The Fifth International Conference on Railway Technology
RAILWAYS 2022
22–25 August 2022
Montpellier, France

Proceedings of the Fifth International Conference on
Railway Technology:
Research, Development and Maintenance
Edited by J. Pombo
Civil-Comp Conferences, Volume 1, Paper 8.11
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.1.8.11

A DEM study on the effects of sleeper elasticity on vertical railway track settlement

P. Pircher, N. Kumar and K. Six

Virtual Vehicle Research GmbH
Graz, Austria

Abstract

Maintenance work on ballasted railway tracks due to the differential settlement along the track is a time-consuming and cost-intensive task. The mechanical properties of the sleeper, especially the sleeper's bending behaviour under load, influence how the wheel-rail contact forces are transferred through the ballast bed to the ground, which in turn significantly affects track settlement. A deeper physical understanding on the interaction between the railway sleepers and the ballast can therefore help to improve railway infrastructure and reduce maintenance work. To study the dynamic sleeper-ballast interaction numerically the discrete element method (DEM) is a commonly used tool to get insight into the physical effects inside the ballast bed. However, in recent DEM related research the sleeper was rarely considered as an elastically deformable body and a simple yet accurate sleeper model that considers proper mechanical properties of the sleeper is still missing. Therefore, a model was developed that uses the particle facet model (PFM) to implement a sleeper with a smooth surface into the DEM framework without the need of time-consuming coupling methods. This approach enables railway track simulations that consider the effects of sleeper elasticity on the discrete ballast realistically. Box-test simulations were carried out, in which the elastic sleeper model was placed on a compacted ballast bed and then cyclically loaded. The results obtained from the simulations are in qualitative agreement with the literature. Additionally, it was shown that the simulation outcome heavily depends on the initial (filling) configuration of the ballast bed. The modelling approach offers a realistic integration of elastic sleepers into railway track DEM simulations and is able to provide deeper insights into the underlying physics of the sleeper-ballast interaction. Studies of complex railway track phenomena, like hanging sleeper situations, are thus made possible.

Keywords: elastic sleeper, discrete element method, DEM, yade, track settlement, railway ballast, sleeper-ballast interaction, particle facet, pfacet, flexible sleeper, box test, cyclic loading

1 Introduction

Part of ongoing research is developing a deeper physical understanding of ballasted railway tracks. The interaction between the central components meaning rails, sleepers, and the ballast bed in dynamic load cases is particularly interesting. Literature has shown that the sleeper's mechanical properties strongly influence the total stiffness of the track and its long-term settlement behaviour and has more impact than the support modulus of the ballast bed [1, 2, 3]. In laboratory tests it was shown that under static loading soft sleepers develop a pronounced W-shaped deflection profile along their length and apply less uniformly distributed pressure onto the ballast bed with pressure peaks directly below the rails [2, 3, 4]. However, in long-term experiments with numerous load cycles a hogging shape of the sleeper was observed because the resilient movement of the sleeper ends lead to substantial gapping in that region, which can accelerate ballast deterioration due to impact loads and thus sleeper settlement [4, 5]. Additionally, due to the hogging shape, the ballast beneath the sleeper centre becomes stiffer and denser with loading cycles resulting in reduced settlement in the middle of the sleeper [4]. Furthermore, studies have shown that the in-service bending behaviour of composite sleepers can lead to asymmetric sleeper settlement [6].

Due to the discrete nature of the ballast, the discrete element method (DEM) is considered an appropriate and commonly used numerical tool to simulate the bulk behaviour of railway ballast. Kumar et al. [7] used DEM simulations to investigate the influence of elastic layers in railway tracks, using a sleeper modelled as a rigid (and therefore inflexible) body. A sleeper built up by bonded spheres was used by Gao et al. [8] and Nishiura et al. [9], but both sleeper models offered a geometrically rough surface that interferes with a precise sleeper-ballast contact representation. To extend the exact sleeper shape with elastic properties, a DEM-FEM coupling method was developed by Song et al. [10]. However, coupling methods typically are high in effort and tend to be slow in terms of computation time. In addition, an accurate definition of the contact behaviour between the two solvers is a complex task and a proper interface for the data exchange is needed.

Therefore, a simple and accurate elastic sleeper model for DEM railway track simulations is essential. In the following, a novel modelling approach to model elastically deformable railway sleepers in a DEM framework is presented.

