BILINGUAL PUBLISHING CO.
Pioneer of Global Academics Since 1984

Frontiers Research of Architecture and Engineering

https://ojs.bilpublishing.com/index.php/frae

Study on Influence of Ballast Spring Modulus on Track Structure Based on Finite Element Method

Tian Yang[*]

China Railway (Tianjin) rail transit investment and Construction Co., Ltd. Tianjin, 300000, China

ARTICLE INFO	ABSTRACT

The finite element method is used to simulate the orbital structure, and the finite element model of "rail - sleepers - ballast" can be established. The model of the elastic modulus of different ballast and sleeper is calculated, and the rail displacement, the sleeper stress and the fastening force are deduced. The results show that the elastic modulus of the ballast can be increased to reduce the displacement of the rail and the supporting force of the fastener, but the stress of the sleeper will be increased. When the modulus of elasticity increases, the rail displacement, small.

1. Introduction

Ballast track is widely distributed in China, is an important form of railway transportation. In the course of operation, there are often uneven subsidence problems, the need for regular track maintenance measures to maintain. In the process of settlement and maintenance of ballast track, due to the deformation, crushing and grading of ballast itself changes, its elastic modulus will change accordingly. As an important part of ballast track, the change of elastic modulus of ballast will seriously affect the stability of track structure. In order to study the dynamic response of ballast to track structure, scholars at home and abroad have carried out a series of numerical analysis.

In the simulation analysis, the discrete element method is mostly used by the scholars around the world. Cundall [1] took the lead in introducing the discrete element method to study ballast. Ting [2] adopts two-dimensional ellipse to simulate ballast. This method cannot consider the three-dimensional contact effect of ballast under real conditions, which is greatly different from the actual situation. Xu Yang [3] et al. established a ball cluster unit model that could fit the real partieleshape of ballast, and built a box model for the track bed composed of different grain composition and partieleshape ballast, and focused on analyzing the influence of grain composition and partieleshape on the mechanical properties of the track bed. Xiao Hong [4] et al. used three-dimensional spherical particles to simulate ballast, but did not consider the geometric size characteristics of ballast, and could not accurately simulate the occlusal characteristics of ballast. In terms of experiments, Shi Xiaoyi used finite element simulation to study and analyze the stress distribution in railway tracks. At the same time, he reviewed the predicted settlement results

Corresponding Author:
Tian Yang,
China Railway (Tianjin) rail transit investment and Construction Co., Ltd. Tianjin, 300000, China;
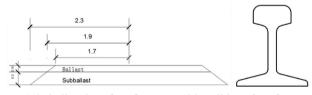*Email: 971351161@qq.com*

through large-scale triaxial tests. Liu Qingjie et al. tested the change of ballast when the continuous train passed by the way of installing the bulk particle pressure gauge in the sleeper. But in the aspect of finite element simulation, the existing research is very limited [1-3].

In this paper, ABAQUS finite element simulation software is used to establish the contact finite element model between the track superstructure and ballast. Relative to the discrete element method to simulate the real ballast irregular partieleshape and the characteristics of the inertia characteristics, the finite element method to simulate ballast as rail infrastructure contact with sleeper, as a common engineering simulation software, ABAQUS contact module contains a separate, can guarantee the stability of finite element model of each part in contact. Under this premise, this paper focuses on analyzing the influence of the change of the elastic modulus of ballast on the response of each part of the track structure [4,5].

2. Establishment and Validation of the Finite Element Model

2.1 Finite Element Modeling

The finite element model of "rail - sleeper - ballast" is established in ABAQUS. The model is composed of rail, fastener, sleeper, ballast and bottom ballast. In the finite element model, point-to-point springs are used to replace fastener. The section diagram of each component is shown below.

