Ballasted Track Maintenance Modelling Using DEM

Jean-Francois Ferellec, Eric Chapteuil, Nicolas Docquier, and Olivier Lantsoght

Abstract The ballast layer is a crucial component of railway tracks and it is hence essential to maintain it using adequate processes like tamping and stabilization. These will ensure that the density of the ballast layer is high enough to avoid shearing and settlement of the track under traffic. Ballasted tracks settle unevenly under the passage of trains. These geometrical defects are corrected by tamping which consists of lifting individually the sleepers and compacting the ballast underneath using vibrating tines. After tamping, the ballast layer is not homogeneous in terms of density along the track and requires stabilization before being commercially operational. This stabilization is performed either by regular trains at lower speeds for a given period hindering commercial operations, dynamic stabilization, or crib compaction. All these processes rely on vibrating the ballast layer using different approaches and have mainly been based on empirical observations. This paper describes an analysis of these ballasted track maintenance processes and their optimization using the discrete element numerical approach. This approach considers a granular material as an assembly of objects interacting through a specific contact law. In the present study, the code called LMGC90 has been used. The study includes a comparison of the processes in terms of ability to compact the ballast layer and lateral mechanical resistance of the track and their optimization. The final purpose of the project is to be able to specify optimal functioning parameters for all these processes.

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1 Introduction

Railway engineers struggle more and more maintaining ballasted tracks within their allowed budgets. Optimizing the maintenance operations became a challenge for many railway network owners in order to remain competitive in comparison with road or air transports. The principal maintenance operations are based on empirical observations and have barely changed for decades. Innovative numerical tools have emerged in parallel allowing a detailed analysis of their physical mechanisms and actions on ballast and hence their potential improvement.

The maintenance processes concerned are tamping, dynamic stabilization and crib compaction. The differential settlement of the track due to traffic is corrected by tamping which consists of repositioning the sleepers at their right location vertically and transversally and compacting the ballast underneath to keep them in place. After tamping the track requires stabilization of the ballast layer which is performed by letting regular trains roll on the track at lower speed hindering commercial traffic, by dynamic stabilization or crib compaction. Dynamic stabilization requires special equipment which simultaneously applies a load on the rails and vibrates them laterally and therefore also the sleepers and ballast surrounding them. The energy transmitted to the ballast is used to rearrange the grains and compact the ballast layer. In the crib compaction process, the ballast located between the sleepers and the shoulders is directly compressed using vertical compactors.

Analyzing experimentally these maintenance processes will quickly become costly in terms of time and budget. This paper describes the use of the numerical approach called discrete element method coupled with multibody system formalism to analyze and optimize tamping and, investigate crib compaction as an alternative to dynamic stabilization. The following sections explain this numerical approach and its application to reduce ballast fragmentation due to tamping and to compare the performance of crib compaction with that of dynamic stabilization.

2 Modelling via a MBS-DEM Coupling

On one hand, the Discrete Element Method (DEM) is a well-established approach to model granular material such as the ballast. It allows accounting for each grain of the media and its interactions with other particles. On the other hand, Multibody System (MBS) formalism enables to account for the dynamics of mechanical systems composed of several bodies connected by various kinds of joint. In particular, those methods are particularly adapted to study the dynamics of the maintenance machines (tamping machine, compacting machine or dynamic stabilizer).

Since the maintenance processes of the track imply dynamic interactions between the ballast and the machines, it is proposed to analyze and optimize their efficiency using a unified MBS-DEM modelling approach. This section gives a short summary of the two methods used for this paper. It then explains briefly how they are coupled. More details can be found in [1].

When considering DEM, the contact laws between the particles and the way they are handled deserve special attention. Classically, one can distinguish two main families. First, methods based on the «Molecular Dynamics» approach resort to regularized contact laws such as a spring-damper law and thus enable interpenetration between grains [2]. Estimating equivalent stiffness at the contact point is a tricky task. Furthermore, the equivalent stiffness may be very high, especially for ballast stones, requiring small time steps to avoid numerical instabilities. In contrast, the «Contact Dynamics» approaches consider a rigid contact and impose to solve at each time step the contact problem at the geometrical and dynamic levels for the whole set of particles. In particular, the method used in this paper is based on the Non-Smooth Contact Dynamics (NSCD) approach proposed by Moreau and Jean [3, 4]. This technique allows considering larger time steps but requires solving a complex contact problem which may be time-consuming. This second approach is used for the present work.

