



DEM ANALYSIS OF THE INFLUENCE OF BALLAST PROPERTIES ON SLEEPER LONGITUDINAL RESISTANCE IN RAILWAY TRACKS

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Abstract

The longitudinal resistance of sleepers in ballasted track systems is critical for maintaining track stability under thermal and train-induced forces. This resistance governs the relative movement between sleepers and ballast, influencing track creep, rail stress distribution, and structural integrity. This study develops a three-dimensional discrete element method (DEM) model to simulate the longitudinal mechanical behavior of a sleeper embedded in granular ballast particle. Under gradually increasing longitudinal loads, the simulation captures the complete load–displacement response. The obtained sleeper longitudinal resistance satisfies the requirements specified in relevant design codes and falls within the range of previously reported experimental results. Parametric analyses reveal the influence of the ballast friction coefficient and contact stiffness on longitudinal resistance. The findings provide guidance for ballast material selection and for improving the long-term longitudinal stability of railway tracks.

Keywords: ballasted track, discrete element method, longitudinal resistance, ballast particle properties, parametric analysis

1 Introduction

The longitudinal stability of ballasted railway tracks plays a crucial role in ensuring the safe and reliable operation of railways. Under the combined effects of thermal expansion of continuous welded rails and longitudinal forces induced by train braking and acceleration, the track structure is subjected to significant longitudinal forces. The ability of the track to resist these forces largely depends on the longitudinal resistance provided by the ballast particles. This resistance governs the relative displacement between sleepers and ballast, influencing key performance aspects such as track creep, rail stress distribution, and overall track durability. Therefore, understanding and accurately predicting the longitudinal resistance of sleepers in ballasted tracks is essential for the design, maintenance, and long-term stability of railway infrastructure. Many railway researchers worldwide have conducted extensive studies on sleeper longitudinal resistance, focusing on evaluating track quality, particularly to determine whether newly constructed or maintained tracks meet acceptance standards. For example, Zhang et al. [1] tested over 70 sleepers and obtained average ballast longitudinal resistance values of 8.4 kN/sleeper, 9.1 kN/sleeper, and 9.1 kN/sleeper at a displacement of 2 mm for three test sections, respectively. Ma [2] further reported that the ballast longitudinal resistance ranged from 15.1 to 21.2 kN per sleeper on bridge sections. Wang et al. [3] obtained that the longitudinal resistance at a curved CWR track (radius 250 m) ranges from 8 to 27 kN per sleeper.

Besides, Yang and Zhu [4] and Chen et al. [5] reported an average measured ballast longitudinal resistance of approximately 18.1 kN and 22.5 kN per sleeper, respectively. The above literature review shows that ballast longitudinal resistance varies between 8 and 27 kN per sleeper under different track conditions, with a relatively wide range of fluctuation. With respect to evaluating ballast bed condition following maintenance operations, Xiao et al. [6] studied the effect of tamping and stabilizing machines on ballast bed condition through field experiments. They reported that the longitudinal resistance was 9.18 kN in the initial state, decreased to 8.35 kN after tamping (a reduction of 9.0%), and increased to 14.87 kN after stabilization (an increase of 78.1%). Liu et al. [7] conducted longitudinal resistance tests on 15 sleepers after each tamping operation, and found that, compared with the untreated condition, the ballast longitudinal resistance decreased by 3.01%, 12.84%, and 17.39% under the respective tamping conditions. Moreover, Zeng et al. [8], Chen et al. [9], and Li [10] also investigated the resistance characteristics of ballast beds under different maintenance operations.

In addition, researchers have further investigated sleeper resistance under varying track structures and environmental conditions. For example, Xiao et al. [12] conducted field tests on sandy and clean railway tracks to examine the effect of sand intrusion on ballast longitudinal resistance. The results showed that the resistance per sleeper was 12.26 kN in the sandy section and 9.55 kN in the clean section, indicating that sand intrusion increased the longitudinal resistance by 28.4%. Liu et al. [11, 13] tested the longitudinal-displacement resistance of fiber-reinforced foamed urethane (FFU) composite sleepers and concrete sleepers in ballast beds. The results showed values of 16.54 kN for concrete sleepers and 6.84 kN for composite sleepers. In addition, the sleeper longitudinal resistance decreased by 22% as the humidity increased from 34% (dry) to 91% (wet). Recently, researchers have gradually applied the discrete element method to study ballast longitudinal resistance. Guo et al. [14] investigated the effects of nail length and number on resistance. The results showed that, compared with two nails, using four nails increased lateral and longitudinal resistance by 20.2% and 10.6% for 100 mm nails, and by 37.0% and 33.5% for 200 mm nails, respectively. Aela et al. [15] studied the effect of crib ballast height variations on the longitudinal resistance using DEM modeling and found that the presence of crib ballast plays an important role in the longitudinal resistance of sleepers. Furthermore, Xiao et al. [16] used a DEM-MBD co-simulation method to analyze the influence of manual tamping on sleeper longitudinal resistance.

