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Mechanical behavior of heavy-haul railway track structure based on finite element method

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***Abstract*—With the increase of axle load, train speed and freight demand of heavy haul railway, the load on the train track is becoming more and more serious. In order to study the mechanical characteristics of train track in detail, a 3D model coupled train track, sleeper and foundation is established by using finite element method in this paper, and the effect of the heavy haul train loads, sleeper and track bed parameters on mechanical characteristics of train track were analyzed. The results shown that the stress on the track surface is large. The upper surface of the track is compressed, the bottom of the track is mainly tensile, the maximum displacement of train track is in the middle of the two adjacent load points. The maximum stress and vertical displacement of track increase with the increase of train axle load. When the elastic modulus of sleeper increases, the maximum stress and displacement of track gradually decrease, but the change is small. When the sleeper spacing decreases, the maximum stress and displacement of the track gradually decrease, and the change is more obvious. When the sleeper thickness increases, the maximum stress of the track decreases gradually, but the vertical displacement of the track increases.**

Keywords—Heavy-haul railway; Mechanical analysis; Finite element method；ABAQUS

I. INTRODUCTION

Track is an important structure in railway transportation. With the rapid development of China's railway transportation industry, there are higher requirements for train axle load and running speed [1], which makes the role between track and train under heavy-duty railway transportation more complex, and then puts forward higher requirements for the bearing capacity of train track structure. The mechanical characteristics of track under train load are complex [2-3], and its analysis process involves geometric nonlinearity and material nonlinearity. When analyzing the action of track and wheel rail, the comprehensive influence of track bed and foundation should be considered.

Some researches on wheel rail action and track force have been done by scholars. Yang [4] established a two-dimensional model by using the finite element method to simulate the moving train through the moving wheel load vibrating at a certain frequency, so as to study the foundation vibration effect under different train running speeds. Wang [5] adopted the elastic foundation beam method and regarded the moving load of the train as the moving load acting on the Timoshenko beam, so as to deduce the foundation reaction force under the action of the train. In addition, El-sayed [6] studied the mechanical response of track including concrete sleeper and fastener system to coupled vertical and transverse loads by establishing a 3D finite element model. The existing research on the foundation deformation under train load is more detailed, but the interaction between wheel and rail is ignored, and the contact between train track and sleeper is key factor that affect the deformation of train track. The traditional theoretical analysis method cannot reflect the stress concentration of train track. Therefore, a 3D model coupled train track, sleeper and foundation is established by using finite element method in this paper, the mechanical characteristics of the train track under different loads, sleeper types, sleeper spacing and sleeper thickness are analyzed. The research results can provide theoretical support for the construction and design of the train track.

II. CALCULATION MODEL

A. Basic assumptions

In order to simplify the solution process of the finite element model, according to the solution method of the finite element model, the following simplified assumptions will be made in this paper:

(1) The soil is isotropic material, and does not contain impurities such as sediment and gravel, does not consider groundwater, and the surface is flat without bulge and depression.

(2) The sleeper is a rectangular block, and the tie algorithm is used to replace the fastener between the sleeper and the rail.

(3) The ballast bed is also regarded as an isotropic body.

B. Geometric model and material parameters

The general nonlinear finite element software ABAQUS is used to establish the finite element model, and the whole soil model is set as 12m × 7.4m × 4m. The cross section of the train track is I-beam, the section size is shown in Figure 1. The gauge adopts the standard gauge of 1.435m [7]. The sleeper section is simplified as a cuboid, with a length of 2.5m, a width of 0.3m and a height of 0.2m. There are 1667 sleepers / km along the longitudinal direction of the track [7], and the geometric model is shown in Figure 2.

Mohr-Coulomb model is adopted for the constitutive model of soil and ballast, and the specific parameters of density ρ, cohesion *c*, friction angle ϕ, elastic modulus *E* and Poisson's ratio μ are shown in Table 1 [7-9]. In all cases considered in this paper, the expansion angle is assumed to be zero [7], the train track and sleeper are described as linear elastic model [7], the train track adopts heavy rail, and the sleeper adopts type III reinforced concrete.

