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► **To cite this version:**

Gilles Saussine, Emilien Azéma, P.E. Gautier, Robert Peyroux, Farhang Radjai. Numerical modeling of the tamping operation by Discrete Element Approach. World Congress Rail Research, 2008, South Korea. pp.1-9. hal-00686441

HAL Id: hal-00686441

<https://hal.science/hal-00686441v1>

Submitted on 10 Apr 2012

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Numerical modeling of the tamping operation by Discrete Element Approach

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Abstract

Ballasted tracks have been widely used because of their flexibility from the point of view of construction and maintenance. The deterioration of the railway track under heavy train traffics induces various irregularities in the track mainly due to differential settlement. In order to restore the initial geometry of the track, the ballast tamping operation is currently in use. In this work, we focused on the influence of tamping on ballast compaction by means of three-dimensional Discrete Element Method (DEM) simulations.

Introduction

Deterioration of the track geometry by apparition of irregularities under circulation is an important source of maintenance cost. This deterioration is mainly caused by the settlement of the substructure which tends to depend on the site conditions. The ballast is one component of the track which assumes important functions: retain track position, transmit efforts to the underlying materials, provide drainage for water falling onto the track and can be rearranged during maintenance to restore track geometry. For this last case ballast providing the fastest and most economical method of restoring track geometry by using the tamping process.

The tamping process is currently used to restore the geometrically track position. The method compacts the ballast below the sleepers through vibration and pressure squeezing forces. The process involves lifting the sleeper to a desired level and inserting tamping tines into the ballast with the lifted sleeper between each pair of tines. The tamping tines then squeeze ballast to fill the void underneath the lifted sleeper. The impact from the insertion of the tamping tines into the ballast and the high squeezing force have been found to cause particle breakage [13]. The main objective of the operation is to fulfill the void under the sleeper by compaction process.

The ballast compaction process in confined case is actual field of research. The dynamics of dense granular materials subjected to vibrations involves collective phenomena resulting from kinematic constraints (steric exclusions, weak spatial dimensions) and energy dissipation [8]. Three different states can be distinguished depending on the intensity and frequency of vibrations: gas-like or fluidized state, solid-like state, liquid-like state. In most work reported on vibrated granular media, the collective dynamics of the particles and the influence of various parameters related to the material or the driving system have not been investigated in all details. Moreover, in nearly all studies, spherical or nearly spherical particles in 3D or disks or polygons in 2D have been used [1].

A better understanding of the compaction by tamping process is important for the long term stability of track. The discrete element approach has been used in the work of X. Oviedo [12] to characterize in two dimensions the influence of frequency on tamping ballast process. This work has underline the different ballast state, liquid, gaz, solid and the influence of vibration on the connection of grains and sleeper base at the end of the process. From the numerical developments of three-dimensional discrete element approach [7,4] which can take into account the ballast grains shape some investigations have been carried on a sample composed of ballast bed, sleeper and eight tamping tines in order to reproduce ballast tamping.

The paper will focus on the different phases of the tamping process, namely the penetration of tamping tines in the ballast and squeezing of ballast between tines [3]. We begin with an introduction to the numerical method, then we present the results obtained on the numerical simulation of tamping process for different vibration frequencies.

1. Numerical procedures

The simulations were carried out by means of the contact dynamics (CD) method with irregular polyhedral particles. In this section we present the properties of this numerical method and compare it to a more classical numerical approach molecular dynamics (MD).

The CD method is based on implicit time integration and nonsmooth formulation of mutual exclusion and dry friction between particles in case of contact [9,10,5,4,7]. The equation of motion for each particle are written in term of differential inclusions in which velocity jumps replace accelerations. The unilateral contact interactions and Coulomb friction law are represented as set-valued force laws according to convex analysis.

The approach is characterized by a time-stepping approximation, and in this work we use a time integrator like theta - method. The implementation of the time-stepping scheme requires that the contacts taken into account in the considered step are geometrically described: definition of contact normal and contact location.

The contact law is defined by a nonsmooth relation between the normal force and the normal relative velocity, signorini conditions, and the Coulomb friction law friction force and sliding velocity at a contact are not related together via a mono-valued function. The collision law is taken into account by introducing a restitution coefficient which relates the relative velocities before and after contact. In our simulations where we consider a dense packing, we choose 0 for the normal and tangent restitution coefficient.

