IV International Conference on Particle-based Methods – Fundamentals and Applications
PARTICLES 2015
E. Oñate, M. Bischoff, D.R.J. Owen, P. Wriggers & T. Zohdi (Eds)

NON-SMOOTH CONTACT DYNAMIC APPROACH FOR RAILWAY ENGINEERING: INVESTIGATION OF BALLAST BEHAVIOUR UNDER STABILISATION PROCESS

JEAN-FRANCOIS FERELLEC[1], ROBERT PERALES[2], PIERRE-EMMANUEL LAURENS[1], MICHEL WONE[3], JULIA PLU[1] AND GILLES SAUSSINE[1]

[1]Direction Technique SNCF
6 av. François Mitterrand, 93574 La Plaine Saint Denis Cedex, France
congreso@sncf.fr

[2]AD'missions
20 rue Brunel, 75017 Paris, France

[3] ITG
24-26 rue de la Pépinière, 75008 Paris, France

Key words: Ballast, railway, stabilisation, polyhedron, DEM, NSCD.

Abstract. Railway maintenance procedures include the stabilisation of ballasted tracks. The procedure of dynamic stabilisation which consists in vibrating laterally the rail while applying a vertical load is analysed using a discrete element code based on non-smooth contact dynamics. The ballast stones are modelled realistically using polyhedrons based on real ballast stones scans. The evolution of the compaction level and contact number between particles is analysed during the dynamic stabilisation process. A model is proposed to predict settlement. The results of simulation show the effectiveness of this maintenance procedure. It also points out the relevance of the model to predict settlement.

1 INTRODUCTION

Traffic on railway lines becoming faster, more frequent and with higher loads require very strict maintenance procedures of railway tracks. The compaction or stabilisation of ballasted tracks is essential as it impacts the lateral resistance of the track which counters the buckling force of rails. This is particularly the case of the very common long welded rails along which build up large forces due to temperature variation of up to seventy degrees in French standards.

Procedures to stabilise or compact ballasted tracks rely mainly on models based on empirical observations and the fundamental mechanical phenomena involved in the ballast during these procedures are not fully understood.

Experimental in-situ or laboratory testing campaigns to analyse the mechanical behaviour of the ballast during the different types of maintenance procedures are costly both in terms of time and budget. To avoid these constraints engineers in charge of maintenance have opted for the numerical approach among which the continuous method is the most popular. In the case of ballasted track behaviour analysis, this latter presents however limits in representing the ballast material as it cannot reproduce the basic mechanics at the scale of the ballast stones which is essential in explaining the global behaviour of the ballast. The discrete element method (DEM) which models a granular material as interacting particles [1] is a more adequate numerical approach to analyse the mechanical behaviour of railway ballast and particularly the phenomena occurring during ballast stabilisation.

DEM has been developed in multiple variants in which the contact between the particles can be treated in different ways and where the shape of the particles is modelled in a more or less realistic way. In this latter the most common shape is the sphere as it facilitates the interaction treating process between the particles easier. Spheres however usually render the behaviour of real granular materials only in a qualitative way because of their simple shape. Efforts have been made to get models giving more quantitatively reliable results leading to some improvement [2-6] but failing to catch the irregular shape of real particles. In the last decade, newer models managed to reproduce the shape of real particles and in particular ballast stones [7-14] but they remained quite demanding in terms of computation time. In parallel of these recent realistic shape models, emerged a class of DEM taking into account the polyhedral shapes of ballast stones and based on an approach called non-smooth contact dynamic (NSCD).

The NSCD method is based on an implicit time integration of the equations of dynamics and a non-smooth formulation of steric exclusion and friction between particles [15-16]. This method requires no elastic repulsive potential and no smoothing of the Coulomb friction law for the determination of the contact forces between the particles as the conventional DEM models mentioned before would. For this reason, the simulations can be performed with large time steps compared to molecular dynamics or explicit DEM approaches.

In this paper, we propose an investigation of the process of ballast stabilisation using NSCD. In this process, the railway sleepers are loaded laterally along their main axis with a cyclic load and vertically with a constant simultaneous load in order to compact the ballasted track. A three-sleeper track section is modelled using LMGC90 an NSCD code where the ballast stones are represented by polyhedrons of irregular shapes based on real ballast particles scans and the sleepers by polyhedrons also based on regular geometry of real sleepers. Two different approaches are used to load the middle sleeper: an analytical vibration model and a sleeper acceleration spectrum measured in situ during a dynamic stabilisation. The dynamic stabilisation is preceded by a tamping process to prepare the ballast as it would on a real track. Finally the evolution of the solid fraction or compaction level of the ballast under the middle sleeper is analysed to verify the efficiency of the whole procedure.