2 Methods

The simulation setup is based on the work of Kumar et al. [7] and represents one sleeper section of a regular straight track. However, several adaptations were made, that are explained in detail in [11]. First, the box was enlarged to accommodate the full sleeper and its surroundings. Second, the ballast representation consisting of three non-overlapping spheres of different radii was increased from a major axis of 40 mm to 72 mm to reduce the number of particles and thereby computation time. The third change was the sleeper model that uses the particle facet model (PFM) from Effeindzourou et al. [12-15] instead of a rigid (inflexible) sleeper.

The PFM approach uses nodes, cylinders, and so-called particle facets (PFacets). Nodes are the core bodies of the model and the interactions between the nodes define the elastic behaviour of the body. Cylinders and PFacets are mathematically defined as the Minkowski sum of a sphere and a line or facet respectively, and hence allow the modelling of smooth surfaces. Contacts between PFacet bodies and external particles are covered by introducing a virtual sphere within the PFacet element at the contact point and thus are computed like a regular sphere-sphere DEM contact [12-15].

The sleeper model has the shape of a wooden sleeper and was designed and meshed in *Gmsh* [16] as shown in Figure 1, and then imported into the DEM framework. Moreover, the sleeper model was calibrated accordingly to depict correct bending behaviour.

The simulation was conducted in the DEM framework of Yade [17] and starts with particle creation and ballast bed preparation. In this phase, a cloud of ballast particles is generated, and the particles then fall to the floor of the box and spread accordingly due to a reduced friction coefficient and Young's modulus. In the next phase, the material properties are updated to the correct values and the ballast bed is compressed to achieve a well-compacted, dense, and flat bed. In the third phase, the sleeper is implemented and dropped onto the ballast bed and a linearly increasing vertical load is applied at the railhead positions, as visualised in Figure 2. Once the force reaches 5 kN per railhead the consolidation process is complete. Afterwards, cyclic vertical loading between 5 kN and 40 kN per railhead with a frequency of 3 Hz is applied for ten cycles.

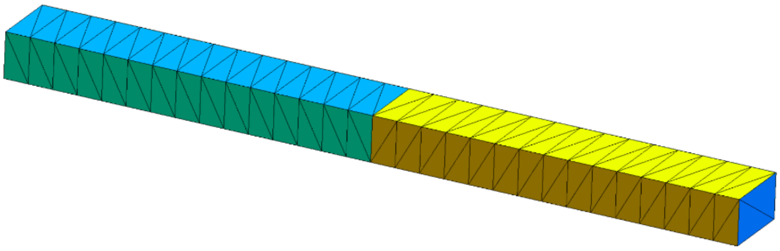

Figure 1: The sleeper model design including the mesh [11]

3 Results

After the cyclic loading, simulation data of the sleeper-ballast interaction was exported and analysed. The number of contacts between the sleeper and the ballast is an important factor, which affects the contact stress at the sleeper-ballast interface and thus sleeper settlement. During cyclic loading, the number of contacts between the sleeper and the ballast varies for the lowest and highest load respectively. Although not an apparent saturation for the number of contacts was seen, it is expected that the number of contacts stabilises after further cyclic loading. The deflection profile of the sleeper at the highest load of each cycle is shown in Figure 3. The first cycle is represented in a light grey colour and increased line darkness represents an increase in cycles. The locations of the rails are indicated by red dashed lines. A pronounced W-shaped deflection profile can be seen from the first cycle onwards. Additionally, due to the discrete nature of ballast, a slight slope has formed along the sleeper's length. The gap between the deflection profiles reduces continuously with loading cycles, which means that track settlement slows down with cycles. This decreasing settlement rate with load cycles is classical track settlement behaviour as observed in experiments and several empirical models [18, 19, 20]. Regarding the pressure distribution at the sleeper-ballast interface, it was observed that the pressure at higher loads was higher directly below the rails, which lead to more settlement in this area. Moreover, the pressure at lower loads increased in the sleeper centre over the cycles. This behaviour entails a significant sleeper centre binding and development of possible gaps at the sleeper ends.

To verify the obtained results, five additional ballast beds were generated and went through the same simulation procedure. The additional setups have shown similar qualitative bulk behaviour that agrees with the literature and shows the effects of different initial configurations of the ballast bed.