For a collection of particles, for each time step, the aim is to solve the core problem in order to find for each contact between particles the local relative velocities and the local reactions. This interaction problem is solved by an iterative solver called non-linear Gauss-Seidel which consists to solve a single contact problem with other contact forces treated as known and consequently updating interaction, until a certain convergence criterion is fulfilled.

At a given step of evolution, all kinematics constraints implied by enduring contacts and the possible rolling of some particles over others are *simultaneously* taken into account, together with the equations of dynamics, in order to determine all velocities and contact forces in the system. The method is thus able to deal properly with the *non local* character of the momentum transfers, resulting from the perfect rigidity of particles in contact. The CD method makes no difference between smooth evolution of a system of rigid particles during one time step and nonsmooth evolutions in time due to collisions or dry friction effects.

The MD-like methods are based on regularization schemes where impenetrability is approximated by a steep repulsive potential and Coulomb's law by a viscous- or elastic-regularized friction law, to which smooth computation methods can be applied. In this case the choice of a viscous parameter or elastic properties is not easy in particular with particles with irregular shape. This regularization implies the choice of smaller time step in order to preserve the stability of the integration scheme comparing to the CD approach. The uniqueness is not guaranteed by CD approach for perfectly rigid particles in absolute terms. However, by initializing each step of calculation with the forces calculated in the preceding step, the set of

admissible solutions shrinks to fluctuations which are basically below the numerical resolution. In MD-based simulations, this "force history" is encoded by construction in the particle positions.

We used LMGC90 which is a multipurpose software developed in Montpellier, capable of modeling a collection of deformable or undeformable particles of various shapes (spherical, polyhedral, or polygonal) by different algorithms [4].

2. Numerical study of ballast tamping

2.1 Numerical parameters

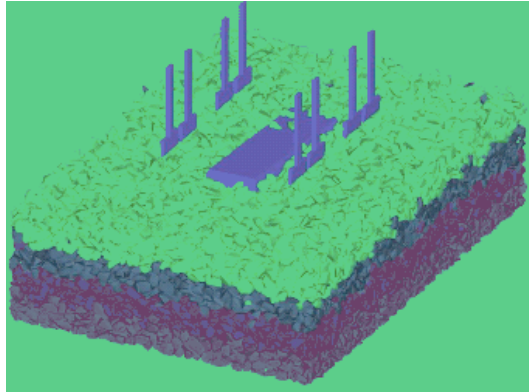


Figure 1 : Sample of ballast submitted to ballast tamping process

The numerical simulations take into account a set of rigid grains with a polyhedral shape which come from digitalization of railway ballast grains. The considered sample presented on figure 1 contains nearly 30000 particles which respect the ballast granulometry, 25/50 mm. The density is fixed to 2700 kg/m^3 .

The particles are initially placed in a rectangular box ($L=2 \text{ m}$, $l =1.4 \text{ m}$, $H=0.6 \text{ m}$) and deposit under gravity. Then grains have been remove to introduce a sleeper with an initial gap with the ballast bed of 1 cm.

The coefficient of friction between the particles is fixed to 0.5, and 0 with the walls. The restitution coefficient is fixed to zero because we consider dense sample of grains.

We impose the harmonic force on the tamping tines horizontally and imposed a vertical velocity for the 8 times of 1 m/s. Then we focused on the ballast behaviour under the sleeper and the compaction process for the different phases of tamping cycle: penetration, squeezing, tamping tines lift.

2.2 Ballast compaction

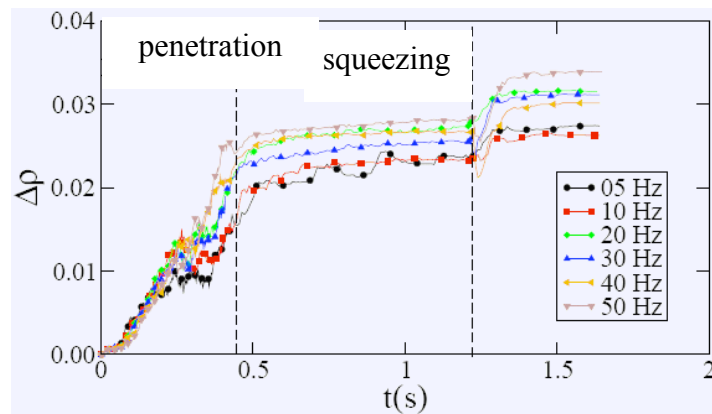


Figure 2 : Evolution of the compaction gain under the sleeper.