（a）ballast interface figure　（b）rail interface figure

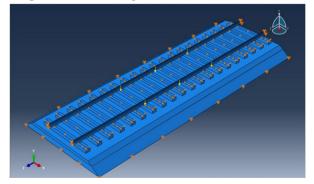**Figure 1.** Section diagram of the finite element model

Figure 2. Finite element model of "rail - sleeper - ballast"

Ballast is divided into ballast and bottom ballast. Dif-

ferent elastic modulus is selected when modeling, and the section diagram of rail pillow is simplified to 0.23 m×0.18 m×2.6 m cuboid, rail and ballast length are 12 m. The complete model is shown in Figure 2, where the yellow arrow is the loading position. Three groups of the same vertical loads are added to the model, with a value of 148400N. The boundary conditions restricting the three directions of the bottom ballast ground, rail head and sleeper bottom are set on the model respectively. Contact between rail and sleeper selection of "point-point" spring instead of fastener, the stiffness of $6*10^7$ N/m, sleeper and ballast, ballast and bottom ballast use of "surface-surface" contact. The parameters selected for each component of the model are shown in Table 1.

Table 1. "rail - sleeper - ballst" model parameter table

Material parameters	Elastic Modulus E/pa	Poisson's ratio υ
Rail	$2.1*10^{11}$	0.3
Sleeper	$1.3\ 10^{10}$	0.3
Ballast	$1.5\ 10^8$	0.27
Bottom ballast	$5?10^7$	0.35

2.2 Finite Element Model Verification

In ABAQUS, implicit and Explicit solving algorithms correspond to the ABAQUS/Standard and ABAQUS/Explicit analysis modules, both of which are capable of solving a variety of problems. Implicit modules are used to analyze the model established in this paper, and Newmark integral method is adopted. It adopts the following assumptions:

$$\dot{u}_{t+\Delta t} = \dot{u}_t + \left[(1+\delta)\ddot{u}_t + \delta\ddot{u}_{t+\Delta t}\right]\Delta t \quad （1）$$

$$u_{t+\Delta t} = u_t + \dot{u}_{t+\Delta t} + \left[\left(\tfrac{1}{2}-\alpha\right)\ddot{u}_t + \alpha\ddot{u}_{t+\Delta t}\right]\Delta t^2 \quad （2）$$

Where　and　are parameters determined by integral accuracy and stability. For　and , Equations (1) and (2) correspond to the linear acceleration method because they can be obtained from the integration of the linear assumed acceleration expression over time interval .

$$\dot{u}_{t+\tau} = \ddot{u}_t + \frac{\left(\ddot{u}_{t+\Delta t}-\ddot{u}_t\right)\tau}{\Delta t} \quad （3）$$

In the formula,.

After the finite element model is calculated according to the selected integral method, the calculation results are extracted. In order to compare the measured results of the sleeper with built-in bulk gauge adopted by scholars such as Liu Qingjie in the United States, the pressure at the contact point between the rail and the sleeper was extracted from the calculation results, as shown in Figure 3.
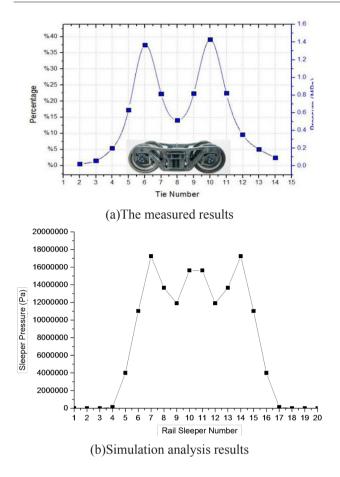
(a)The measured results

(b)Simulation analysis results

Figure 3. Sleeper pressure diagram under wheelset load

As can be seen from the figure, the sleeper pressure reaches its peak at the action of the wheelset. Since a bogie is adopted in the actual measurement, while three groups of vertical forces are applied to the rail in the simulation model, half of the simulation results can be selected for comparison when comparing the results, and the sleeper stress distribution law is consistent with the actual measurement.

In literature [6], scholars such as Huang Hui used the method of applying static force and sticking strain gages on the waist and axis of the rail to test the wheel-rail vertical force continuously. In order to compare with its results, the rail strain was extracted from the calculation results, as shown in Figure 4, and its distribution rule was the same as that of the rail strain extracted in Literature [7].

