Study on mechanical maintenance method of ballasted track of high-speed railway based on nonlinear discrete element theory

Abstract: To study the electrical performance of high-speed railway ballasted work and the long running and rotating characteristics of the bed, different design methods are adopted. The longitudinal and transverse resistance of the bed increases with the increase in the ballast grading width. When ballast particle gradation is the lowest interpolation between envelope line and envelope line boundary, the longitudinal and transverse resistance of the bed work according to special requirements. With the increase in the shoulder width, the transverse resistance of running bed increases, while the longitudinal resistance remains constant. When the shoulder width is more than 400 mm, the longitudinal and transverse resistance of the bed works according to the required specifications. Maintenance costs for the various ballasts running on high-speed trains are not cheap. The test results show that the workability can be reduced, and improved by using complete asphalt or stone instead of tussah. Daily cleaning work only accounts for about 10% of the tussah, especially emergency work and special riders should not spend time working. The rubber cushion in sleeper and asphalt concrete cushion in ballast have their advantages and disadvantages in improving the strength of bed. In fact, it should be stipulated in the case file.

Keywords: discrete element method, ballasted track, mechanical maintenance, nonlinear

1 Introduction

Ballastful track is the standard mode of Chinese railway. Its advantages are low cost, low vibration and noise, easy maintenance, and so on. Because it is granular, its mechanical properties are complicated. As the outer protection of the bed track, it can prevent the change in the running line, prevent the expansion of cross wedge rolling (CWR) operation, and stabilize the CWR. The longitudinal resistance of the running bed prevents the running wire from being too long. The good state of ballast walking bed is very important to ensure the safety and improve the performance of running die. It bears the load train directly from the sleeper, delivering sleep stress, maintaining the runner’s geometry, and providing the runner with flexibility and mobility [1].

The running characteristics of high-speed railway are high speed, high density, and small size. In order to achieve high safety and high ride comfort, the track structure must have high ride comfort and high stability. High ride comfort is the guarantee of ride comfort. Its core is to maintain the good geometric state of the track structure for a long time. The track structure is required to provide reasonable shape, geometric size, good internal quality, and high-precision maintenance quality, so as to ensure the high comfort and safety of train operation. High stability refers to the ability of the track to maintain high smoothness and balanced elasticity, and maintain the effectiveness and integrity of components under high-speed operation conditions. Its connotation is less maintenance or no maintenance [2]. The track structure has the advantages of good stability, lasting track geometry, less maintenance workload, good durability, small dead load in phase II of the bridge, reduced tunnel clearance, reduced excavation area, and high comprehensive economic benefits. In addition, the CWR on the track without tussah is not easy to expand, and there will be no stone tussah splashing on the track and high-speed driving. It has been more and more widely used in foreign passenger dedicated lines, and its laying range has developed from bridges and tunnels to soil subgrade and turnout area. The massive laying of tussah-free track structure on passenger-dedicated line has become the development trend of high-speed railway all over the world [3].


2 Literature review

A lot of research has been done on the longitudinal and transverse resistance of track bed in China. Feng and Tan obtained the equivalent transverse resistance of ballasted track bed of type III concrete sleeper by testing the resistance of track bed in subgrade, road bridge transition section, and bridge section [4]. Schramm et al. studied the differences of bed-rail outer protection in lower working processes at different construction stages [5]. Xie et al. studied the test methods of track bed compactness and longitudinal and transverse resistance of track bed in the test section of CWR of Qinghai–Tibet railway, sorted and analyzed the data, and obtained the regression equation of longitudinal and transverse resistance of track bed, which can provide reference for the value of design resistance of CWR [6]; Chen et al. fitted and determined the longitudinal and transverse resistance curves of type III concrete sleeper ballasted track bed through in-situ test and mathematical statistical analysis of test data. In the research on the three-dimensional discrete element model for generating irregular ballast particles [7], Chung and Wu proposed a new method, that is, first establish the sphericity base surface of ballast particles, then triangulate the obtained sphericity base surface to obtain the node spherical coordinates composed of several triangles, and finally randomly generate the concave convex ballast surface according to the relationship between triangles and nodes [8]. Based on Minkowski sum theory, Muramatsu and Shizawa proposed a ballast particle modeling method by expanding the polyhedron unit. The specific method is: in the three-dimensional coordinate system, two polyhedrons of arbitrary shape are superimposed according to certain rules to form a new spatial polyhedron [9]. So et al. proposed a modeling method using digital image processing technology. The specific process of this method is to place three cameras in three mutually perpendicular directions to obtain the views of ballast particles from three coordinate axis directions, and then the three cylindrical structures formed by the three views are superimposed and crossed in space to obtain the specific outline of ballast particles [10]. Cheng et al. refined and improved the relatively rough ballast particle shape established by previous scholars by using the clump algorithm in the discrete element program PFC3D software, but still could not accurately establish the relationship between the three-dimensional model of ballast and the particle contour characteristics of real ballast [11]. Song et al. cut the spherical space using a set of two parallel faces. Although this method can take into account the volume fraction of ballast particle gradation and other conditions, because the shape of the particle model established by this method is relatively regular, there is still a large gap with the actual shape of ballast particles, and the simulation results are still not accurate [12].