The penetration phase is characterized by applying on tamping tines a driven velocity and stop when the space between the top of the tamping tine plate and the sleeper base is 2 cm free. The numerical computations put in evidence (Fig. 2):

- a similar evolution of during 0.1 s which represents the time to the bottom of tamping tines to reach the sleeper base. During this phase the compaction under sleeper increase without influence of frequency,
- when the bottom part of tamping tines is under the sleeper, the evolution of the compaction depends of the vibration frequency applied.

As a result for this phase, the increase of frequency gives a better compaction under sleeper.

The squeezing phase is characterized by applying a harmonic horizontal force on the tamping tines during 0.8 s. For all frequencies we observe an increase of the compaction under the sleeper. But it is important to notice that the compaction gain during this phase is more important for a low frequency, 5 Hz. For this frequency the time relaxation of ballast grains under the action of tamping tines is more important, which implies a better compaction increment for each vibration period of tamping tines.

The last phase when the tamping tines go out of the ballast bed is characterise by:

- a similar evolution of compaction under sleeper, a little decrease of compaction level during 0.1 s and increase of ballast compaction until the tamping tines are into the ballast bed,
- the final level of compaction is clearly influenced by the vibration frequency. For 50 Hz, the compaction gain during this last phase is the more important.

From these investigations on the influence of frequency on the compaction level of the tamping process, the penetration phase contributes to 50 % of the total compaction obtain at the end of the cycle. The high frequencies about 40 Hz – 50 Hz are not characterized by a ballast liquefaction for all the sample. It has been noticed a local liquefaction of ballast around the tamping tines.

2.3 Evolution of the ballast structure under the sleeper

The ballast behaviour under the action of tamping tines can be characterized by two indicators:

- the coordination number, z , which represents the average number of neighbors for one grain in the sample,
- the number of grains in contact with the sleeper, N_c .

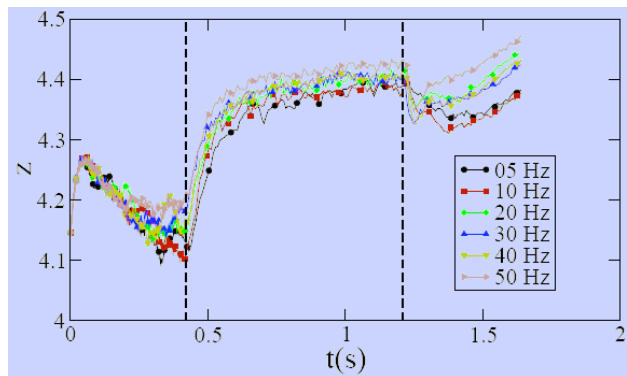


Figure 3 : Evolution of the coordination number under the sleeper.

The coordination number is a local descriptor of compacity at the grain scale. The evolution of z is similar for all frequencies. During the penetration phase, we can notice a decrease under the action of tamping time of the coordination number. In this phase, even if the global compaction level increase, the local compaction is influenced by the vibrations which implies a lost of contacts between grains (Fig. 3).

During the squeezing phase, the coordination increase quickly during the first vibration cycle to reach a steady state. The action of global compaction modifies the local grain arrangement by increase the contact number between grains.

During the last phase the coordination number follows the evolution of the compacity under the sleeper with a similar evolution for each frequency. We can notice an increase of the coordination number of the complete tamping cycle.