The first section of this paper describes the NSCD approach and the corresponding LMGC90 code used in the analysis. The second part presents the dynamic stabilisation process in details and explains the configuration of the simulation. The final part discussed the results of the simulations in terms of evolution of the solid fraction, settlement and number of contacts between particles below the sleeper before concluding.

2 NON-SMOOTH CONTACT DYNAMIC MODEL

In this study, the simulations were carried out by means of the non-smooth contact dynamics (NSCD) method with irregular polyhedral particles. In this section we present the properties of this numerical method and compare it to the classical numerical approach called molecular dynamics (MD).

The NSCD method is based on implicit time integration and non-smooth formulation of mutual exclusion and dry friction between particles in case of contact [15-17]. The equation of motion for each particle is 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 non-smooth relation between normal force and normal relative velocity and Signorini conditions. 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 normal and tangent restitution coefficients equal to zero.

In an assembly 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 in solving 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 NSCD method makes no difference between smooth evolution of a system of rigid particles during one time step and non-smooth evolutions in time due to collisions or dry friction effects.

The MD-like methods are based on regularisation schemes where impenetrability is approximated by a steep repulsive potential and Coulomb's law by a viscous or elastic regularised 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 regularisation implies the choice of smaller time step in order to preserve the stability of the integration scheme compared to the NSCD approach. The uniqueness is not guaranteed by the NSCD approach for perfectly rigid particles in absolute terms. However, by initialising 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 here the NSCD based LMGC90 code which is a multipurpose software developed in Montpellier (France) and capable of modelling a collection of deformable or non-deformable particles of various shapes (spherical, polyhedral, or polygonal) by different algorithms [18].

3 SIMULATION OF DYNAMIC STABILISATION OF BALLASTED TRACK

3.1 Dynamic stabilisation concept

During maintenance, a ballasted track follows a specific sequence of procedures. The first step usually consists of correcting the geometry of the track by tamping. In the tamping process, each sleeper is lifted up before a set of vibrating tampers is inserted into the ballast on each side of the sleeper until their ends are located under the sleeper level. The ballast under the sleeper is then squeezed by these tampers. The tampers are finally retracted and moved to the next sleeper. After tamping the lateral resistance of the track is reduced hence the track requires stabilisation before being operational. This stabilisation can be performed naturally by relying on successive passages of trains of regular traffic at reduced speed leading to a relatively long period before the track is fully operational. This phase can however be speeded up by using the process of dynamic stabilisation.

The dynamic stabilisation is performed using equipment rolling on the rails, vibrating laterally the track and applying a vertical load simultaneously. The degree of stabilisation can be controlled by tuning the vibration frequency, vertical load or rolling speed. The objective of dynamic stabilisation is to reorganise the ballast stones, increase the lateral resistance of the track and homogenise the compaction of the ballast. It constitutes a faster alternative to the natural stabilisation using regular traffic.

3.2 Configuration of simulation

The track section sample used to analyse the dynamic stabilisation process is illustrated in figure 1. It presents a shoulder on one side and a vertical containing wall on the other side as if a contiguous line existed. 90000 ballast particles, which are represented by polyhedrons based on real ballast stone scans, are generated in a parallelepiped volume and settled under gravity. Three sleepers are created inside the ballast at the right positions replacing some of the ballast stones. The shoulder of the track is then created by removing some of the ballast stones. The sample obtained this way is a non-dense state. The middle sleeper is then tamped using a set of sixteen tampers (figure 1) before going through the dynamic stabilisation process. In this case the outside sleepers act as boundary conditions and are not tamped or stabilised. The friction coefficient between the particles and between the particles and sleepers has been determined equal to 0.8, the density of the ballast stone to 2700kg/m^3.

