Research on Railway Ballast With the Optimal Sphere Filling by Using Discrete Element Model

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Abstract: DEM (discrete element method) is an effective method to study the dynamics of ballast track. The DEM assumes that the ballast is composed of spheres and the optimal combination of spheres in single ballast is the key to study ballast tracks by using DEM. A track ballast model using DEM is established with accurate ballast profile that is filled with spheres obtained by using a binocular 3D scanner and the Bubble Pack algorithm; In this paper, a direct shear test is adopted to study mechanical properties of the track ballast filled differently. The optimal sphere filling method is chosen using a ballast model based on DEM. The results show that: the volume filling rate $\omega$ of the ballast is negatively correlated with the radius ratio $r$ of the small ball and the large ball that are adjacent, and positively correlated with the overlap angle $\phi$ of the two adjacent balls; with the same volume filling rate, the smaller ratio $r$ is, the greater number of spheres is, and the closer the maximum shear stress of numerical calculation is to the measured level; for general engineering calculations, the optimal combination with a volume filling rate of 0.8 should be used for calculation.

1. Introduction

DEM (discrete element method) is an effective method to study the dynamics of ballast track. As numerical calculation develops, research unit of DEM has evolved from the early disc and sphere to the arbitrary particle with irregular shape. When modeling the ballasted track with DEM, ballast with irregular shape is usually inlaid or bonded by multiple spheres. Therefore, scholars from home and abroad pay much attention to how to optimally fill the ballast with spheres, a first clue to build the ballast track model with DEM.

Jing [1] mentioned using PFC 2D connecting rods to combine 7 two-dimensional discs into particle clusters to simulate the crushing mechanism of ballast under cyclic loading in PFC 2D. Xiao [2] uses three-dimensional spherical particles to simulate the ballast, but the occlusal characteristics between ballast particles cannot be accurately simulated since the geometric characteristics of the ballast particles are not considered. McDowell [3-4] uses PFC3D connecting rods to generate composite particle clusters with irregular shapes, using bonding units with 2, 4, and 8 balls to simulate ballast particles to study the cracking laws of ballast particles and the influence of ballast particle shape on the performance of the ballast bed. The results show that bonding units with 8 balls enhance the interlocking between particles that restrains the rotation of the particles in the sample to a certain extent, which reflects the real circumstances even better. Tutumluer [5-8] extracts the shape of ballast...
particles by three-dimensional scanning, and selects 11 typical polyhedrons to simulate the real ballast particles. However, the shape of real ballast particles is quite random, the polyhedrons selected cannot reflect the real ballast particles.

Research presents in this paper can help to better resolve these limits mentioned above.

Taghavi’s proposal [9] is based on 2D and Bubble Pack algorithm that a profile after triangular meshed can be filled by two adjacent spheres with radius ratio $r$ and overlapping angle $\phi$. These two factors can be controlled in order to fill different profiles. Results can be found from Bubble Pack algorithm that when $r$ is smaller and $\phi$ is larger, the more densely the larger and smaller balls are filled, the closer the result is to the real ballast profile.

In the particle discrete element method, the indicators to measure the filling of the ballast include the total number of spheres, the mass filling rate of the 3D ballast profile, and the volume filling rate of the 3D ballast profile. When the ballast is regarded as the homogeneous, its mass filling rate and volume filling rate can be converted to each other. In this article, the volume filling rate of the ballast serves as the control index.

A track ballast model using DEM is established with accurate ballast profile that is filled with spheres obtained by using a binocular 3D scanner and the Bubble Pack algorithm; A direct shear test is adopted to study mechanical properties of the track ballast filled differently. The optimal sphere filling method is then given.