Despite extensive studies efforts to characterize the longitudinal resistance behavior of ballasted tracks, the influence of ballast particles on sleeper longitudinal resistance has not been investigated. In this study, a three-dimensional DEM model of ballast bed is established. And then, the effects of ballast particle friction and contact stiffness on the longitudinal resistance are investigated. This research will improve the understanding of sleeper longitudinal resistance governing by ballast material parameters and can offer theoretical guidance for optimizing ballast selection.

2 DEM modelling of sleeper longitudinal resistance

Figure 1 illustrates the sleeper–ballast bed DEM model employed in this work. The model consists of four sleepers, which are labeled as sleeper No. 1, sleeper No. 2, sleeper No. 3, and sleeper No. 4. The spacing between adjacent sleepers is 0.6 m, while the distances from sleeper No. 1 and sleeper No. 4 to the boundary are both 0.3 m. The ballast bed has a thickness of 0.35 m, and the remaining geometric features, including the ballast shoulder profile, conform to the specifications of the Chinese railway standards [17]. Detailed information on the modeling procedure and model parameters can be found in the referenced literature [18-20].

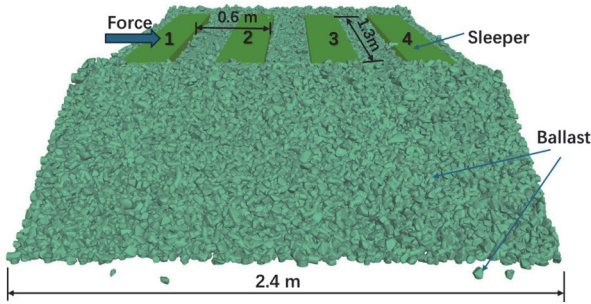


Figure 1 The 3D DEM model of sleeper and ballast bed

To obtain the longitudinal resistance of the ballast bed, a gradually increasing force is applied at the centroid of the sleeper, while the longitudinal displacement of the sleeper centroid is recorded simultaneously. The simulation is terminated when the longitudinal displacement reaches 3 mm. The sleeper longitudinal resistance is defined as the resultant force provided by the ballast at the sleeper ends, bottom, and sides when the sleeper longitudinal displacement reached 2 mm. The arrow in figure 1 indicates the loading direction applied to sleeper No. 1. By sequentially applying the same loading procedure to each sleeper, the ballast longitudinal resistance corresponding to all four sleepers is obtained. Figure 2 illustrates the relationship between the applied force and sleeper displacement for one sleeper. As shown in the figure, the longitudinal resistance of the sleeper increases nonlinearly with increasing sleeper displacement. When the sleeper displacement reaches 2 mm, the longitudinal resistance of the ballast bed is 11.7 kN for sleeper No. 1, 12.9 kN for sleeper No. 2, and 13.9 kN for sleeper No. 3. Because the boundary conditions of the model affect the calculated results during the longitudinal loading of sleeper No. 4, the data for this sleeper are excluded from the analysis. These values are slightly higher than the longitudinal ballast resistance of 10 kN typically reported for normal railway lines in the Chinese standard [17], and fall within the range of 8–27 kN reported in existing experimental studies. Overall, these results indicate that the DEM model provides a reliable prediction of the sleeper longitudinal resistance.

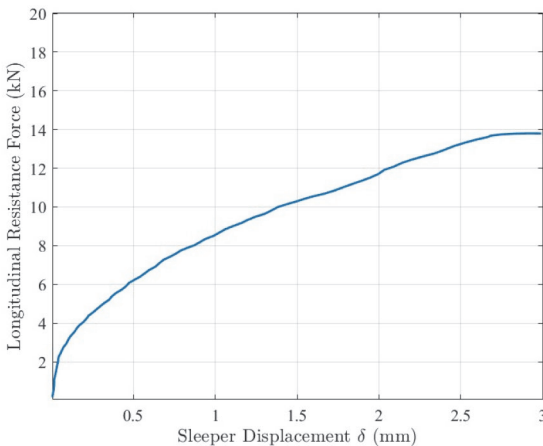


Figure 2 Relationship between the lateral force and displacement of sleeper

3 Effect of ballast parameters on sleeper longitudinal resistance

In railway standards of various countries, ballast materials such as limestone and granite are permitted for use, and their material parameters exhibit certain differences. In this subsection, different ballast materials are simulated by varying key parameters in the linear contact constitutive model within the DEM software, including the friction coefficient and contact stiffness. The ballast friction coefficient is set to 0.5, 0.6, and 0.7, while the ballast contact stiffness is set to 1×10^7 N/m, 2×10^7 N/m, and 3×10^7 N/m respectively.