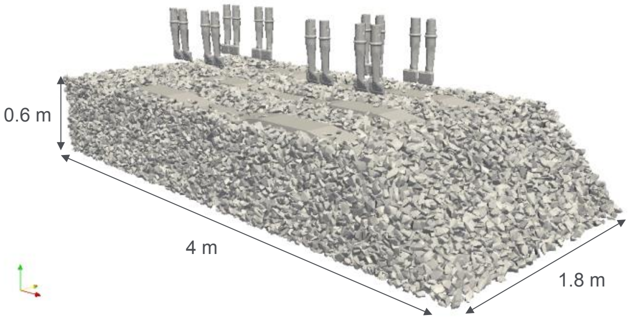

Figure 1: Track section sample configuration

3.3 Loading pattern

Two approaches were used to load the middle sleeper for the dynamic stabilisation. The first consist of exciting the sleeper using a signal based on the specifications of the stabilising equipment (figure 2.a). The lateral velocity of the sleeper oscillates with a sinusoidal amplitude evolution corresponding to the displacement of the stabilising equipment along the track. Two sinusoidal periods are implemented to represent two successive stabilising equipments. Simultaneously two vertical loads shaped in a sinusoidal way are applied corresponding to the displacement of the same two successive stabilising equipments.

The second approach used the lateral acceleration spectrum of a sleeper measured in-situ during a campaign of dynamic stabilisation. The lateral velocity obtained from the acceleration spectrum by simple integration is then applied to the middle sleeper as in the first approach. As for the vertical load, is it similar to the one used in the first approach. For industrial confidentiality reason, the lateral acceleration spectrum is not divulged in this paper.

Both approaches are based on a dynamic stabilisation process with a vibration frequency of 25Hz and amplitude of 2.5mm and a rolling speed of 2000m/h.

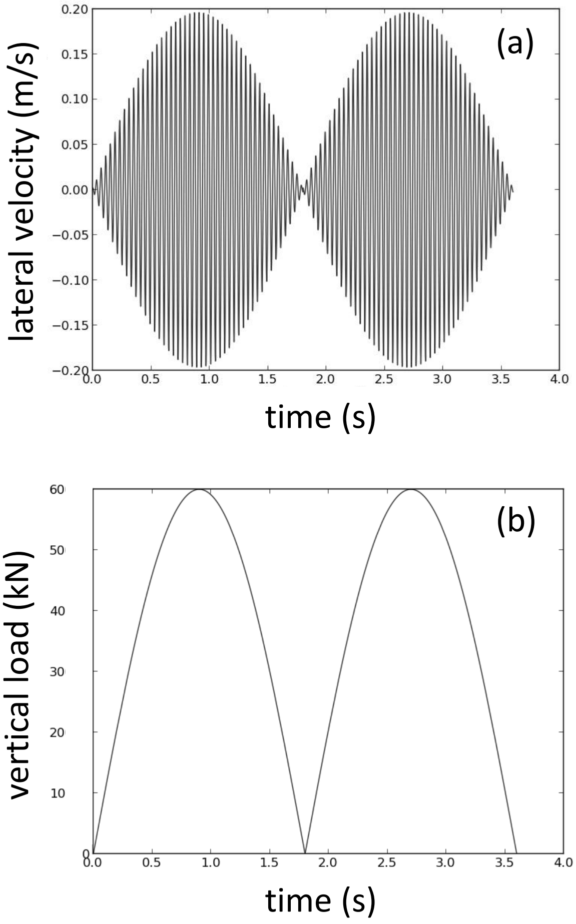

Figure 2: Lateral velocity of sleeper (a) and applied vertical load (b)

4 SIMULATION RESULTS

4.1 Compaction level

Compaction level or solid fraction, that is the fraction of solid phase inside the ballast, is one of the measurable parameters in simulations that help to measure the efficiency of the stabilisation process: a substantial gain in solid fraction is an indicator of a successful stabilisation. Solid fraction evolution is measured here under the middle sleeper for the stabilisation and also the tamping phase beforehand.

Figure 3 shows the evolution of the solid fraction gain during the tamping process. At the beginning of the process the solid fraction presents a slight decrease which is linked to the insertion of the tampers which disturb the ballast stones arrangement. Then during the squeezing phase of tamping, the solid fraction is progressively increased to reach a level of 6% approximately. The simulation clearly shows that tamping improves the compaction of the ballast under the sleeper.