The NSCD method considers the equation of motion at the velocity level in terms of differential measure allowing for discontinuities of the velocity:

$$\mathbf{M}_G \mathrm{d}\mathbf{v}_G = \mathbf{f}_G(\mathbf{q}_G, \mathbf{v}_G, t)\mathrm{d}t + \mathbf{H}_G(\mathbf{q}_G)\mathrm{d}\mathbf{I}_U$$

where $\mathbf{q}_G$ is the vector of generalized coordinates describing the absolute position and the orientation of grains; $\mathbf{v}_G$ is the vector of generalized velocities of grains which is composed of the translation velocities $\mathbf{v}_i$ and the angular velocities $\boldsymbol{\omega}_i$ of each grain i; $\mathbf{M}_G$ is the mass matrix; $\mathbf{f}_G$ represents the non-linear dynamic terms and the force applied on the system; $\mathrm{d}\mathbf{v}_G$ is the differential measure associated with the velocity (it encompasses the continuous variation of the velocity and possible velocity jumps); t is the time, $\mathrm{d}t$ is the corresponding standard Lebesgue measure; $\mathrm{d}\mathbf{I}_U$ is the impulse measure associated with the contact reactions (it is composed of contributions of regular contact forces and possible impacts); $\mathbf{H}_G$ is a mapping operator between the global and contact local coordinates.

This set of equations must be completed by contact and impact laws. For the maintenance process application, Signorini-Coulomb is considered (see Fig. 1). The Signorini condition imposes a non-penetration condition while the Coulomb law corresponds to dry friction. In addition, impacts with null restitution are considered.

MBS formalisms are based on the same fundamental equations, i.e. the Newton–Euler equations. Several approaches exist, in particular for the description of the kinematics of the multibody chains. In the present work, relative coordinates are used [5]: the position and orientation of each body is defined with respect to a parent body (see Fig. 2). The variables of the system correspond to the degrees of freedom of the joints. In case of MBS presenting a tree-like structure (see Fig. 2a), i.e. there

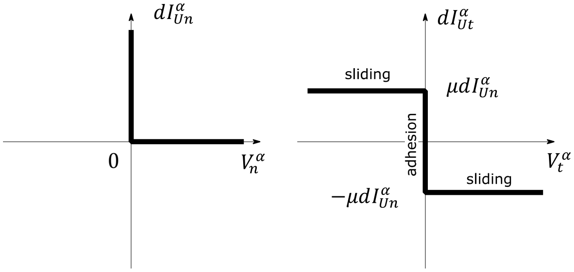

Fig. 1 Illustration of the Signorini-Coulomb law for a contact α between two particles. Left: in the normal direction, the Signorini condition imposes a complementarity relation between the normal component V_n^{α} of the relative velocity and the normal reaction $\mathrm{d}I_{Un}^{\alpha}$. Right: the Coulomb law defines sliding and adhesion zones for the relation between the tangential reaction $\mathrm{d}I_{Ut}^{\alpha}$ and the tangential component V_n^{α} of the relative velocity depending on the normal reaction and the friction coefficient μ

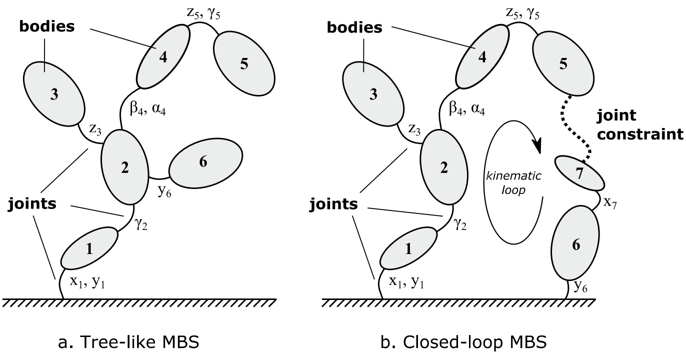

Fig. 2 Defining the kinematics of a multibody system (MBS) using relative coordinates. Left: a MBS with a tree-like structure: there is one path only between each body and the absolute frame. Right: a closed-loop MBS presenting a kinematic loop: one of the joints must be replaced by an algebraic constraint

is only one path from each body to the absolute frame, the equations of motion result in a system of ordinary differential equations (ODE). Formulated in terms of differential measure this set of equations can be written as follows:

$$\mathbf{M}_M(\mathbf{q}_M)\mathrm{d}\mathbf{v}_M = \mathbf{f}_M(\mathbf{q}_M, \mathbf{v}_M, t)\mathrm{d}t + \mathbf{H}_M(\mathbf{q}_G, \mathbf{q}_M)\mathrm{d}\mathbf{I}_U$$

where $\mathbf{q}_M$ is the vector of joint position; $\mathbf{v}_M$ is the vector of joint velocities; $\mathrm{d}\mathbf{v}_M$ is the differential measure associated with the multibody joint velocity; $\mathbf{M}_M$ is the mass matrix; $\mathbf{f}_M$ groups the non-linear dynamic terms, the forces/torques applied on the system and the joint forces/torques; $\mathbf{H}_M$ is the global–local mapping operator that links the multibody generalized coordinates to the contact coordinates.

Many MBS present kinematic loops (see Fig. 2b) which implies adding algebraic constraints, resulting in a set of differential–algebraic equations (DAE). In that case, the coordinate partitioning technique [5, 6] is used to reduce the DAE set to an ODE system presenting the same form as for tee-like MBS (See Ref. 1 for details).

The interaction between the machine and the ballast comes from the contact between ballast stones and some parts of the machine. Thus the dynamic coupling of the two-equation sets results from the contribution of the contact problem and leads to the following system:

$$\begin{bmatrix} \mathbf{M}_G & 0 \\ 0 & \mathbf{M}_M(\mathbf{q}_M) \end{bmatrix} \begin{bmatrix} \mathrm{d}\mathbf{v}_G \\ \mathrm{d}\mathbf{v}_M \end{bmatrix} = \begin{bmatrix} \mathbf{f}_G(\mathbf{q}_G, \mathbf{v}_G, t) \\ \mathbf{f}_M(\mathbf{q}_M, \mathbf{v}_M, t) \end{bmatrix} \mathrm{d}t + \begin{bmatrix} \mathbf{H}_G(\mathbf{q}_G, \mathbf{q}_M) \\ \mathbf{H}_M(\mathbf{q}_G, \mathbf{q}_M) \end{bmatrix} \mathrm{d}\mathbf{I}_U$$

This set of equations is discretized using a monolithic and implicit scheme, following the Moreau time-stepping method [2, 7]. The non-linear force vector $\mathbf{f}_M(\mathbf{q}_M, \mathbf{v}_M, t)$ is integrated explicitly. For the granular media, non-linearities of $\mathbf{f}_G(\mathbf{q}_G, \mathbf{v}_G, t)$ come from the angular velocity and require a specific treatment. The global–local mapping is used so as to formulate the dynamic equation in the local frame where the contact problem is solved. For this purpose, a Non-Linear Gauss-Seidl (NLGS) procedure is used. It consists of solving each contact one by one, assuming the others are solved. The operation is repeated several times until the algorithm converges to a solution.

The method is implemented by coupling two software programs: LMGC90[1] developed for the modelling of granular materials and ROBOTRAN[2] dedicated to MBS. On one hand, ROBOTRAN computes the kinematics and the dynamics of the multibody chains [8]. It is based on a symbolic approach which enables it to easily give access to the equations of motion to LMGC90. On the other hand, LMGC90 calculates the dynamics of the ballast grains. Furthermore, LMGC90 gathers internal data with information coming from Robotran to perform a collision detection. Then, the NLGS algorithm of LMGC90 solves a monolithic contact problem accounting for the dynamics of both systems. The contribution of the contact problem solution is then accounted for in the dynamics of each system by the corresponding software.

The multibody model of the machine is illustrated in Fig. 3 is composed of 8 rigid bodies. It presents 2 kinematic loops. The mainframe is assumed to follow a vertical motion controlled by a joint force. Hydraulic actuators are modelled using two bodies connected by a prismatic joint where the squeezing force is applied. They are mounted on an eccentric shaft driven by a joint torque. This results in 4 degrees of freedom for the tamping unit. The ballast and the sleeper are modelled by convex polyhedra. The friction between the particles and between the particles and sleepers is set to 0.8, the restitution coefficient at contact to 0 and the rock density 2700 kg/m^3. The interaction of the two subsystems results from the contact of the tamping tool (arms and tines) with the ballast grains.

[1] https://git-xen.lmgc.univ-montp2.fr/lmgc90/lmgc90_user.

[2] http://www.robotran.eu.