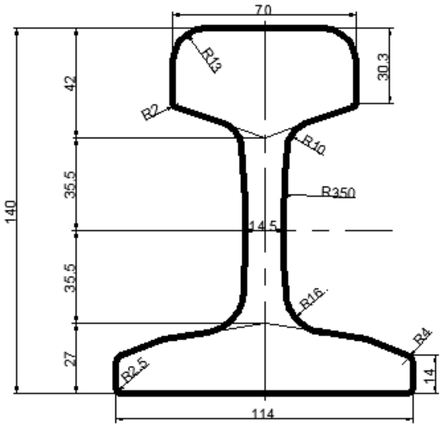

Fig. 1. Dimension of track structure

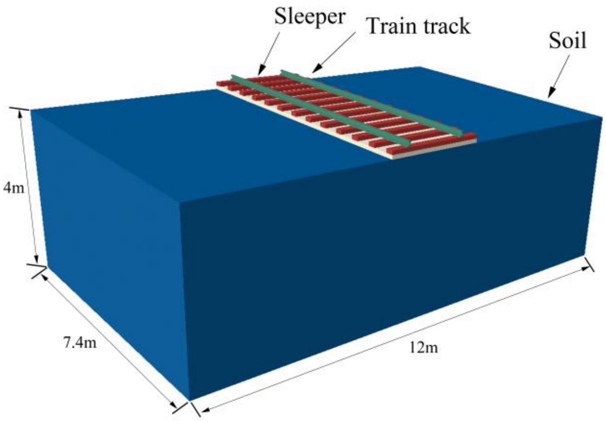

Fig. 2. Geometric model

Table1.Model material parameters

	ρ(kg/m^3)	E(MPa)	μ	ϕ(°)	c(kPa)
Soil	190	18	0.4	18	20
Track bed	1950	190	0.25	34	80
Track	7810	210000	0.3	-	-
Sleeper	2400	35000	0.17	-	-

C. *Finite element model and boundary conditions*

In the numerical model, the load applied by the train corresponds to the train wheel in space, a concentrated force is applied at the wheel rail contact point to describe the interaction between the wheel and rail [10], and the sinusoidal function is used to represent the wheel rail force at a point on the top surface of the track, as shown in Equation (1).

$$P(t) = P\sin 2\pi ft \tag{1}$$

Where P(t) is the pressure at the contact point; P is the dynamic wheel load; *f* is the frequency of load action; *t* is the time when the wheel set passes through this point.

The moving load of the train can be equivalent to the static load. Calculate the wheel static load according to the train axle load in the specification, and then multiply it by the coefficient 1.3 times of the maximum static load to simulate the train load [10]. Based on the analysis of the joint position of the train, there are four groups of wheels where the wheels and loads are densely distributed, as shown in Figure 3. The distance between two adjacent wheels in the same carriage is 1.8m, and the distance between two adjacent wheels in different carriages is 1.5m [7].

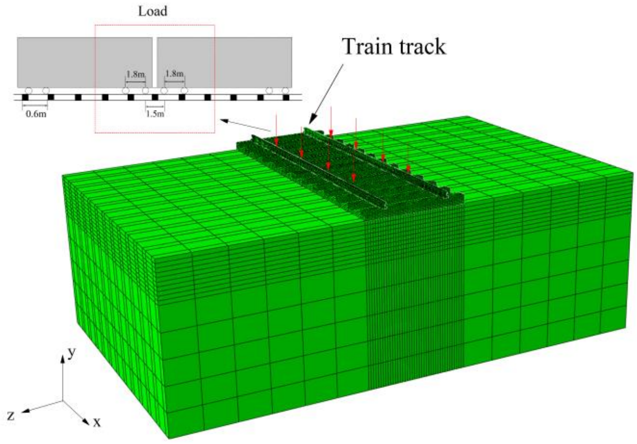

Fig. 3. Finite element model

In the numerical analysis, the X-Y and Y-Z surfaces of soil are constrained in the Z direction and X direction respectively. The bottom surface (x-z surface) of the soil is constrained in the XYZ direction, and the upper x-z surface is set as a free surface [11]. ABAQUS/explicit analysis method is used to simulate the loading process. The numerical analysis is divided into two steps: gravity loading step and train loading step. In the gravity loading step, the gravity load is applied to the whole model. In the train load step, the train load is applied on the train track along the Y direction. Eight-node reduced integral element (C3D8R) is used to simulate soil, sleeper and train track, and the mesh of train track is refined. The finite element model is shown in Figure 3.