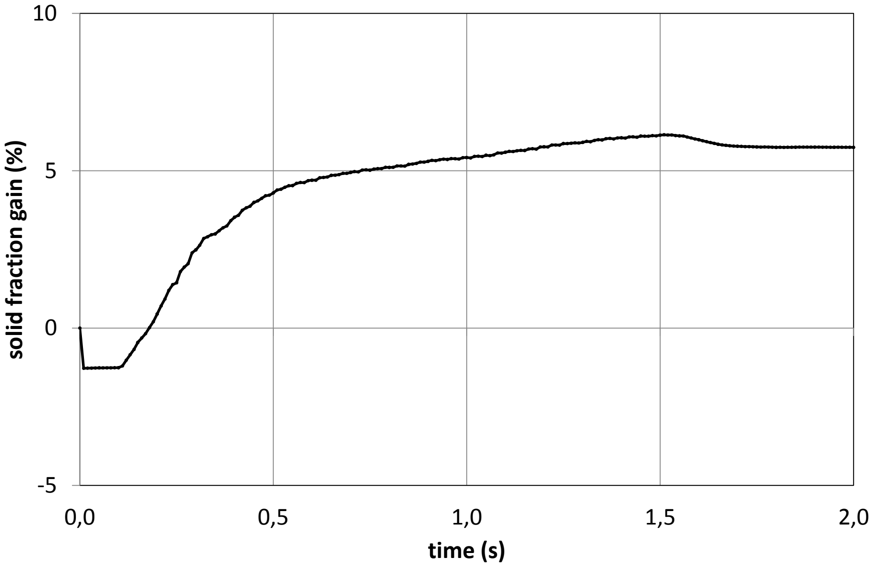

Figure 3: Solid fraction gain evolution during tamping

Figure 4 shows the evolution of the solid fraction in the simulation of the stabilisation using the first approach to model the vibration of the sleeper, the vibration model represented on figure 2. During application of both vibration waves, it shows a progressive gain of solid fraction with a decreasing rate reaching a final gain level of 4%. The first vibration wave offers a 3% gain higher than the second one only equal to 1%. The action of the vibration waves is not linear with time. Any additional wave would probably give a solid fraction gain lower than 1%. These results seems to show that the dynamic stabilisation process as described above, that is using two waves of vibrations, is enough to stabilise the ballasted track. Any additional passage of the equipment would not bring any substantial improvement.

The approach using the sleeper lateral acceleration spectrum presents a similar trend but with slightly lower gains in compaction. Figure 5 shows the evolution of the solid fraction in the simulation of the stabilisation using this second approach. The total gain reaches a maximum of around 3.3%. This difference can be explained by the fact that the acceleration spectrum was measured with a type of sleeper different from the simulation one. But as for the first approach, the first vibration wave offers a higher gain than the second wave: 2.5% compared to less than 1%. These second simulation results confirm that two waves are enough to stabilise the track.

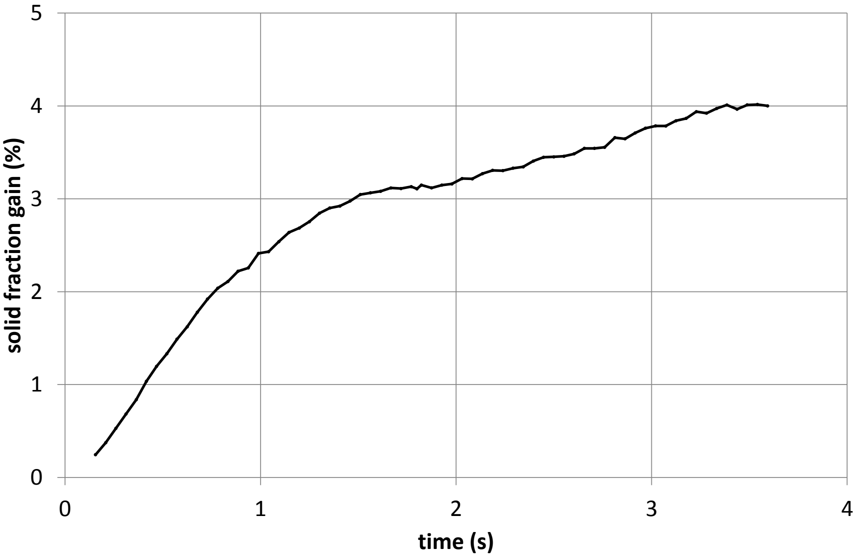

Figure 4: Solid fraction gain evolution during dynamic stabilisation using vibration model