By combining the two simulation analyses with the measured results, it can be concluded that the model used in this paper has a good similarity with the measured results under the action of vertical force.
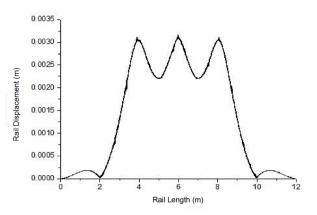

Figure 4. rail strain distribution

3. Calculation Result Analysis

In order to analyze the influence of ballast and sleeper on the response of track structure under different elastic moduli, four groups of different working conditions were selected for calculation. The parameters of each working condition are shown in Table 2. Working conditions one to three for the selection of different ballast elastic modulus of wood sleeper influence analysis, working conditions three, four for the same ballast elastic modulus of wood sleeper and concrete sleeper influence analysis [8,9].

Table 2. calculates four groups of working conditions

	Ballast	Bottom ballast	Sleeper
Working condition 1	75	25	$1.3*10^4$
Working condition 2	150	50	$1.3*10^4$
Working condition 3	211	140.7	$1.3*10^4$
Working condition 4	211	140.7	$3.25*10^4$

Number rail, sleeper and fastener, in which the fastener number is the same as the sleeper number, as shown in Figure 5. The finite element model has a symmetrical structure, so when analyzing the calculation results, only No. 1 rail and No.1-No.10 sleeper can be used for analysis to reflect the overall response.
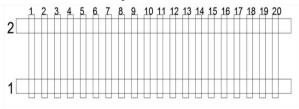

Figure 5. finite element model of each part number

Comparative analysis of elastic modulus of different ballast.With the repeated action of the train load, the sedimentation of the trackbed accumulates gradually, which will lead to the sedimentation of the trackbed or even the whole track structure. The uneven sedimentation of

trackbed caused by the non-uniformity of railway structure along the longitudinal track and the difference of track state will lead to the uneven track surface, directly affect the smooth operation of the high-speed train, increase the workload of maintenance and maintenance, reduce and weaken the strength and stability of the track structure, and threaten the safety of driving.

There are two main factors to produce the settlement of the trackbed, one is the original dense ballast particles under the action of the relative position of the particles change, further compaction of the track bed; The second is particle crushing under cyclic load.Is due to the change of the elastic modulus of ballast, in view of this problem, this paper carried out a detailed analysis [10].

Figure 6 is the rail displacement cloud diagram under the working condition 1. It can be seen from the figure that the rail displacement is the most obvious when the vertical force is used, and the displacement is basically zero at both ends of the rail far away from the point of operation. Figure 7 is the sleeper stress cloud diagram under working conditions. It can be seen from the figure that the sleeper stress is also relatively obvious near the point of operation,in the analysis, only the No.6-No.10 sleepers with obvious results are taken for analysis.
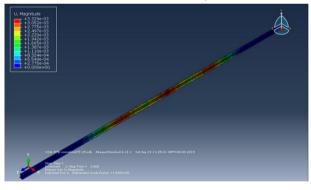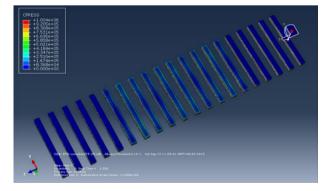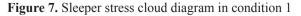

Figure 6. Rail displacement cloud diagram in condition 1

Figure 7. Sleeper stress cloud diagram in condition 1

Taking sleeper No.6-No.10 in the working condition 3 as an example, the stress distribution of sleeper under the action of vertical force is extracted, as shown in Figure 7. With the horizontal length of the sleeper as the abscissor, it can be seen that the stress at the contact point between the sleeper and the rail reaches the peak. By the sleeper number, it can be seen that the stress of the No.7 sleeper, which is used for vertical force, is the largest.
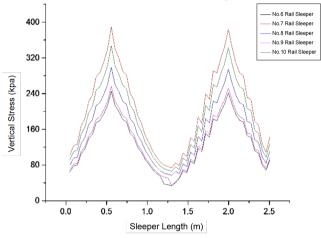

Figure 8. condition 3 No.6-No.10 sleeper stress distribution

In order to compare the change of sleeper stress under different elastic moduli, the stress of sleeper No. 10 in working conditions 1 to 3 is extracted, as shown in Table 3. Among them, the stress of sleeper in working conditions 1 to 3 gradually increases, the stress of sleeper in working conditions 2 increases by about 21.3% compared with that in working conditions 1, and the stress of sleeper No. 10 under working conditions 3 increases by about 21.8% compared with that in working conditions 2. Therefore, with the increase of the elastic modulus of ballast, the sleeper stress gradually increases.