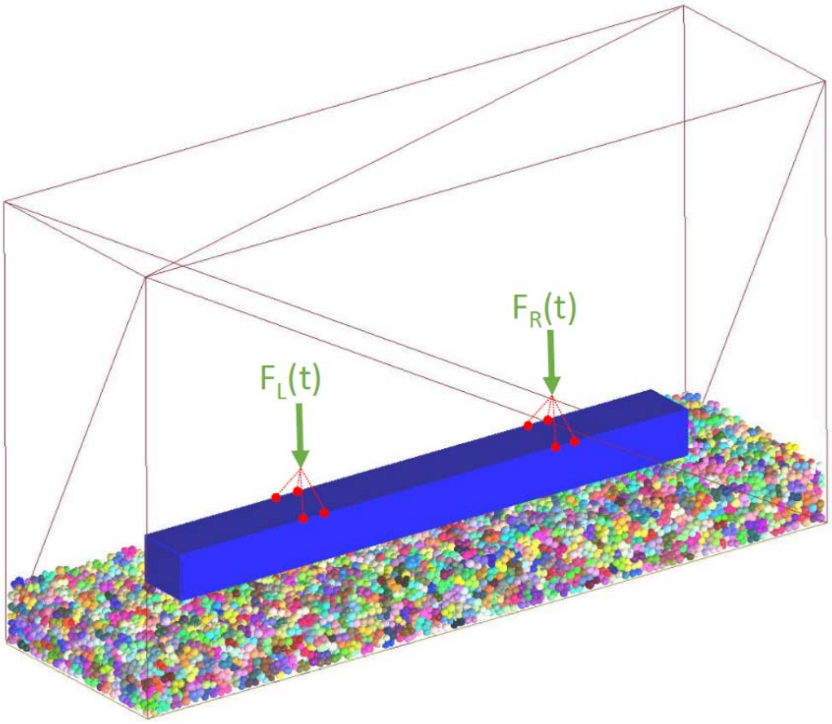

Figure 2: The loaded sleeper in the simulation setup [11]

4 Conclusions and Contributions

A new modelling approach to include elastically deformable sleepers into DEM railway track simulations was presented. The proposed modelling method using the particle facet model allows to model the elastic behaviour and the smooth surface of the sleeper accurately, while keeping the required effort low. Box-test simulations were conducted, in which cyclic vertical loading was applied on the sleeper at two locations representing the positions of the railheads. The simulation results are in qualitative agreement with the literature and the following conclusions can be drawn:

1. The number of contacts between the sleeper and the ballast oscillates between a high and low value.
2. A W-shaped deflection profile of the sleeper can be observed, which is more pronounced under higher loads.
3. Under cyclic loading the sleeper can develop a slope along its length due to the discrete nature of the ballast.
4. At higher loads the pressure from the sleeper onto the ballast directly below the rails is higher than elsewhere at the sleeper-ballast interface.
5. For the investigated loading cycles, the pressure at the sleeper centre increases with loading cycles for the unloaded state.

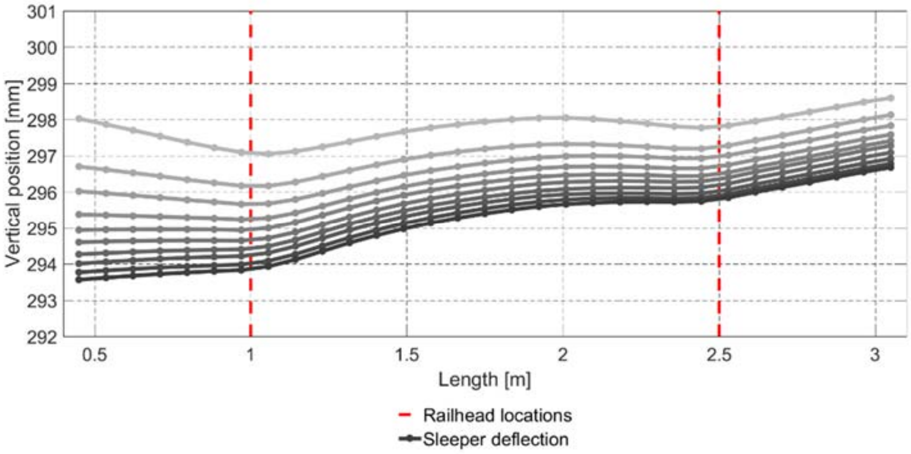

Figure 3: Sleeper deflection at maximum load of each cycle (increasing darkness represents increasing number of cycles) [11]

The fact that for the load cycles considered in this work, the sleeper can develop a slope along its length and an increase in the pressure at the sleeper centre for the unloaded states can be observed, suggests that the applied load is not distributed evenly onto the ballast and changes over the loading cycles. Further investigations in this regard with a higher number of load cycles will be considered in the future. Parametric studies on the ballast particle size will also be conducted as particle dimensions can have a strong impact on load distribution and settlement behaviour. Additionally, it is of interest to microscopically analyse the ballast bed, such as force chains within the bed, to examine how the load is transferred from the sleeper to the ground. By looking at the contact points between the sleeper and the ballast as well as computing the offset between the sleeper surface and the nearest ballast particle, a clear view on gap development between the sleeper and the ballast is expected. Extending the research with the aforementioned analyses enables the precise studying of physical effects within the track and can thereby lead to improved railway infrastructure components. Selected results of the analyses will be presented at the conference.