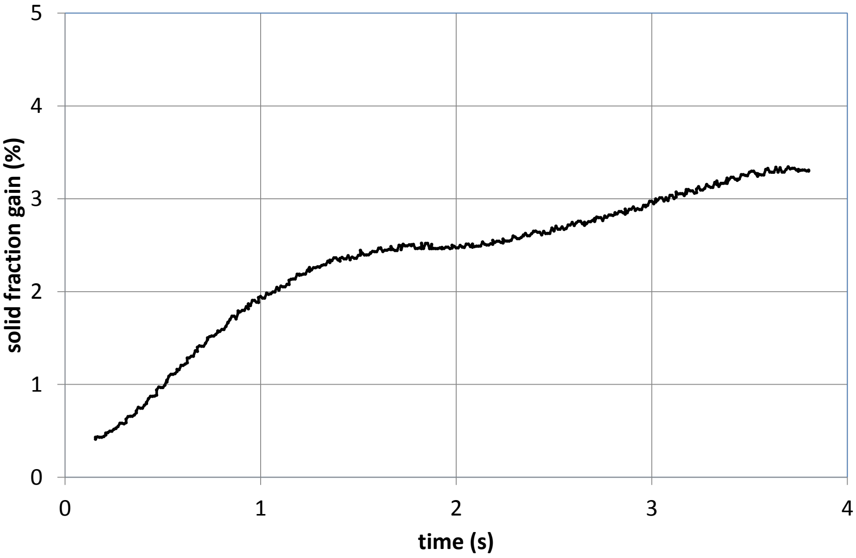

Figure 5: Solid fraction gain evolution during dynamic stabilisation using acceleration spectrum

4.2 Settlement

Figures 6 and 7 respectively show the settlement of the middle sleeper for the analytical vibration model and the spectrum approach. As expected the first approach, which gives the higher compaction gain, offers a higher final settlement of approximately 35mm while the second approach reaches 28mm. In agreement with the compaction, the first vibration wave gives a higher settlement than the second one. There is a clear correlation between the settlement and the solid fraction gain. The dynamic stabilisation is associated with a settlement of the track.