Table 3. Stress of sleeper No. 10

	kpa	psi
Working condition 1	235	34.1
Working condition 2	285	41.3
Working condition 3	347	50.4

In addition to the sleeper stress, the rail displacement and the coupler support reaction are selected as the parameters to reflect the response of the track structure. Because the model established in this paper is of symmetrical structure, one side of the rail is taken as an example when extracting rail displacement and reaction force of coupler support. The extraction results are shown in Figure 8 and Figure 9. The distribution law of rail displacement and coupler support reaction force under different working conditions is consistent, both reach the peak value when the vertical force is used, and the minimum value is at both ends of the rail, and the left and right symmetric

state is in line with the actual situation. By comparing the results of working conditions 1, 2 and 3, it can be seen that the order of rail displacement and reaction force of coupler support from large to small is: working conditions 1, 2 and 3. Therefore, with the increase of the elastic modulus of ballast, the rail displacement and the reaction force of the fastener gradually decrease.
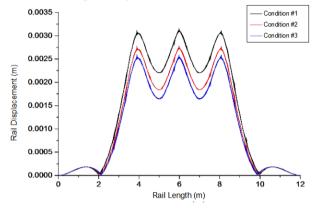

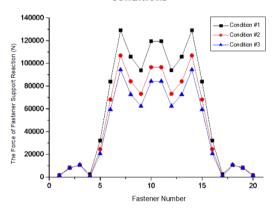**Figure 9.** Rail displacements under different working conditions

Figure 10. Support reaction force of fastening under different working conditions

Comparative Analysis of the Change of Sleeper Elastic Modulus

With the development of the railway, today there is a ballast railway not only laid wooden sleepers, but also laid concrete sleepers in some high-speed lines. The model built in this paper is also applicable to high-speed lines, in order to study the influence of different sleeper on the response of track structure, the working condition 3 and working condition 4 are selected for comparison calculation, that is, the elastic modulus of sleeper is changed under the same ballast elastic modulus. The selected representative parameters are still sleeper stress, rail displacement and fastening support reaction.

Since only the elastic modulus of the sleeper is changed in the calculation, the distribution rule of the calculated results of the extracted parameters remains unchanged. Taking sleeper No. 10 as an example, the sleeper stress peaks under working conditions 3 and 4 are extracted, as shown in Table 4.

Table 4. Stress of sleeper No.10

	kpa	psi
Working condition 3	347	50.4
Working condition 4	270	39.2

As can be seen from the table, under the same elastic modulus of ballast working condition 4 in the No.10 sleeper stress peak than working condition 3 reduce about 22.2%, that is, with the increase of sleeper elastic modulus, the stress decreases. By comparing other calculation results of working condition 3 and 4, it can be seen that the rail displacement and reaction force of the coupler under working condition 3 are greater than that under working condition 4, that is, with the increase of the elastic modulus of sleeper, the rail displacement, reaction force of the coupler and sleeper stress all decrease.

Comparison of Results

Considering the irregularity characteristics of ballast track, the paper analyzed the sensitive irregularity of ballast track on the existing speeding line and its influence. At the same time, considering the detailed structure of vehicle and track, and based on the vehicle-track dynamics theory, the paper established a coupling dynamic analysis model that could consider the track and its foundation in detail. Among them, the space coupling model of trackbed and sleeper discusses the mechanical behavior mechanism of macroscopic trackbed through analyzing the change rule of microscopic parameters.

Based on the discrete element theory, the authors of the literature mentioned above can study the mechanical properties and behavior of particles from the microscopic perspective, which is suitable for simulating and analyzing the interaction and movement relationship between complex combination particles, and establish the sleeper-track bed discrete element model. Considering the vehicle load and environmental impact will make ballast continuous cracking lead to its elastic modulus change, have an impact on the sleeper hand. In the calculation and analysis, the elastic modulus of ballast is 80 Mpa, 100 Mpa, 120 Mpa, 140 Mpa, 160 Mpa, and the double-wheel load is used to analyze the force of sleeper. The calculation re-

sults are shown in Table 5.