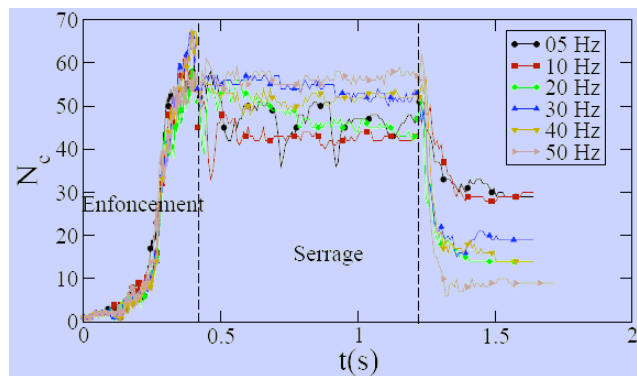


Figure 4 : Evolution of the number of grains in contact with the sleeper

The evolution of the number of grains which are in contact with the sleeper base can be interpreted as a stability indicator of the system. During the penetration phase, we observe an increase of N_c with a similar evolution for all frequencies. N_c reach an average value of 55 grains in contact with the sleeper (Fig. 4).

The squeezing phase is characterized by a lost of contact with low frequencies and more important variations. For 5 Hz, these variations have an amplitude of 10 grains and are the signature of the relaxation of the system and the higher level of compaction already observed. The last phase is characterized by an important decrease of the number of grains in contact with the sleeper:

- for 5 and 10 Hz, the average value at the end of the tamping process is about 30 grains,
- for 20, 30 and 40 Hz, the average value is about 20 grains,
- for 50 Hz, only 10 grains are in contact with the sleeper.

The high frequencies in the last phase of the process imply the migration of the grains on the side of sleeper in direction of the holes created by the motion of tamping tines out the ballast bed. This migration is induced by the transmission of vibrations between the grains.

As a result of a better compaction under the sleeper, the connection between ballast and sleeper base is less important for high frequency and the connectivity between ballast grains increase. This connectivity will be an important parameter to consider for vertical resistance of ballast sample.

2.4 Evolution of the ballast micro-structure under the sleeper

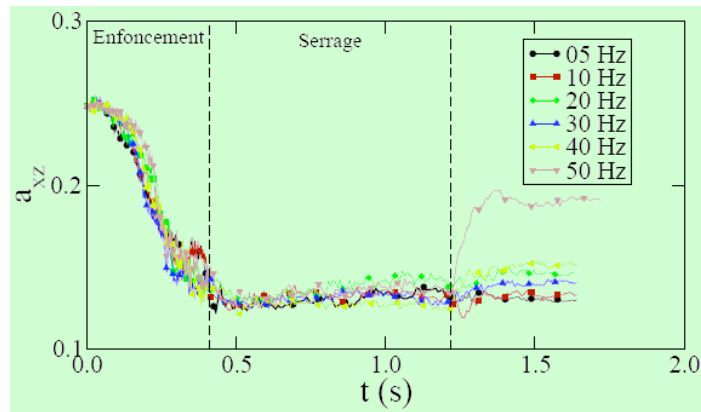


Figure 5 : Evolution of global anisotropy of the system in the plane (Oxy).

The origin of resistance of dense granular packing has been investigated for two dimensional systems composed of disk or polygons and recently for polyedra with ballast grain shape. The global anisotropy of system submitted to a sollicitation is a signature of the capacity of a granular sample to resist to an effort.

$$F = \frac{1}{N_c} \sum_{c \in V} n_\alpha^c n_\beta^c$$

Equation 1: Definition of Fabric Tensor.

A common approach to define the anisotropy of a system is to consider the probability distribution $P(n)$ of the contact normals n which are generically nonuniform. The probability density function P of contact normals provides detailed statistical information about the fabric tensor [2]. The Fabric tensor is calculated by considering for each contact c of the volume V , the dyadic product between the component of contact normal (eq. 1). The anisotropy of the system can be evaluated with the eigenvalues of the Fabric tensor. It has been shown that the origin of resistance for a sample of digitalized of ballast grains can be relate to the force anisotropy in the system [3].

On the figure 5, we can observe a decrease of the global anisotropy of the normal contact network. From this result on the evolution of the contact network we can underline:

- the lost of resistance of the ballast layer under the sleeper, in particular the decrease of anisotropy onto the lateral direction. This a clearly signature of the decrease of lateral resistance after a ballast tamping operation,
- the ballast tamping modifies the contact network which support cyclic vertical loading. The anisotropy of normal orientation or force network can be indicators to evaluate by mean of numerical simulations to improve the vertical stability of ballast layer.

- the vibration frequency has not an important role on this parameter, the penetration velocity and the squeezing force seems to be the parameter which control the evolution of this indicator.