D. *Model validation*

The field measured data are used to verify the reliability of the finite element model which is established in this paper. Ding [7] conducted field measurement on Shuohuang heavy haul railway. Using the track structure parameters in the literature, the finite element model is established and calculated, and the numerical simulation results are compared with the measured data, as shown in Figure 4. The difference between the numerical simulation results and the field measured data is small, that is, the finite element method can accurately simulate the mechanical characteristics of heavy haul railway track structure.

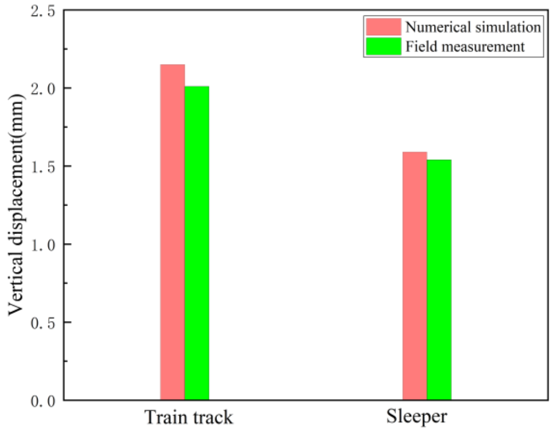

Fig. 4. Comparison of calculation results

III. ANALYSIS OF CALCULATION RESULTS

A. Stress-strain analysis

When the axle load of heavy haul train is 200kN, the von Mises stress distribution of track and foundation structure is shown in Figure 5. It can be seen from the figure that when the load is applied, the stress distribution of the two tracks is basically the same. There is stress concentration on the track surface, and the position of stress concentration is consistent with the action point of train load. In addition, the stress outside the load action point on the track surface is small, and the high stress area expands along the track axis centered on the load action point. The track structure is simplified as an I-beam when modeling. According to the stress distribution of the track cross section at the load action point, the stress on the upper surface of the track is large, and the maximum stress is in the middle of the upper surface. The stress of the track decreases gradually along the vertical direction, and the waist of the track section is also the area where the stress is concentrated. The stress in the lower part of the track is relatively small and mainly concentrated on the lower surface of the track.