3 Research methods

3.1 Discrete element method

Discrete element method was originally used to establish a two-dimensional model of rock blocks and analyze the stability of their slopes [13]. In the following years, Cundall proposed a discrete element method using disk or spherical particles to simulate, which uses the force and displacement of particles to reflect the force and deformation of the simulated material. After years of innovation and development, the theory, algorithm, and program of discrete element method have been continuously improved, and has become an indispensable mainstream analysis method in the fields of geotechnical engineering, geological engineering, and so on. It is suitable for simulating the deformation and failure process of discrete particle assemblies under quasi-static or dynamic conditions. It is applied in fields such as rock and soil mechanics, brittle material processing, powder compaction, discrete particle transportation, etc.

Discrete element method uses discrete particle system to simulate the material. Through the calculation of single particle using dynamic equation, the motion law of the whole particle system is obtained, so as to simulate the overall force and deformation of the material [14]. Since each discrete element is regarded as an independent unit to be studied in the simulation process, the following assumptions are made in the numerical simulation process of discrete element software PFC3D50:

1) By default, all particles in the model are regarded as rigid bodies, and the total deformation of each particle is the total deformation of the model;
2) The particle cluster is composed of spheres as the basic unit, and is composed of multiple overlapping small spheres;
3) The particle cluster model is a rigid body, and the boundary can be deformed;
4) The transmission mode of force and torque between particles is realized through contact and is constantly updated;
5) The contact between particles is all flexible contact, and the two contact points can overlap.

Because ballast materials vary in size and shape, it is important to adjust each ballast to physical conditions
when simulating ballast particles. Because all deformation of ballast beds is caused by the sliding and rotating of ballast particles against each other, it is not necessary to simulate the internal changes in each particle. When the particle cluster is formed from multiple spheres, it is easier to calculate the contact force of the material and allows the contact surfaces to overlap by half, which is consistent with the deterioration of ballast particles, which is important for the simulation. The above assumptions are based on the behavior of Ballast particles in Ballast footpath and the mathematical simulation of ballast bed in medium-high speed railway in this article [15].

The spherical particle bed model is generated based on the fraction of high-speed rail, and then the spatial randomness of the long axis azimuth is realized by using the variation according to the principle of volume, position, and approximate size. Group according to random number, and simulate the random arrangement of ballast in real time. The efficiency and precision of ballast simulation, while the number of basic items constituting particle mass exceeds 8, reflects the degree. This article selects five ballasts for analysis. The average particle swarm consists of 10 cylinders. The structure has ballast contact stiffness of 550 MN/m, ballast tangential contact stiffness of 550 MN/m, wall contact stiffness of 900 MN/m, wall tangential stiffness of 900 MN/m, ballast particle density of 2,400 kg/m$^3$, particle friction of 0.5 and wall friction of 0.5.

3.2 Model verification and analysis

In order to identify the accuracy and electrical characteristics of different ballast resistors, the length and revolution of ballast bed were measured in the ballast bed at the test site of Changzhou-Xiangtan intercity railway. When testing the external protection of the bed made from line [15], an attempt should be made to install a jack and pressure sensor on one end of the sleeper and a directional dial on the other end of the sleeper before removing the fastener and bottom rail pad of the sleeper. Then, the change of sleeper rail can be identified. The load is graded load. The transverse resistance test diagram of track bed is shown in Figure 1. When the longitudinal resistance of track bed is tested, the fastener is first removed and the test is carried out in the rail pad of sleeper. The jack and pressure sensor are installed in the middle of the sleeper, and the indicator plate is installed at both the ends of the sleeper to identify sleeper switch. The average cost of sleep replacement is 2,000 yuan, and the load is graded load [17].