2.5 Influence of tamping parameters

The main result of the study of the complete tamping process is the great importance of the penetration phase which contributes to 50 % of the final compaction gain. During this phase the highest frequency induce the highest gain in terms of compacity under the sleeper.

During the penetration phase, the velocity can be controlled and three velocities have been imposed to the tamping tines: 1 m/s, 1.5 m/s and 2 m/s.

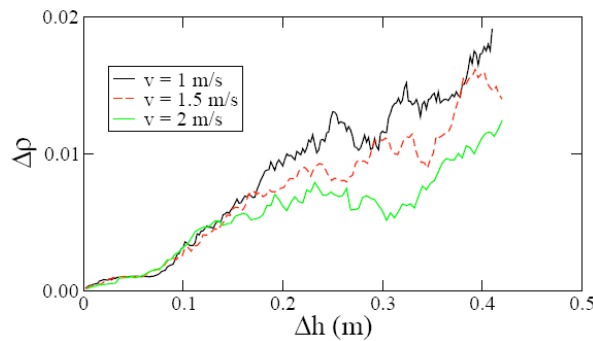


Figure 6 : Evolution of compaction for different velocities during penetration phase.

The figure 5 represents the evolution of compaction gain for the different velocities. We can notice a similar evolution for each case and in the final state the compaction level is less important for a high velocity. With the increase of penetration speed, the number of vibration cycles imposed to ballast is less important and the compaction process is less efficient. For these numerical computations, the final number of grains in contact with the sleeper is the same, about 60 grains.

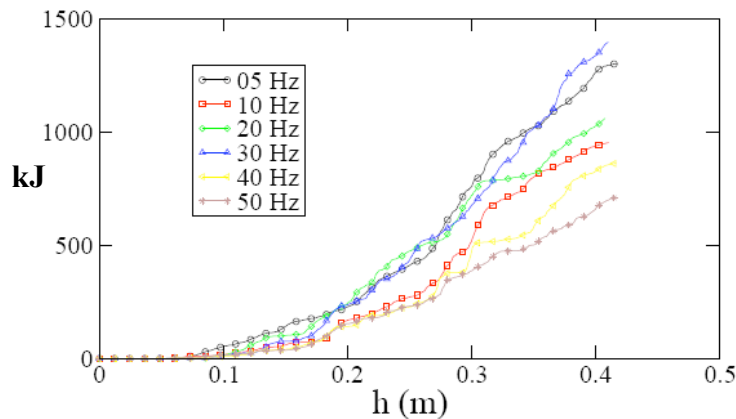


Figure 7 : Evolution of energy consumed by tamping tines during the penetration phase.

On the figure 6 the energy consumed by tamping tines are presented during the penetration phase. A high vibration frequency seems to have an important role to obtain an easier penetration of tamping tines. The local ballast liquefaction around tamping tines is a potential explanation of these results. Nevertheless in our case the energy evaluated is directly linked to the initial ballast configuration and a statistical approach is needed to explain the influence of frequency on the effort on tamping tines.

3. Conclusion

The objective of this paper is to propose a numerical study of ballast tamping by using three-dimensional discrete element approach. The ballast tamping process is currently employed for maintenance to restore track geometry and the main goal of the process is to obtain a good compaction under the sleeper.

However the compaction of dense granular packing is an active domain of research and three-dimensional granular tools which take into account angular grain shape allow new investigations. The numerical investigations presented in this paper consider a sample of digitalised ballast grains which is submitted to ballast tamping cycle with different frequency or penetration speed.

The main results obtain are:

- the important role of the penetration phase which contributes to 50 % of the final compaction gain,
- the increase of frequency will increase the compaction under the sleeper for the penetration phase and the last phase,
- the decrease of vibration frequency in the squeezing phase will increase the compaction gain which can be relate to the relaxation time of ballast under the action of tamping tines,
- the increase of penetration speed decrease the level of compaction,
- the tamping process decrease the resistance properties of ballast sample by modifying the organisation of contact and force network.

From these numerical results it will be interessant to evaluate this trends for different ballast state or shape and evaluate the vertical resistance under dynamic cyclic loading.

Acknowledgements

The authors gratefully acknowledge M. Valery from RFF (Réseau Ferrée de France) and Region Languedoc-Roussillon who provide the funding for this research.

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