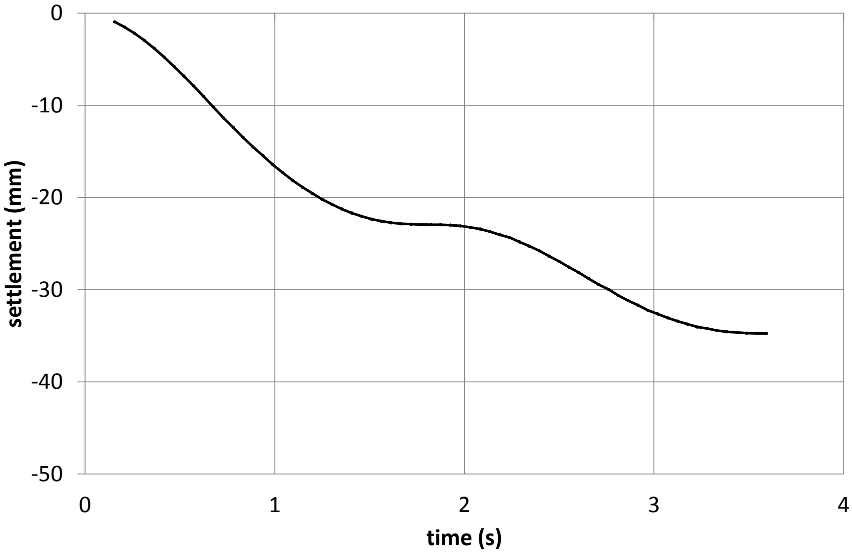

Figure 6: Settlement during dynamic stabilisation using vibration model

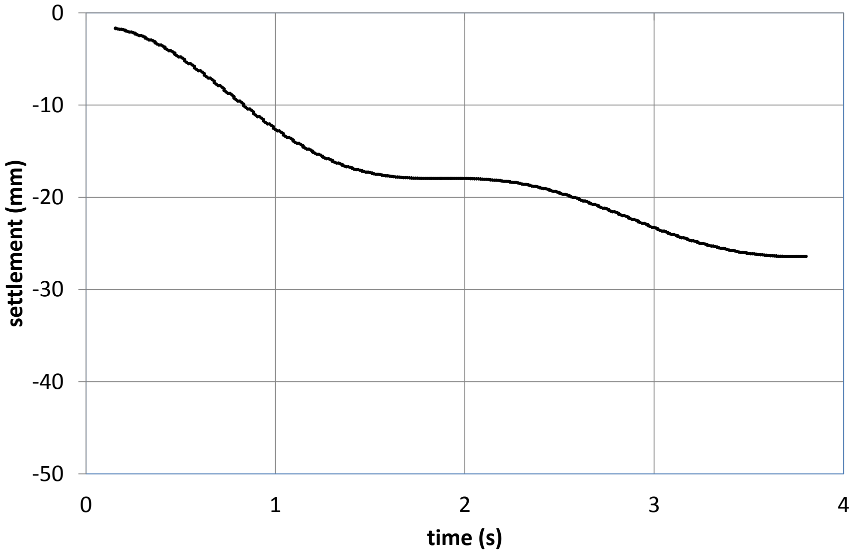

Figure 7: Settlement during dynamic stabilisation using acceleration spectrum

Previous simulations have been performed at SNCF (main railway company in France) to establish a model to estimate the settlement z of a track after a dynamic stabilisation which is based on research performed on pile insertion using vibrations [19]. Under a vertical load *F* and lateral vibration of amplitude a and frequency ν, the sleeper settlement z is estimated using the following equation:

$$z^2(t) = k.a.l.t.\nu.2\pi\frac{F}{m.g} \tag{1}$$

where k is a constant function of the sleeper shape, l the width of the sleeper, t the time and m the mass of ballast below the sleeper. As explained in section 3, the stabilising equipment is moving along the track at a constant speed. Subsequently each sleeper will actually be subject to the lateral vibration and vertical load illustrated on figure 2: a 25Hz lateral vibration and vertical load with varying amplitudes. In the end, the sleeper settlement is actually the combination of successive settlements due to vibrations of different amplitudes a_i and loads of different levels F_i:

$$z^2(t) = \sum_{i=1}^{n} k.a_i.l.t.\nu.2\pi\frac{F_i}{m.g} \tag{2}$$

Figure 8 shows a comparison of sleeper settlement during stabilisation obtained from the settlement model and from the simulation using the analytical lateral vibration and vertical load models of figure 2. Both curves present very similar trends pointing out the relevance of the settlement model proposed. It shows that this settlement model can be used to estimate track settlement assuming parameter k is known for the type of sleeper used on the track.

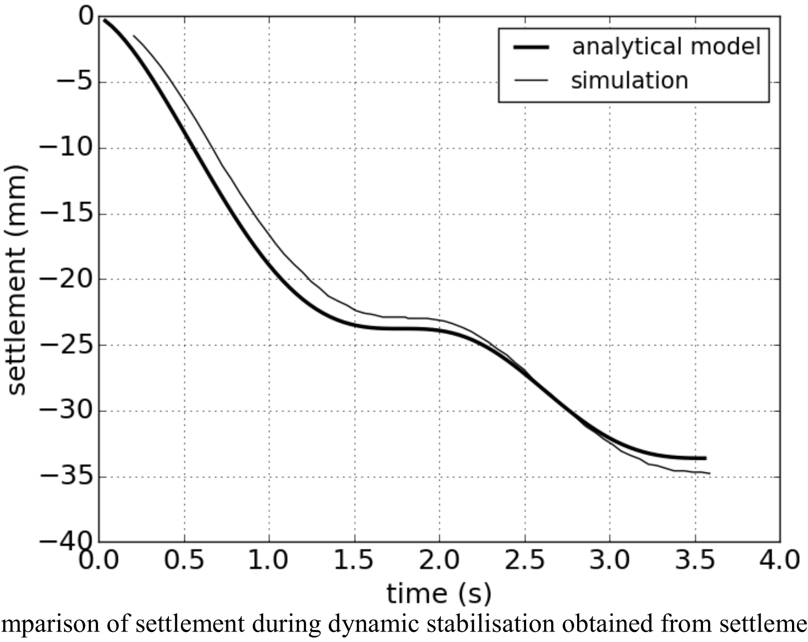

Figure 8: Comparison of settlement during dynamic stabilisation obtained from settlement model (▬) and from simulation with analytical vibration model (—)

4.3 Number of contacts

The evolution of the number of contact per ballast stone, or coordination number, helps understanding the phenomena occurring during the dynamic stabilisation process. Figures 9 and 10 show the evolution of the coordination number during the stabilisation for both vibration models for the ballast located under the middle sleeper. Each vibration wave clearly decreases the coordination number from 4 to 3.5. Each wave actually fluidises to a certain extent the ballast hence reducing the number of contacts between ballast stones. As a vertical load is applied simultaneously, this fluidised phase promotes the compaction of the ballast vertically. The rearrangement of the ballast stones is facilitated. The fluidisation temporarily reduces the resistance to shear of the ballast as a granular material. After stabilisation the coordination number returns to tis initial value of 4. In its final more compacted state, the ballast has hence probably reached a higher level of shear strength which in turn translates into a higher lateral resistance of the sleeper.