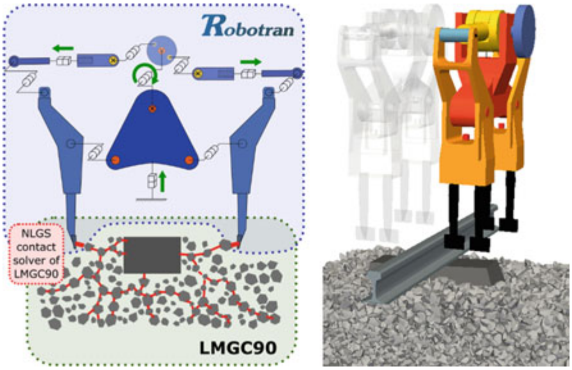

Fig. 3 Illustration of the strongly coupled MBS-DEM modelling of the tamping operation. Left: Schematic view of the model of one type of tamping machine modelled in Robotran interacting with a granular model of the track in LMGC90. The LMGC90 contact solver ensures the dynamic monolithic coupling between the two subsystems. Right: Screenshot of the 3D model before the machine enters the ballast

3 Maintenance Operations Modelling

3.1 Reduction of Ballast Fragmentation Due to Tamping

Tamping is a process used to put back into place the sleepers which have settled under traffic: each sleeper is lifted to its right position and the ballast under it is compacted in order to maintain it at that position. Tamping can be decomposed into two phases: insertion of the compacting tines on both sides of the sleeper and then squeezing of the ballast beneath that sleeper (Fig. 4). Although the tines are vibrating, the insertion phase can substantially damage the ballast hindering its shearing strength. One of the objectives of the present study was to reduce that degradation by measuring the

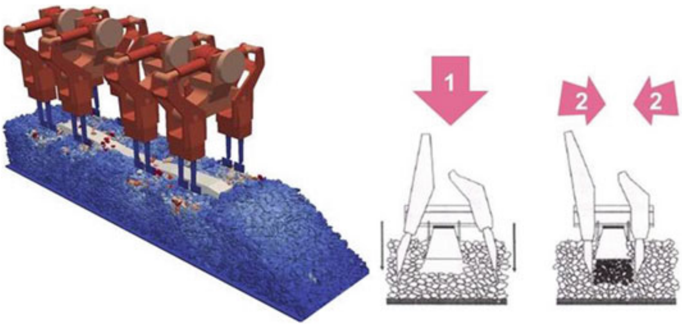

Fig. 4 Configuration of tamping simulations

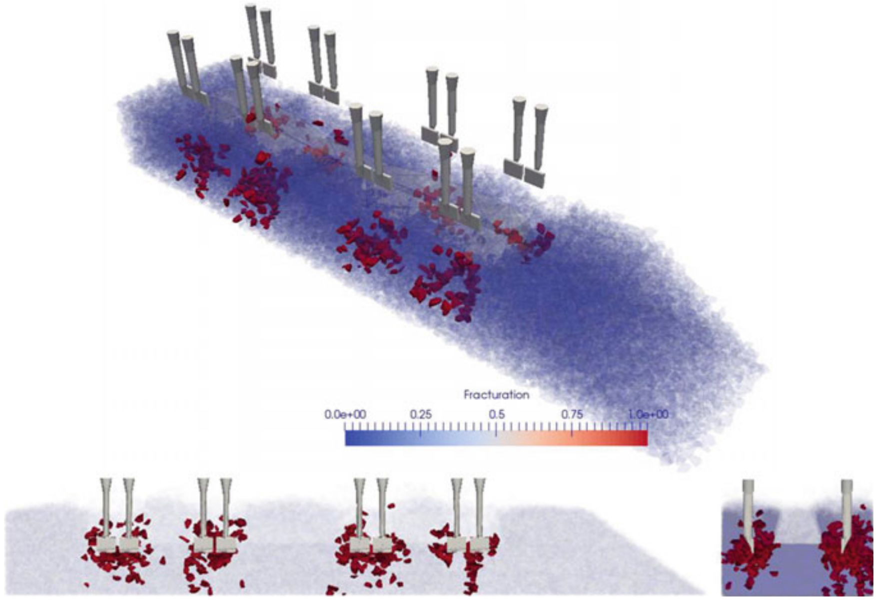

Fig. 5 Localization of fractured grains (in red) within the ballast layer

stress sustained by the ballast grains during tamping using the ability of the discrete element method to monitor the forces acting on each of them.