The lateral resistance of the track bed refers to the resistance of the track bed against the lateral displacement of the track frame. It is an important factor to prevent the expansion of the track and maintain the stability of the seamless track. The main factors affecting the lateral resistance of the track are the fullness of the track bed, the shoulder width of the track bed, the height of the track bed shoulder, the type and particle size of the ballast, the influence of line maintenance operations, and the type of sleepers. The lateral resistance of the track bed consists of the frictional resistance between the two sides and the bottom of the sleeper and the contact surface of the track bed and the shear resistance of the track bed at the end of the sleeper.

4 Result analysis

4.1 Test and simulation values of transverse and longitudinal resistance of track bed

In the discrete structure model of ballast walking bed sleeper, after the ballast is fully compacted, the sleeper is pushed horizontally and longitudinally, and the transverse and longitudinal resistance of running bed center is simulated by filling the contact force between the sleeper and ballast [18]. In situ measurement results and separation model simulation of transverse and longitudinal resistance of track bed are shown in Figures 2 and 3, respectively.

The measurement of curvature in Figures 2 and 3 is the relative strength of the burst points measured by 25 sleepers to indicate the equilibrium state of the ballast bed. According to the resistance of ballast bed, the sleeper sleep protection is 2 mm, the measured value of lateral resistance of ballast bed is 15.13 kN, and the simulated value is 15.97 kN. The measured value is 22.45 kN and the simulated value is 23.34 kN. In terms of measured
values, the correlation coefficients between measured values and simulated values in the two figures are 0.958 and 0.928, respectively. It can be seen that the bed track pattern formed by the separation of materials can affect the relationship between bed walking and sleep. Through the adjustment function of the simulated value, the relationship between the transverse resistance $Q$ value of bed flow and the change $y$ in sleep rate changes according to the working force. According to formula (1) breastfeeding information

$$Q = Q_0 - B y^2 + C y^3 N,$$  

(1)

where $Q_0$ – initial transverse resistance of track bed (kN); $y$ – lateral displacement of sleeper in track bed (mm); and $B$, $C$, $Z$, and $N$ – drag coefficient.

Research shows that $N$ can be taken as 4/3. The fitting function equation of transverse resistance of ballast bed is given by

$$Q = 4.92 - 10.38y + 18.71y^{3/4}.$$  

(2)

The fitting function equation of longitudinal resistance of ballast bed is given by

$$Q = 11.57 - 12.93y^{3/4}.$$  

(3)

### 4.2 Analysis on influencing factors of longitudinal and transverse resistance of track bed

The longitudinal and transverse resistance of running bed is very important to determine the visibility of running bed, and many factors affect its size. The effects of ballast gradation, sleeping depth, slope, and shoulder width on the walking bed were studied [20].

The ballast bed is a granular body, and its small size has great influence on the mechanical properties, strength, safety, and maintenance of the ballast bed. At the same time, the grade of ballast plays a decisive role in preventing the residual deformation and particle breakage of ballast bed. At present, China’s high-speed ballasted railway adopts super ballast [21]. At present, there are few studies on the effect of particle size on bed flow resistance. In this article, the discrete element analysis software PFC3D is used to establish a super ballast trail model, and the horizontal and longitudinal resistance of the trail is studied. The scoring envelope of the super ballast is shown in Figure 4.
This article is divided into three working conditions according to the screening quality percentage of super graded ballast, as shown in Figure 4. Working condition 1 is the upper envelope of super graded ballast grading envelope, working condition 3 is the lower envelope of super graded ballast grading envelope, and working condition 2 is the interpolation between them. From condition 1 to condition 3, the relationship between transverse and longitudinal resistance of track bed and ballast grading is shown in Figure 5. From condition 3 to condition 1, fine particles gradually increase, the total number of ballast per unit volume increases, and the ballast grading becomes wider [22]. It can be seen from Figure 5(a) and (b) that from condition 3 to condition 1, the transverse resistance of track bed is 10.92, 13.25, and 15.79 kN, and the longitudinal resistance of track bed is 18.36, 20.27, and 20.8 kN, respectively. The longitudinal and transverse resistance of track bed gradually increases. As the ballast grading becomes wider and the particle size distribution becomes wider, more fine particles can be filled into the gap of coarse particles, which can increase the compactness of the main road bed, increase the force transmission capacity of the track bed, reduce the settlement of the track bed, and increase the service life of the main road bed.

### 4.3 Suggestions on vibration reduction and maintenance measures for ballasted track on high-speed railway bridge

The influence of rubber cushion under sleeper, ballast cushion under ballast, and combined damping cushion on mechanical characteristics of bridge track bed is compared and analyzed, and the recommended damping measures of bridge track bed under high-speed driving condition are put forward. As shown in Figure 6(a) and (b), the comparison of the influence on mechanical properties of track bed under the condition of using only the under-sleeper rubber pad with stiffness of 60 kN/mm, asphalt concrete pad, and combined asphalt concrete pad shows the rigidity of 140 kN/mm [23–27].