Acknowledgements

Virtual Vehicle Research GmbH has received funding within COMET Competence Centers for Excellent Technologies from the Austrian Federal Ministry for Climate Action, the Austrian Federal Ministry for Digital and Economic Affairs, the Province of Styria (Dept. 12) and the Styrian Business Promotion Agency (SFG). The Austrian Research Promotion Agency (FFG) has been authorised for the programme management.

References

[1] Taufan Abadi et al. “Effect of Sleeper Interventions on Railway Track Performance”. In: *Journal of Geotechnical and Geoenvironmental Engineering* 145.4 (2019)

[2] Choman Salih et al. “Effect of bending and compressive modulus of elasticity on the behaviour of timber-alternative railway sleepers supported by ballast”. In: *Case Studies in Construction Materials* 15 e00597 (2021)

[3] Choman Salih et al. “Novel Bending Test Method for Polymer Railway Sleeper Materials”. In: *Polymers.* 13.1359 (2021)

[4] E. Ferro, J. Harkness, and L. Le Pen. “The influence of sleeper material characteristics on railway track behaviour: concrete vs composite sleeper”. In: *Transportation Geotechnics* 23.100348 (2020)

[5] Aran van Belkom. “A simplified method for calculating load distribution and rail deflections in track, incorporating the influence of sleeper stiffness”. In: *Advances in Structural Engineering* 23.11 pp. 2358–2372, (2020)

[6] U.S. Department of Transportation - Federal Railroad Administration. “Performance of plastic composite ties in revenue service”, *Technical report* (May 2011)

[7] Nishant Kumar et al. “Micro-mechanical investigation of railway ballast behavior under cyclic loading in a box test using DEM: effects of elastic layers and ballast types”. In: *Granular Matter* 21.4 pp. 1–17, (2019)

[8] Liang Gao et al. “Discrete element method of improved performance of railway ballast bed using elastic sleeper”. In: *Journal of Central South University* 22.8 pp. 3223–3231, (2015)

[9] Daisuke Nishiura et al. “Computers and Geotechnics Novel discrete element modeling coupled with finite element method for investigating ballasted railway track dynamics”. In: *Computers and Geotechnics* 96 pp. 40–54, (2018)

[10] Weimin Song et al. “Interaction between Railroad Ballast and Sleeper: A DEM-FEM Approach”. In: *International Journal of Geomechanics* 19.5, (2019)

[11] Paul Pircher “A DEM model for elastic sleepers to study dynamic track behaviour”. Master’s Thesis. Montanuniversität Leoben, (2021) DOI: 10.34901/mul.pub.2021.5.

[12] Anna Makouala Effeindzourou et al. “Modelling of deformable structures in the general framework of the discrete element method”. In: *Geotextiles and Geomembranes* 44.2 pp. 143–156, (2016)

[13] Anna Makouala Effeindzourou et al. “A general method for modelling deformable structures in DEM”. In: *Proc. 4th Int. Conf. Part. Methods - Fundam. Appl. Particles 2015* pp. 744–754, (2015)

[14] Anna Makouala Effeindzourou et al. “Efficient discrete modelling of composite structures for rockfall protection”. In: *Computers and Geotechnics*. 87 pp. 99–114, (2017)

[15] Anna Makouala Effeindzourou. “Numerical Investigation of the Energy Absorption Capacity of Rockfall Protection Measures for Underground Portals”. PhD Thesis. University of Newcastle, (2016)

[16] Christophe Geuzaine and Jean François Remacle. “Gmsh: A 3-D finite element mesh generator with built-in pre- and post-processing facilities”. In: *International Journal for Numerical Methods in Engineering* 79.11 pp. 1309–1331, (2009)

[17] Václav Šmilauer et al. “The Yade Project”. In: Yade Doc. 2nd ed. (2021)

[18] Juan Carlos Quezada et al. “Predicting the settlement of coarse granular materials under vertical loading”. In: *Nature.com: Scientific Reports* 4 pp. 2–6, (2014)

[19] Taufan Abadi et al. “A Review and Evaluation of Ballast Settlement Models using Results from the Southampton Railway Testing Facility (SRTF)”. In: *Procedia Engineering 143 - Advances in Transportation Geotechnics* 3 pp. 999–1006, (2016)

[20] Xu Zhang et al. “Investigation of track settlement and ballast degradation in the high-speed railway using a full-scale laboratory test”. In: *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit* 233.8 pp. 869–881, (2019)