Figure 5 highlights in red the ballast grains which have sustained a pressure higher than the granite fragmentation threshold of 12 MPa (internal SNCF source) during tamping. Fragmentation is localized around the trajectory of the tines and occurs more significantly at the end of insertion. These results confirmed that tamping is very aggressive to ballast.

Different solutions have been analyzed to fluidize the ballast and hence temporarily reduce its shearing strength to facilitate the insertion of the tines but they have proved insufficient to reduce ballast fragmentation [9]. The present study explored the optimization of the insertion speed of the tines. The authors observed that the fragmentation of the ballast grains is higher at the end of the insertion and tried to decelerate the tines before they reach their final depth. In order not to increase the total tamping time, which can hinder maintenance operations, it was necessary to set the initial speed higher: in the end the longer the deceleration phase the higher the initial speed. Figure 6 (left) explains the tine insertion speed profiles analyzed: the conventional constant speed mode and additional profiles including a deceleration with initial speed between 1.7 and 2.5 m/s. Figure 6 (right) shows that even if the initial speed is higher the number of fractured ballast grains tends to decrease. A statistical analysis is necessary to confirm this tendency but because of the granular nature of ballast, deviation from this pattern can still be observed such as the one for 2.3 m/s.

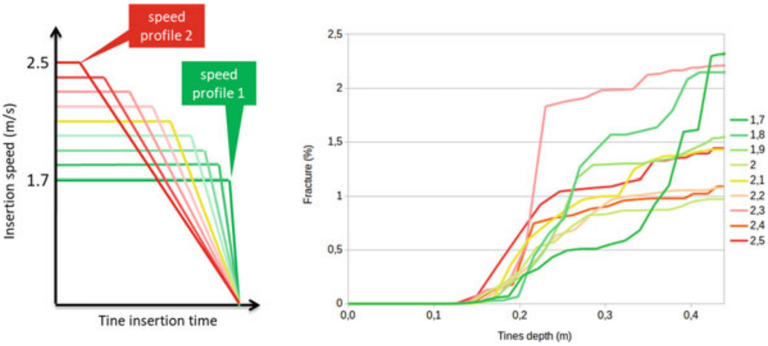

Fig. 6 Insertion speed profiles (left) and related fractured ballast grains numbers (right)

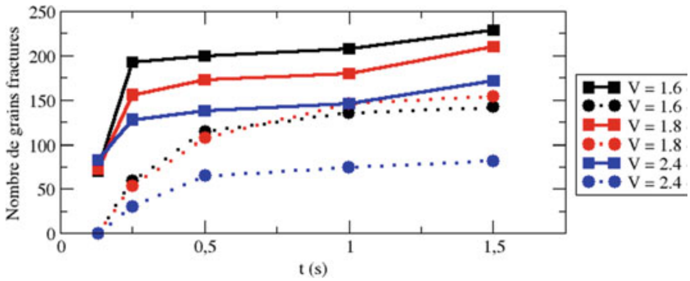

Fig. 7 Number of fractured ballast grains with (dot lines) and without (continuous lines) MBS

The DEM approach coupled with MBS (ROBOTRAN) has been used to model the same process. Figure 7 presents a comparison of the numbers of fractured ballast grains estimated from the stress on the grains at five different times of tamping simulation using MBS or not for three initial insertion speeds and taking into account a 12 MPa fracturing threshold. It shows that the non-MBS approach over-estimates the number of fractured grains as can be expected in a model where the trajectories of the tamping tines are fully defined. The results with MBS confirmed that prescribing a deceleration of the tines at the end of the insertion helps to decrease the fragmentation of the ballast grains.

3.2 Comparison of Crib Compaction with Dynamic Stabilization

Even if it corrects its geometry, tamping is not sufficient to restore the track to full operational conditions: the ballast layer density is not homogeneous anymore and the contacts with the sleeper are reduced impacting, in the same manner, the lateral resistance of the track crucial to prevent rail buckling during heat waves.

This condition after tamping impedes regular traffic and requires that trains travel at lower speeds completing a given tonnage high enough to stabilize the ballast layer. This stabilization corresponds to a denser rearrangement of the ballast grains under the vibrations created by the trains rolling on the track. This rearrangement can be accelerated by transferring directly mechanical energy to the ballast layer by vibrating the rails using dedicated equipment. This is the idea behind dynamic stabilization where the rails are vibrated laterally while a load is applied to them. This process is now systematically applied after tamping on the French railway network. However, there are situations where it cannot be applied, such as on steel bridges because of possible resonance phenomena. Crib compaction is a possible alternative to dynamic stabilization but is barely used in France. Before being implemented, it was assessed experimentally and numerically as in the present study by comparison to dynamic stabilization.