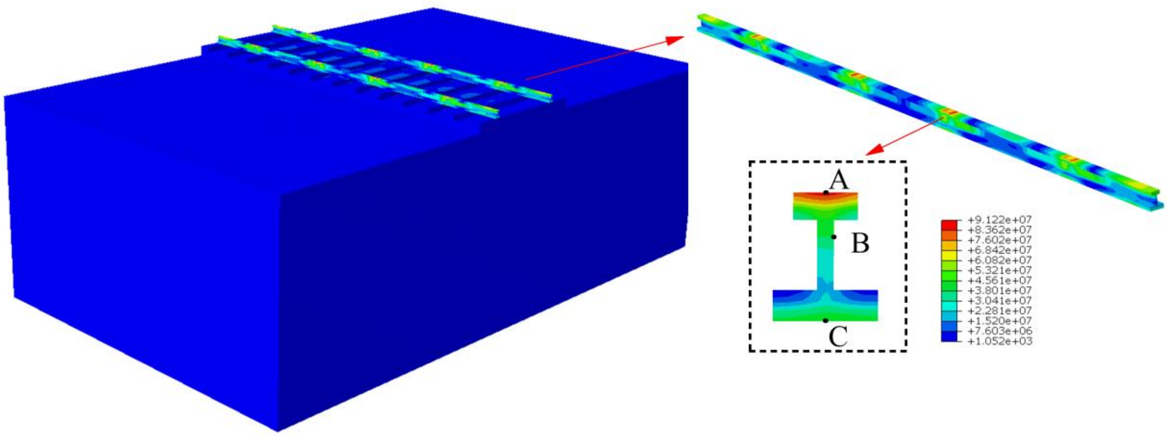

Fig. 5. Von Mises stress distribution

Take the top, waist and bottom of the track section as points A, B and C respectively for analysis (as shown in Figure 5). The stress curve can be obtained along the axial direction of the track, as shown in Figure 6. It can be seen from the figure that the track stress at the load action point at the connection of the train carriage is the largest (as shown in Figure 3, the spacing is 1.5m), and the maximum value is about 91.2MPa, Therefore, the distance between loading points has a great influence on the rail stress. The maximum stress at the waist and bottom of the track section is only 69% and 65% of the maximum stress at the top. In addition, curves A, B and C have similar variation trends, with larger stress at the point of loading and smaller stress at other positions. Due to the small size of the waist (point B) of the track cross section, the stress is larger than that at the bottom of the track. The overall stress of the track is in the elastic deformation stage, which is relatively safe. In the middle of two adjacent load points, there is a large stress, because of the resistance of the lower sleeper to the deformation of the track, resulting in a large stress of the track.

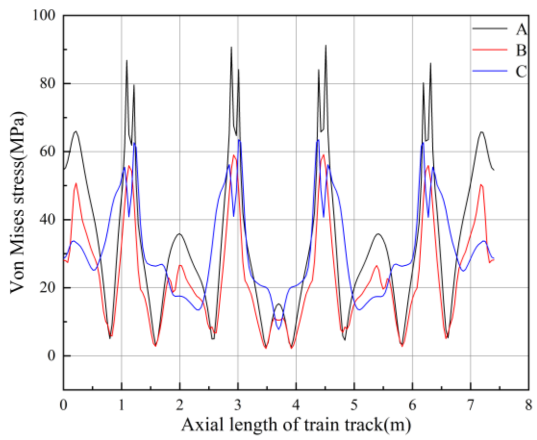

Fig. 6. Von Mises stress distribution in track axial direction

Figure 7 shows the axial strain of the track. It can be seen from the figure that the upper surface of the track at the load point is mainly compressive strain, and the upper surface of the track between the two adjacent load points is tensile strain, because the resistance of the sleeper causes the upper surface of the track to be tensioned. The bottom of the track is mainly in tension, and the high strain area is located at the load point, and there is compressive strain in the local area, which is also the action point of the sleeper. The sleeper can effectively resist track deformation and reduce the high stress-strain area of the track.

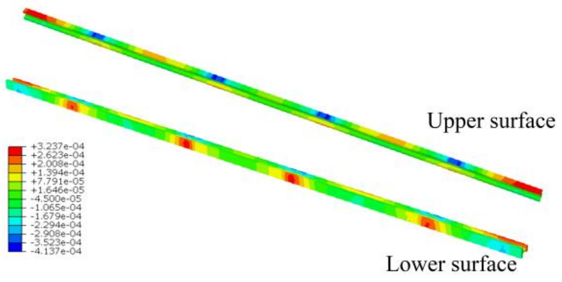

Fig. 7. Axial strain distribution

B. Displacement analysis

Figure 8 shows the vertical displacement distribution of track and foundation. It can be seen from the figure that the stratum has vertical displacement in the area close to the track, with the maximum value of 1.07cm. The area with the largest track displacement is in the middle of two adjacent load points of the train carriage, with the maximum value of 1.49cm. Under the train load, the vertical displacement of the track is more obvious. Therefore, the foundation can be treated to control the stratum and track settlement under the load.

