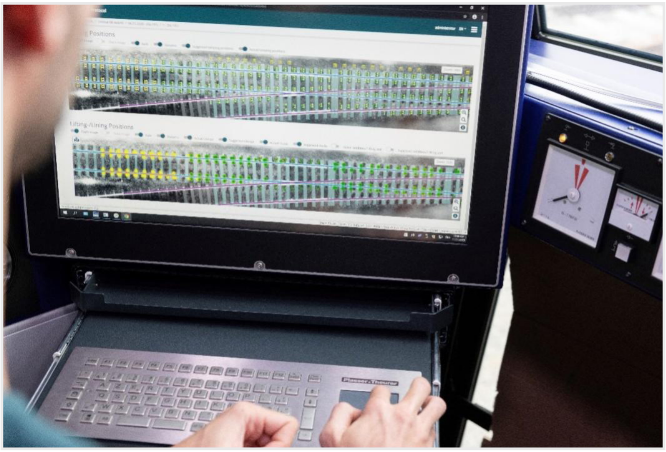

Figure 10: PlasserSmartTamping protocol [7].

Together with the proven asynchronous track tamping principle that Plasser & Theurer has been relying on and that has been proved to be extremely effective over decades, new technologies and developments described in this paper will assure that the core technology is further improved and adapted to meet the increasing demands. The worldwide strive towards automation exists not only to relieve the machine operators, but also to ensure homogeneous work quality and reduce the possibility for an error to occur.

State-of-the-art sensors and control technology implemented to Plasser & Theurer tamping machines are successfully advancing along path to full automation - PlasserSmartTamping - The Assistant, and the usage of artificial intelligence already makes it possible for the system to recognize objects in the track and assign them to the correct category, displays them to the machine operator who then has only to approve or reject recommended actions.

As soon as the recommended action is approved, positioning of the lifting, levelinglevelling and tamping units is carried out autonomously by the machine. The measuring system that has been developed and used to conduct measurements in different ballast condition over the past years, as well as the development of the mechanical model to simulate the tamping action and conduct studies on different ballast parameters, build a strong foundation for the condition-based tamping parameter selection that is needed for a fully automated tamping process. In addition, the automatic adjustment to the ballast resistance and the filling monitoring will prevent isolated defects due to inadequate or incomplete filling of the void under the sleeper, given that ballast compaction that is crucial for producing a precise and durable track layer can only take place when the void has been properly filled. Insufficient compaction not only leads to rapid deterioration of the track position, but also contributes to ballast fouling.

As a results of these new developments, the tamping bank is being transformed and upgraded from a track maintenance tool into an integrated measuring system whose possibilities go far beyond the familiar post-measurement documentation. In addition, machine personnel are supported in producing a long-lasting and precise track position and the infrastructure operator gains valuable data and insights into the condition of the track infrastructure.

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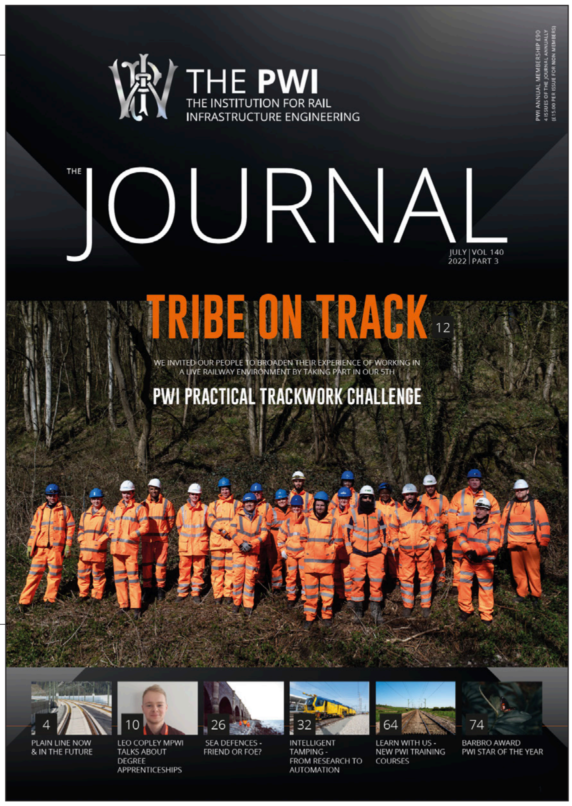

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