3.1 Effect of ballast particles friction

Figure 3 compares the longitudinal resistance of sleeper No. 3 under different ballast friction coefficients with the same ballast contact stiffness of 2×10^7 N/m. As clearly shown in figure 3, with an increase in the ballast friction coefficient, the sleeper longitudinal resistance increases from 9.79 kN to 19.06 kN, representing an increase of approximately 94.7%, and exhibits an approximately linear growth trend. This behavior may be attributed to the enhancement of the interlocking effect among ballast particles and the intensification of the frictional interaction between the ballast and the sleeper. As a result, the overall longitudinal resistance of sleeper is significantly increased.

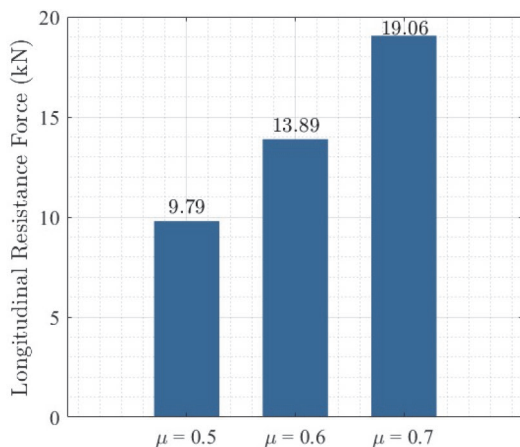


Figure 3 Sleeper longitudinal resistance under different ballast friction coefficient

3.2 Effect of ballast particles contact stiffness

Figure 3 compares the longitudinal resistance of sleeper No. 3 under different ballast contact stiffness conditions with the same ballast friction of 0.6. As shown in figure 4, with increasing contact stiffness, the sleeper longitudinal resistance rises from 11.26 kN to 14.61 kN, representing an increase of approximately 29.8%, which is relatively modest. The increase in ballast contact stiffness primarily affects the contact interactions between the sleeper ends and the shoulder ballast, resulting in a smaller influence on the longitudinal resistance compared to that of the ballast friction coefficient.

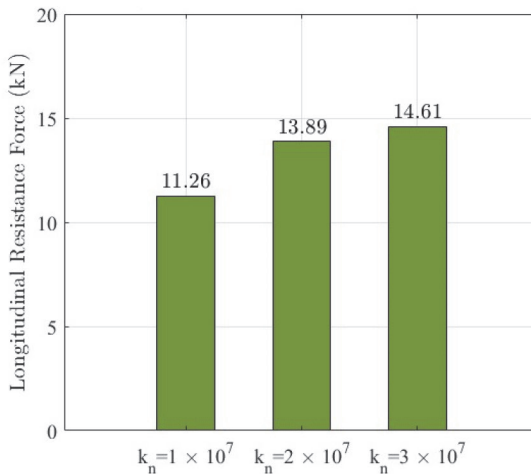


Figure 4 Sleeper longitudinal resistance under different ballast contact stiffness

4 Conclusion

In this study, a three-dimensional DEM model of the sleeper–ballast system is developed, capable of accurately simulating ballast behavior and its interaction with the sleeper. Based on this model, the influence of ballast material parameters on sleeper longitudinal resistance is investigated under gravitational loading conditions. The results show that increasing the ballast friction coefficient from 0.5 to 0.7 leads to a 94.7% increase in sleeper longitudinal resistance, whereas increasing the ballast contact stiffness from 1×10^7 N/m to 3×10^7 N/m results in an 29.8% increase. These findings indicate that the ballast friction coefficient has a significantly greater effect on sleeper longitudinal resistance than the ballast contact stiffness. In the future, experimental studies will be planned and conducted, and findings from existing literature will be further incorporated to validate the accuracy and reliability of the proposed model. Furthermore, this model will be employed to investigate the longitudinal resistance characteristics of sleepers under varying train loading conditions, considering different sleeper geometries and ballast bed states. Through these efforts, a more comprehensive understanding of the longitudinal resistance behavior of railway tracks will be achieved.

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