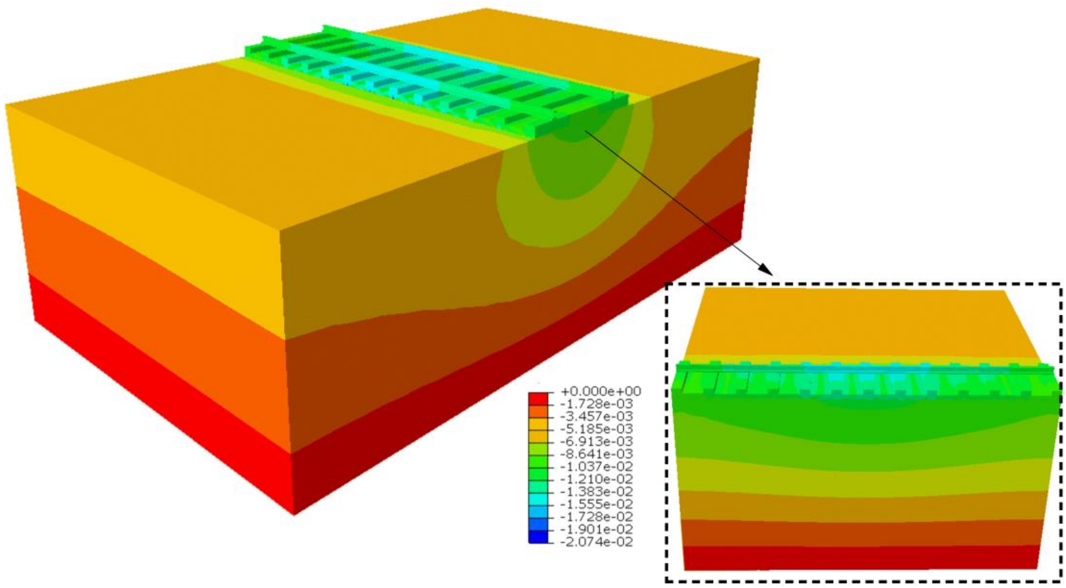

Fig. 8. Vertical displacement distribution

IV. STRESS CHARACTERISTICS ANALYSIS OF HEAVY HAUL RAILWAY TRACK

A. Influence of Axle load

With the development of heavy haul railway, the train axle load has gradually increased in recent years. The increase of train axle load is directly reflected in the obvious effect of train vertical load, so it will have a direct impact on the stress of track structure. The stress characteristics of track structure under axle load of 100kN to 300KN are analyzed respectively. The sleeper is type III concrete sleeper, and the sleeper spacing is 1667 pieces/km. Through simulation calculation, the maximum von Mises stress of track structure under different axle loads can be obtained, as shown in Figure 9. It can be seen from the figure that the maximum von Mises stress of track increases with the increase of train axle load, and the maximum stress of track changes linearly as a whole. When the axle weight is 100KN, the maximum stress is 43.03MPa. When the axle load is 300KN, the maximum stress is 140.3MPa, which increases by 3.26 times, and the influence of train axle load is very obvious. The stress distributions of track structures are similar, and there are stress concentration and high stress area only near the train load point, but the high stress areas tend to extend along the track axis with the increase of train axle load.

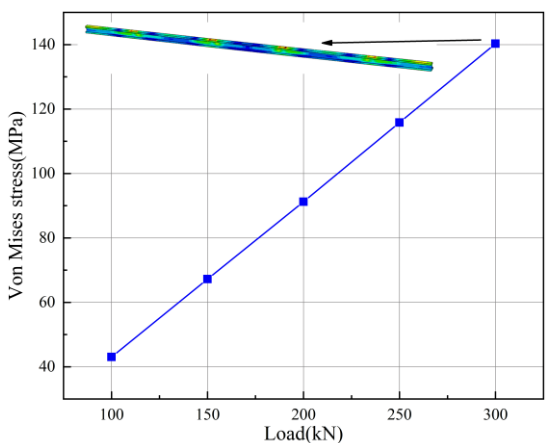

Fig. 9. Maximum stress of track under different axle loads

The maximum vertical displacement of track and stratum under different axle loads is shown in Figure 10. It can be seen from the figure that the maximum vertical displacement of track and stratum increases with the increase of train axle load, and the overall changes linearly. When the axle load is 100KN, the maximum vertical displacement of track and stratum is 0.9cm and 0.75cm respectively. When the axle load is 300KN, the maximum vertical displacement of track and stratum is 2.15cm and 1.4cm respectively, which increases by 2.4 times and 1.9 times respectively. The influence of train axle load on the displacement of structure is very obvious. The overall ground displacement is less than the track displacement, which is mainly due to the existence of sleepers, which can resist the deformation of the track, resulting in relatively small ground displacement.