Table 5. different ballast elastic modulus of sleeper under the force and displacement

Elastic Modulus E/ Mpa	Maximum vertical displacement of sleeper/ mm	Maximum vertical compressive stress of sleeper/Mpa
80	5.925	9.40
100	4.862	9.58
120	4.138	9.72
140	3.611	9.85
160	3.209	9.95

According to Table 5, with the increase of the elastic modulus of ballast, the maximum vertical displacement of sleeper decreases accordingly, and the maximum vertical stress of sleeper gradually increases; Increase the elastic modulus of ballast, the maximum vertical displacement of sleeper decreases gradually, and the maximum vertical stress of sleeper increases gradually. This conclusion is the same as the conclusion obtained by the finite element model established in this paper, so the results obtained in this paper are reliable.

4. Conclusions

Through the finite element method, the "rail - sleeper - ballast" model is established to study the impact of different ballast and sleeper elastic modulus on the response of each part of the track structure. Through numerical calculation and comparative analysis, the following conclusions are drawn:

It is completely feasible to use the finite element method to analyze the ballast track problem. The contact module in ABAQUS can well simulate the contact situation between the various parts of the track structure.

In the selection of the same sleeper, sleeper elastic modulus at the same time, with the increase of the elastic modulus of ballast and the bottom of the ballast, the rail displacement gradually decreases, the sleeper stress gradually increases, the coupler support reaction force decreases.

In the selection of the same ballast and the bottom of the elastic modulus of ballast, with the increase of the sleeper elastic modulus, rail displacement, coupler support reaction force and sleeper stress are reduced.

Due to the reliability of the model, the wheel-rail system can be added on the basis of the model in the future to study the impact of the elastic modulus of ballast on the response of each part of the track under the action of dynamic wheel-rail force.

References

[1] Gilbert B. Discrete numerical model for granular assemblies: Cundall, P A; Strack, O D L Geotechnique, V29, N1, March 1979, P47-65[J]. Sports Illustrated, 1980, 16(4):77.

[2] Ting J M, Khwaja M, Meachum L R, et al. An ellipse−based discrete element model for granular materials[J]. International Journal for Numerical & Analytical Methods in Geomechanics, 1993, 17(9):603-623.
XU Yang, GAO Liang, YANG Guotao, et al.Mechanical modeling of ballast particle and its influence on mechanical properties of track bed [J]. Journal of the China Railway Society, 2014 (9): 73-78.

[3] XIAO Hong, GAO Liang, HOU Bo-wen.Three-dimensional discrete element analysis of vibration characteristics of railway track bed [J]. Journal of Railway Engineering Society, 2009, 26 (9): 14-17.

[4] Journal of Noise and Vibration Control, 2015, 35 (6): 181-184. HUANG Li, LEI Xiao-yan, LIU Qing-jie, et al.Study on Continuous Measurement Method of Wheel / Rail Vertical Force [J].

[5] LUO Qi.Study on mechanical properties of ballasted track bed of high speed railway based on discrete element method [D]. Beijing Jiaotong University, 2014.

[6] FENG Jun-fu.Discrete element analysis and experimental verification of mechanical properties of railway ballast [D]. Dalian University of Technology, 2016.

[7] Journal of Railway Science and Engineering, 2016, 13(6): 1031-1038. JIN Yan, ZHAO Jin-feng, JI Shunying. Discrete element analysis of cumulative sedimentation and deformation modulus.

[8] DU Xin. Discrete element modeling and inertial characteristic optimization of real ballast particles [J]. Journal of the China Railway Society, 2014 (2): 95-102.

[9] Hossain S, Mahmoudi A, Truman C E, et al. Abaqus conference, Warrington, UK[J]. Biochemical Journal, 2004, 181(2):497-506.

[10] Zhuang Zhuo. ABAQUS / Standard Introduction to Finite Element Software [M]. Tsinghua University Press, 1998.

[11] Rose J G, Purcell M L, Liu Q. Suitability of Earth and Granular Materials Pressure Cells for Measuring Railway Trackbed Tie/Ballast Interfacial Pressures[C]//2016 Joint Rail Conference. American Society of Mechanical Engineers, 2016: V001T01A010-V001T01A010.