It can be seen that the application of different vibration reduction measures can improve the dynamic response of ballast bed on the bridge to a certain extent, but the application of vibration reduction measures will increase the vertical deformation of the ballast bed to a certain extent. When different sleeper tracks are used on bridges, the dynamic characteristics of vehicles and track systems will not change; when trapezoidal sleepers are used on box beams and U-shaped beams, respectively, their vibration reduction performance is basically the same, and the Z vibration level insertion loss is about 9 dB. Various vibration reduction measures have their own advantages and disadvantages in the improvement of different mechanical indexes. In terms of reducing the average contact force of ballast particles, the average contact force of ballast particles will be reduced by 11.40, 14.69, and 13.80%, respectively, by using rubber cushion under sleeper, asphalt concrete cushion, and combined vibration reduction measures compared with no vibration reduction measures. In terms of peak value of vibration acceleration of track bed, the combined vibration reduction measures reduce by 6.68% compared with using only rubber cushion under sleeper and by 35.06% compared...
with using only asphalt concrete cushion under ballast. In terms of cumulative settlement of track bed, the combined vibration reduction measures reduce by 2.35% compared with using only rubber cushion under sleeper and increase by 7.99% compared with only using asphalt concrete cushion under ballast. In terms of elastic deformation of the structure under the sleeper, the combined vibration reduction measures reduce by 35.12% compared with using only the rubber cushion under the sleeper, and increase by 66.14% compared with using only the asphalt concrete cushion under the ballast. Therefore, compared with using only one damping cushion, the combined damping measures do not significantly improve the dynamic response of track bed, and will only significantly increase the construction cost [28], so it is not recommended to use. Compared with the asphalt concrete cushion under the ballast, the vibration acceleration of the ballast bed is reduced by 30.41%, but the contact force of ballast particles will increase by 3.85%. The cumulative plastic settlement and elastic deformation under the sleeper of the outer ballast bed are increased by 5.51 and 156.08%, respectively. On the whole, the use of rubber cushion under sleeper on high-speed railway bridge is better than the use of asphalt concrete cushion in reducing the vibration acceleration of track bed, but it will cause large structural deformation. The application of asphalt concrete cushion can improve the mechanical properties of the structure in all aspects in a balanced way. They have their own advantages and disadvantages in different aspects, and should be selected reasonably according to different actual conditions [29].

During the maintenance of track equipment during the trial operation of high-speed ballast railways, various detection methods are used to evaluate the actual quality of the track through the track quality index, which can be used as the basis for macro management and quality control of track irregularity. It can guide the preparation of remediation and maintenance plans and guide the rectification operations. The plan is highly targeted and can effectively reduce the occurrence of equipment diseases. At the same time, it can be used as a consideration and reference for the quality of track fine-tuning in the construction stage, so as to achieve the goals of less deformation and less and quick maintenance under the requirements of stable, safe, and high-speed railway operation.

5 Conclusion

In this article, the accuracy of the structure is determined by analyzing the longitudinal and transverse resistance of the bed and the formation of the discrete unit structure of the ballast track mattress. It can be seen that with the increase in the running bed shoulder width, the change in running bed speed increases, but the length of running bed changes little. When the shoulder width of the bed is 400 mm and above, the longitudinal and transverse resistance of the bed should meet special requirements. When the rubber cushion in the sleeper is combined with the ballast cushion, the visible tightness value of the rubber cushion in the sleeper becomes 1. Linen is not good. When the strength of rubber cushion is in the range of 600–220 kN/mm, the average contact force between Ballast particles and the vertical deformation bed decreases.
with the increase in the oil bed pad area. When the vertical deformation is low, it will increase further. Considering the tightness of the cushion bed, when the strength of the cushion is in the range of 100–180 kN/mm, the combined angle measurement effect is the best. The rubber cushion in sleeper and asphalt concrete cushion in ballast have their advantages and disadvantages in improving the strength of the bed. In fact, it should be stipulated in the case file.

Vibration testing is driven by the requirements of product testing and the development of related technical fields. Therefore, it is necessary to absorb the advanced knowledge obtained from the research of various related disciplines and develop the level of vibration testing to meet the growing development requirements. The author believes that in addition to further enriching and improving the various aspects of the vibration test control field, attention should also be paid to other fields in the future.

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