Both dynamic stabilization and crib compaction were compared numerically using a four sleeper section (Fig. 8). In dynamic stabilization, the lateral speed of the sleepers was set to a cyclic signal of 0.2 m/s at 25 Hz limited in amplitude by a 0.75 Hz sinusoidal envelope, repeated twice. Simultaneously a bell-shaped load of 60 kN was applied. In crib compaction, a vertical vibrating load of 50 Hz/45 kN was applied on the cribs and shoulders of the track for 2 s. These are typical values for both processes.

While in dynamic stabilization the ballast layer surface was barely modified, in the crib compaction process the shoulders of the track were heavily settled by the side compactor (Fig. 9) and in the end the ballast, profile did not comply anymore with the French standard. Figure 10 shows a comparison of the density along the track after tamping, dynamic stabilization and crib compaction. The initial layer of ballast was created by letting ballast grains settle under gravity leading to a homogeneous layer in terms of density around 55% (ratio between volume of rocks and volume of rocks + voids). After tamping, the layer was heterogeneous and presented peaks of density under the sleepers. After crib compaction, the layer was denser and more homogeneous. After dynamic stabilization, the layer was denser but still

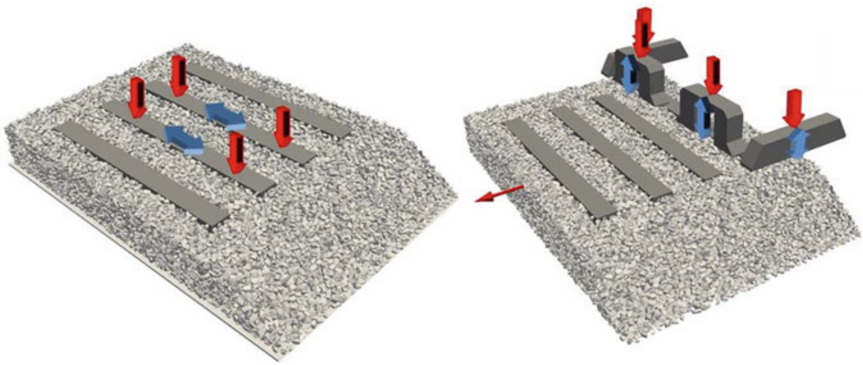

Fig. 8 Concepts of dynamic stabilization (left) and crib compaction (right) in simulations

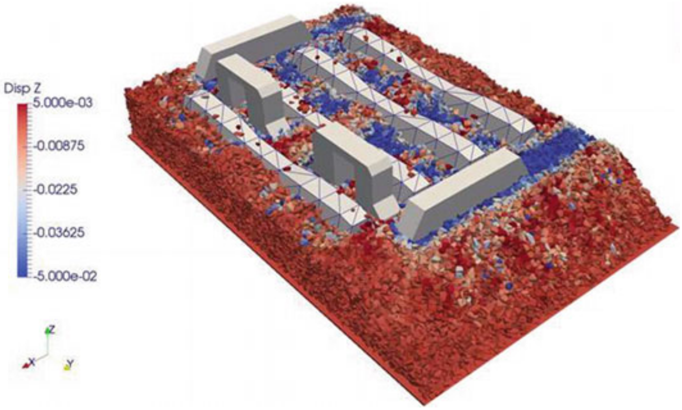

Fig. 9 Settlement of ballast after crib compaction in simulations

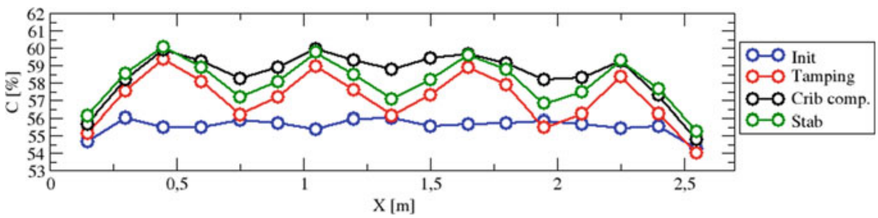

Fig. 10 Density of the ballast layer along the track

heterogeneous. Further simulations of crib compaction without side compactors are underway and seem promising in terms of compaction.