2. Research on the Optimal filling method of ballast using DEM

2.1. Particle Discrete Element Ballast Filling Modeling

From the above analysis, we can see that the value range of $r$ is (0, 1], and the value range of $\phi$ is [0°, 180°]. A 3D scanner is used to obtain profiles of multiple ballasts randomly selected with uniform pin-sheet coefficients in the laboratory. Based on the value range of $r$ and $\phi$, with 0.1 as the step length of $r$ and 20° as the step length of $\phi$, a 2-factor, 10-level orthogonal test is designed for each ballast. A DEM ballast filling test with 10 ballasts, 1000 working conditions in total is carried out. The average filling rate of 10 ballasts was analyzed statistically when the test is finished. The results are shown in Figure 1.

$$\omega = 0.625 - 0.484r + 1.823 \times 10^{-3}\phi + 5.367 \times 10^{-6}\phi^2 + 2.787 \times 10^{-3}r^2\phi + 1.866 \times 10^{-6}r^2\phi^2 - 5.200 \times 10^{-3}r^3\phi$$  (1)
The principle of determination coefficient\cite{10} : Adjusted coefficient of determination $R^2_{\text{adj}}$ and the prediction coefficient $R^2$ are both close to 1, and the difference between the two is less than 0.2, indicating that the coefficients of the fitting equation are valid.

2.2. Research on the optimal filling method with the same volume filling rate
Equation (1) shows that the volumetric filling rate $\omega$ of the ballast is related to $r$, the small to large ratio $r$, and $\phi$, the overlap angle. When the volume filling rate of the ballast is smaller than 0.5, that is, when the volume of the filled sphere is less than 1/2 of the actual ballast profile, the filled ballast has there is a large difference in quality and volume between the filled ballast and the actual ballast. Therefore, when $\omega>0.5$, the filling situation is studied.

Hertz-Mindlin’s contact constitutive is adopted and DEM model contact parameters are determined referring to research from Liu et al.\cite{11}. Taking $\omega=0.8$ as an example, the discrete element direct shear test is performed on ballast particles with different filling combinations, shown in Figure 2.

![Figure 2 DEM direct shear test diagram](image)

Results comparison of numerical calculation of direct shear test and actual test with the same size\cite{12} shown in Figure 3.

![Figure 3 direct shear test diagram](image)

Table 1. Maximum shear stress in various working conditions.

| $\omega$ Range of change | maximum shear stress kPa compared with actual test |
|--------------------------|--------------------------------------------------|

Figure 3 shows: With the same volume filling rate, the smaller ratio $r$ is, the more numbers of spheres is, and the closer the maximum shear stress calculated by the numerical value is.

2.3. Research on the optimal filling method with different volume filling rates
In 2.2, the optimal filling method with different volume filling rates is screened out, and the maximum shear stress is calculated, shown in Table 1.
Table 1 shows that when the volume filling rate is 0.8, the maximum shear stress change rate relative to the actual test is 4.7%~5%. Therefore, the general engineering calculations adopts optimal combination method when the volume filling rate is 0.8 for the best of calculation accuracy and efficiency.

3. The lateral resistance test of gravel ballast bed based on the optimal packing method of discrete element

A discrete element model of the gravel track bed composed of three Type III sleepers is established in accordance with the typical cross-sectional dimensions of China's single-track ballasted track. The Bubble Pack algorithm is used to optimally fill multiple conventional needle-shaped and sheet-shaped ballasts meeting the super ballast standard; the sleepers are modeled by wall units, and the balance issues of complex sleeper gravity is processed through the API interface.

After finish building the model, the volume density of the ballast on the surface of the gravel ballast bed model, 1.70g/cm³ can be tested out. The middle sleeper is pushed laterally and uniformly at a speed of 1mm/s to analyze the lateral resistance of the track bed, which is shown in Figure 5 [11].

Figure 4 shows that the test result of the simulation test of the lateral resistance of the discrete element track bed and the measurement result in the lab are consistent, considering that it’s inevitable that a certain error exists. It can be concluded that the discrete element ballast model with a volume filling rate of 0.8 should be built to better reflect the engineering mechanical properties of the ballast.

4. Conclusion

A track ballast model using DEM is established with accurate ballast profile that is filled with spheres obtained by using a binocular 3D scanner and the Bubble Pack algorithm; A direct shear test is adopted to study mechanical properties of the track ballast filled differently. The optimal sphere filling method is chosen using a ballast model based on DEM. The results show:

(1) The volume filling rate of ballast, \( \omega \) is negatively correlated with \( r \) and positively correlated with \( \phi \).

(2) With the same volume filling rate, the smaller ratio \( r \) is, the larger number of spheres is, and the closer the maximum shear stress calculated is to the real test.

(3) Therefore, the volume filling rate of 0.8 should be taken when calculating for optimal combination.
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