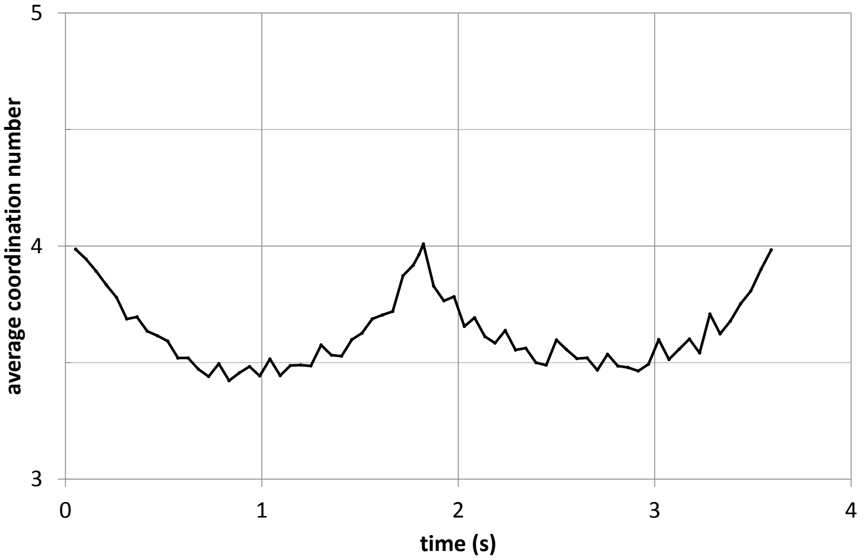

Figure 9: Evolution of coordination number during dynamic stabilisation using vibration model

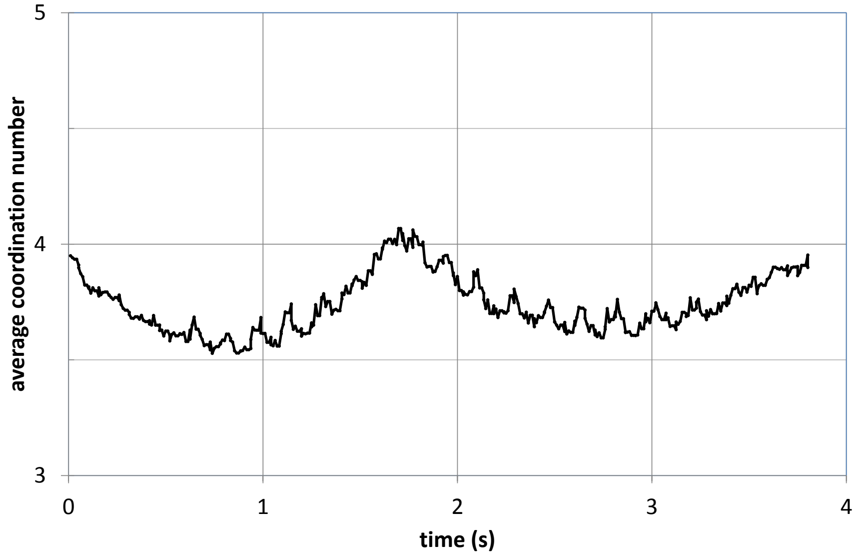

Figure 10: Evolution of coordination number during dynamic stabilisation using acceleration spectrum

5 CONCLUSIONS

- Simulations of the procedure of dynamic stabilisation of ballasted railway tracks have been performed using a DEM code based on NSCD approach which represents the ballast stones as realistic polyhedrons. The gain in compaction level showed that dynamic stabilisation is an adequate procedure to stabilise track. The evolution in compaction gain, settlement and average contact number between ballast stones, also showed that two waves of lateral vibrations, associated with a vertical load, are sufficient to fully compact the ballast and that any additional wave does not bring any substantial improvement.
- A sleeper settlement model for dynamic stabilisation is proposed. A comparison with the simulation settlement shows its relevance for estimation of settlement during dynamic stabilisation process.
- Further simulations are underway to analyse the effect of the stabilisation speed on the compaction. Additional simulations will also be undertaken to check the effect of this method of stabilisation on the lateral resistance of the track in order to establish a model for lateral resistance gain for dynamic stabilisation.