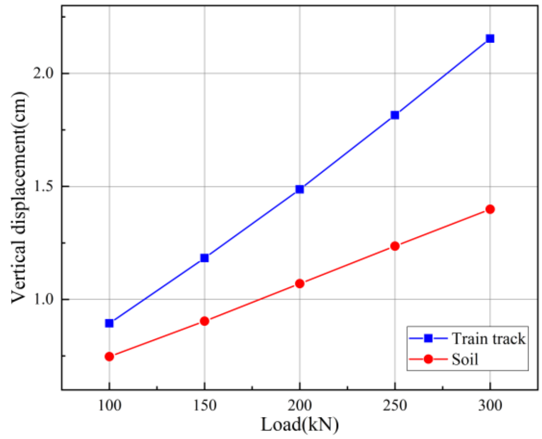

Fig. 10. Maximum displacement of track and stratum under different axle loads

B. Influence of sleeper type

Different types of sleepers have different effects on the track structure. Sleepers are important components to keep the rail stable. They bear the weight, transverse force and longitudinal force transmitted from the rail and transfer them evenly on the track bed. In addition, they connect the two rails together to fix the rail position and keep the rail gauge. The sleeper can also fix the railway direction, so that the railway will not produce longitudinal and transverse displacement due to the force. The specific layout of sleepers shall be determined according to train traffic volume, construction and driving conditions. The sleeper types are mainly reflected in the differences in the elastic modulus of sleepers. When the sleeper spacing is 1667 pieces / km and the train axle load is 200KN, the stress characteristics of track structures under different sleeper types (elastic modulus change: 31GPa to 37GPa) are shown in Figure 11. It can be seen from the figure that when the elastic modulus of sleeper increases, the maximum stress of track gradually decreases, but the change amount is small, and the change rate tends to decrease gradually. When the elastic modulus of sleeper is 31GPa, the maximum stress of track is 91.3MPa. When the elastic modulus is 33GPa, 35GPa and 37GPa, the maximum stress of track is reduced by 0.7 ‰, 0.9‰ and 1‰ respectively. Therefore, although the sleeper can reduce the stress on the track structure to a certain extent, but the effect is small, the specific design scheme of the sleeper can be considered comprehensively to reduce the stress on the track.

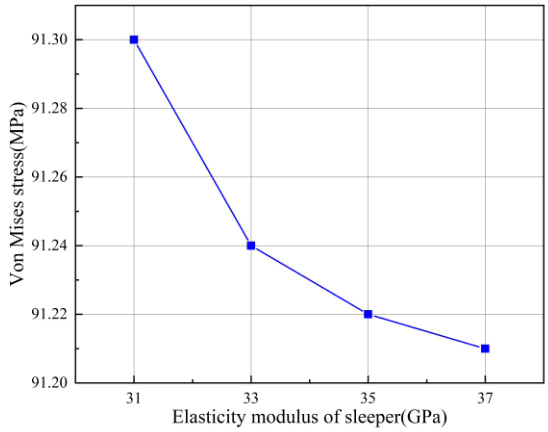

Fig. 11. Maximum stress of track under different sleeper types

The maximum vertical displacement of track and stratum under different sleeper types is shown in Figure 12. It can be seen from the figure that the maximum vertical displacement of track and stratum decreases with the increase of sleeper elastic modulus, but the change is also small, and it changes linearly as a whole. When the elastic modulus of sleeper is 31GPa, the maximum vertical displacement of track and stratum is 1.492cm and 1.068cm respectively. When the elastic modulus is 37GPa, the maximum vertical displacement of track and stratum is 1.485cm and 1.071cm respectively, which is reduced by 0.5% and 0.3% respectively. The influence of sleeper type on the displacement of structure is not obvious. The overall displacement of the stratum is also less than the track , mainly because the larger elastic modulus is, the smaller deformation of the sleeper is, and the smaller deformation of the stratum is.