Figure 11 shows that the two processes worked in opposite ways. Crib compaction pushed the ballast grains of the cribs under the sleepers while dynamic stabilization moved them away from under the sleepers to the cribs leading to a settlement of the track.

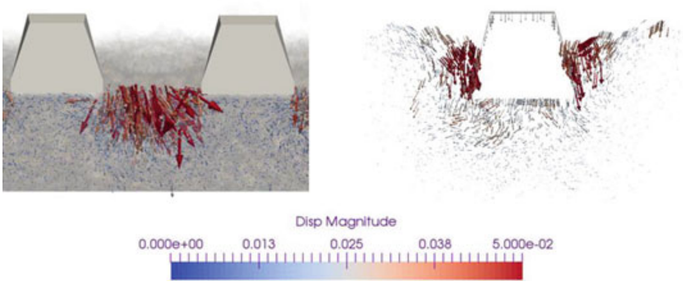

Fig. 11 Displacements of ballast grains in dynamic stabilization (left) and crib compaction (right)

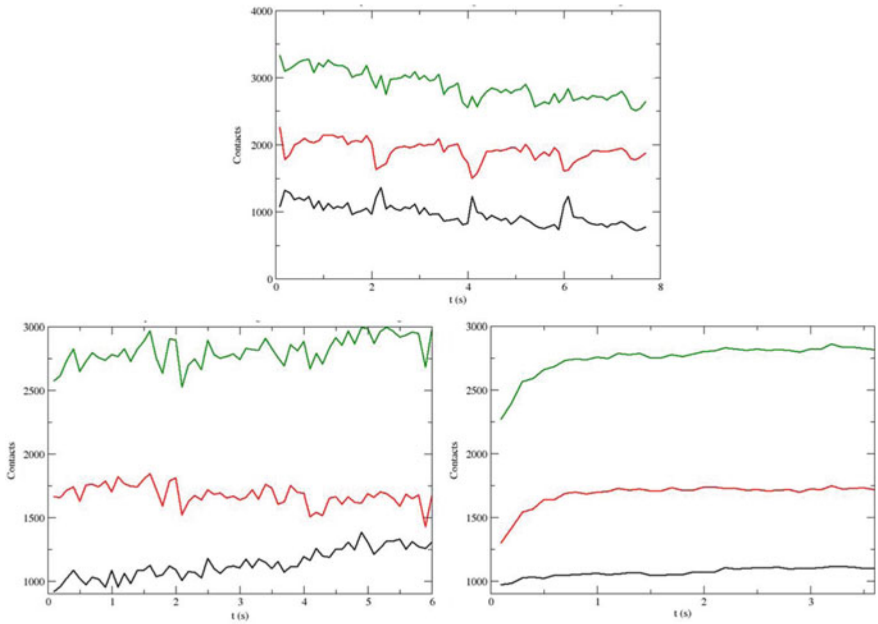

Fig. 12 Evolution of the number of contacts underneath the sleepers (in black) on the sides of the sleepers (in red) and all (in green) during tamping (top), during crib compaction (bottom left) and during dynamic stabilization (bottom right)

The performance of each process can be measured by the number of contacts created between the ballast grains and the sleepers because the more contacts the better the lateral resistance of the track for similar densities. Figure 12 shows the evolution of the number of contacts underneath the sleepers and on the sides of the sleepers during all processes. Tamping obviously decreased the number of contacts particularly under the sleeper confirming the instability of the layer after this process. Crib compaction increased the number of contacts under the sleepers while dynamic stabilization increased the number of contacts on the sides of the sleepers. Previous internal studies have shown that the bottom of the sleeper contributes at a higher level to the lateral resistance than the sides of that sleeper which means that a higher lateral stability can be expected after crib compaction than dynamic stabilization. Further simulations are underway to clarify this assumption.

4 Conclusions

The discrete element approach is an adequate method to analyze and optimize the maintenance processes of ballasted railway tracks and is even more efficient when coupled with the multibody system method.

The simulation results show that the fragmentation of ballast due to tamping can be reduced by controlling the insertion speed of the tines. They also confirm that crib compaction is an efficient alternative to dynamic stabilization in terms of compaction capability and potentially lateral resistance of the track.

Experimental tamping tests are underway to confirm and measure the effect of tamping on the degradation of ballast.

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