REFERENCES

[1] Cundall, P.A. and O.D.L. Strack, A discrete numerical model for granular assemblies. *Geotechnique*, 1979. 29(1): p. 47-65

[2] Williams, J.R. and A.P. Pentland, Superquadric and model dynamics for discrete elements in interactive design. Eng. Comput., 1992. 9: p. 115-127.

[3] Lin, X. and T.T. Ng, A three-dimensional discrete element model using arrays of ellipsoids. Geotechnique, 1997. 47(2): p. 319-329.

[4] Mustoe, G.G.W. and M. Miyata, Material flow analyses of non-circular-shaped granular media using discrete element methods. J. Eng. Mech., 2001. 127(10): p. 1017-1026.

[5] Cleary, P.W., Large scale industrial DEM modelling. Engineering Computations, 2004. 21(2-4): p. 169-204.

[6] Pournin, L., et al., Three-dimensional distinct element simulation of sphero-cylinder crystallisation. Granular Matter, 2005. 7(2-3): p. 119-126.

[7] Hart, R., P.A. Cundall, and J. Lemos, Formulation of a three-dimensional distinct element method - Part II : Mechanical calculations for motion and interaction of a system of many polyhedral blocks. Int. J. Rock Mech. Min. Sci. Geomech. Abstr., 1988. 25(3): p. 117-125.

[8] Matsushima, T., et al., Discrete element simulation of an assembly of irregularly shaped grains: quantitative comparison with experiments, in 16th ASCE Engineering Mechanics Conference, 2003: University of Washington, Seattle.

[9] Abou-Chakra, H., J. Baxter, and U. Tuzun, Three-dimensional particle shape descriptors for computer simulation of non-spherical particulate assemblies. Advanced Powder Technology, 2004. 15(1): p. 63-77.

[10] Wang, L.B., J.Y. Park, and Y.R. Fu, Representation of real particles for DEM simulation

using X-ray tomography. Construction and Building Materials, 2007. 21(2): p. 338-346.

[11] Price, M., V. Murariu, and G. Morrison, Sphere clump generation and trajectory comparison for real particles, in Discrete Element Methods Conference 2007: Brisbane, Australia.

[12] Lee, Y., et al., A packing algorithm for three-dimensional convex particles. Granular Matter, 2009. 11(5): p. 307-315.

[13] Ferellec, J.-F. and G.R. McDowell, A method to model realistic particle shape and inertia in DEM. Granular Matter, 2010. 12(5): p. 459-467.

[14] Ferellec, J.-F. and G.R. McDowell, Modelling realistic shape and particle inertia in DEM. Geotechnique, 2010. 60(3): p. 227-232.

[15] J.J. Moreau, An introduction to unilateral dynamics in Novel approaches in civil engineering, Lecture Notes in Applied and Computational Mechanics, Frémond,M. and Maceri,F., Springer-Verlag 1-46.

[16] J. Moreau, Some numerical methods in multibody dynamics: application to granular materials. European J. Mech. A Solids, 13(4, suppl.), pp. 93-114, 1994. Second European Solid Mechanics Conference (Genoa, 1994).

[17] G. Saussine, C. Cholet, P.E. Gautier, F. Dubois, C. Bohatier, J.J. Moreau, Modelling ballast behaviour under dynamic loading. Part 1: A 2D polygonal discrete element method approach, Comput. Methods Appl. Mech. Eng. 195 (2006) 2841 - 2859.

[18] F. Dubois and M. Renouf Numerical strategies software architecture to the modelling of dynamical systems in interaction. Application to multibody dynamics, in Multibody 2007 proceedings, 25-28 June 2007 - Politecnico di Milano, Milano, Italy

[19] E. Azema, Etude numérique des matériaux granulaires à grains polyédriques: rhéologie quasi-statique, dynamique vibratoire, application au procédé de bourrage du ballast. PhD thesis, university of Montpellier 2, France, October 2007.