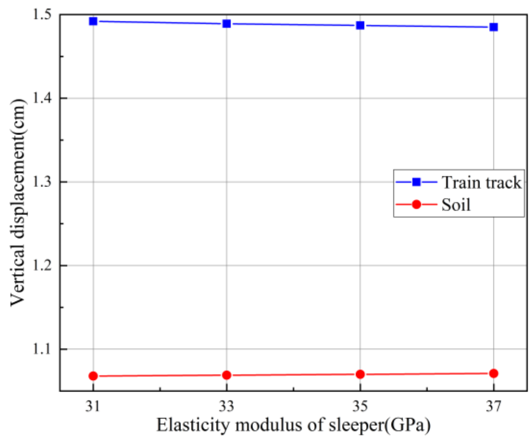

Fig. 12. Maximum displacement of track and stratum under different sleeper types

C. Influence of sleeper spacing

The spacing of sleepers is the distance of sleeper arrangement under the rail. Due to the different track line grades and uses, the number of sleepers laid is different, so the sleeper spacing is also different. Sleeper spacing is one of the important parameters in track structure design. The sleeper spacing is related to the number of sleepers laid per kilometer. If the sleeper spacing is small, the stress of each track component is small, and it is easy to maintain the gauge and direction, which is more important for sections with high train speed. However, if the sleeper spacing is too small, the number of sleepers laid is large, which is not in line with economic benefits. When the elastic modulus of sleeper is 35GPa and the axle load of train is 200KN, the stress characteristics of track structure under different sleeper spacing (1667 pieces / km to 1840 pieces / km) are shown in Figure 13. It can be seen from the figure that when the sleeper spacing decreases, the maximum stress of the track gradually decreases, the change is less than 2MPa, and the change rate gradually decreases as a whole. When the number of sleepers is 1667 pieces / km, the maximum stress of the track is 91.2MPa. When the number is 1840 pieces / km, the maximum stress of the track is reduced by 1.8%. Therefore, the number of sleepers has a slight impact on the track stress characteristics. In the design of heavy haul railway, it can be considered to reduce the sleeper spacing to reduce the track stress.

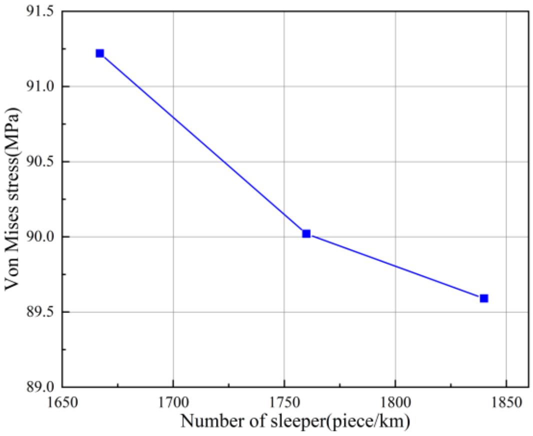

Fig. 13. Maximum stress of track under different sleeper spacing

The maximum vertical displacement of track and stratum under different sleeper spacing is shown in Figure 14. It can be seen from the figure that the maximum vertical displacement of track and stratum decreases with the increase of sleeper elastic modulus. The change of vertical displacement of track is obvious, about 0.04cm, but the change of vertical displacement of stratum is very small. The vertical displacement changes linearly as a whole. When the number of sleepers is 1840 pieces / km, the maximum vertical displacement of track and stratum is 1.447cm and 1.064cm respectively, which is reduced by 2.7% and 0.6% respectively compared with 1667 pieces / km. In addition, the overall stratum displacement is still less than the track displacement. Because the number of sleepers is more, each sleeper shares the force that comes from the rail is lesser, the rail is subjected to the action of sleeper resistance is bigger, resulting in less track deformation.

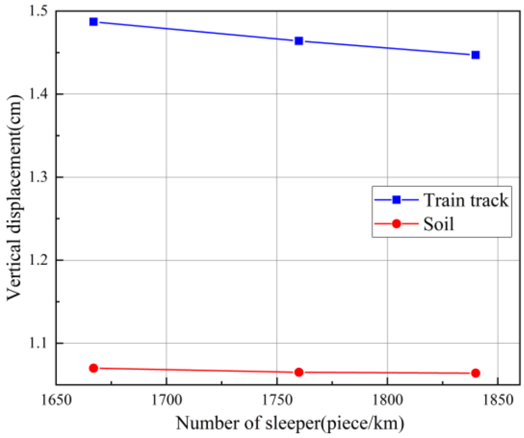

Fig.14. Maximum displacement of track and stratum under different sleeper spacing

D. Influence of sleeper thickness

The sleeper thickness affects the stress characteristics of the sleeper in terms of size. If the sleeper thickness is large, the sleeper stiffness is greater than the underlying stratum, so it can effectively resist track deformation; If the sleeper thickness is small, the economic benefit can be increased to a certain extent. When the elastic modulus of sleeper is 35gpa, the axle load of train is 200kn and the sleeper spacing is 1667 pieces / km, the stress characteristics of track structure under different sleeper thickness (0.2m to 0.35m) are shown in Figure 15. It can be seen from the figure that when the sleeper thickness increases, the maximum stress of the track gradually decreases, the change amount is about 3.4MPa, and the change rate gradually decreases. When the sleeper thickness is 0.35m, the maximum stress of the track is 87.83MPa, which is reduced by 3.7% compared with thickness of 0.2m. Because the greater the sleeper thickness, the greater the stiffness of each sleeper and the smaller the deformation of the corresponding sleeper. Therefore, the sleeper thickness has an obvious impact on the track stress characteristics, and the track stress can be reduced by appropriately increasing the sleeper thickness.

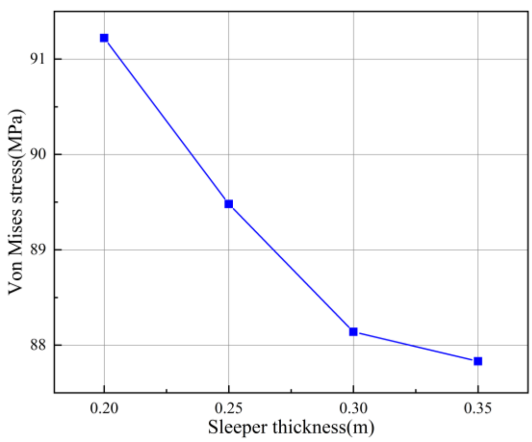

Fig.15. Maximum stress of track under different sleeper thickness

The maximum vertical displacement of track and stratum under different sleeper thickness is shown in Figure 16. It can be seen from the figure that the maximum vertical displacement of track and stratum increases with the increase of sleeper thickness, and the change of vertical displacement of stratum is obvious, about 0.09cm, which is greater than the change of track, because the stiffness of sleeper is much greater than that of lower soil, resulting in easy deformation of lower soil. The vertical displacement of the whole stratum changes approximately linearly, but the change rate of the vertical displacement of the track increases slightly. When the sleeper thickness is 0.35m, the maximum vertical displacement of track and stratum is 1.527cm and 1.163cm respectively, which increases by 2.7% and 8.7% respectively compared with thickness of 0.2m. Although the overall stratum displacement is still less than the track displacement, the gap between them tends to decrease gradually.

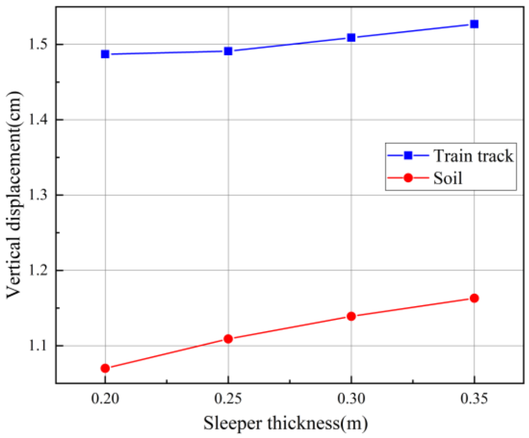

Fig.16. Maximum displacement of track and stratum under different sleeper thickness

V. CONCLUSION

Taking the heavy haul railway track as the research object, the simulation model of heavy haul railway track is established by using the finite element analysis method, the stress and displacement of track are systematically analyzed, and the effects of load, sleeper, track bed and other factors on the stress characteristics of track are studied. The main conclusions are as follows:

(1) When the load is applied, the stress distribution of the two orbitals is basically the same. There is stress concentration at the loading point on the track surface, and the high stress zone expands along the track axial direction with the loading point as the center, and the stress on the track surface is large. The upper surface of the track is compressed, the bottom of the track is mainly tensile, and the high strain area is located around the load point. The maximum track displacement is in the middle of the two adjacent load points of the train carriage.

(2) The maximum stress and vertical displacement of track increase with the increase of train axle load, and the whole changes linearly. When the elastic modulus of sleeper increases, the maximum stress and displacement of track gradually decrease, but the change is small. When the sleeper spacing decreases, the maximum stress and displacement of the track gradually decrease, and the change is obvious. When the sleeper thickness increases, the maximum stress of the track decreases gradually, but the vertical displacement of the track increases.

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