Numerical simulation of force characteristics and contact loss of high-speed railway subgrade

Y H Wang¹,², Xiao H¹,³, Y X Lv¹ and S Lv¹

¹Railway Track Engineering Laboratory, Beijing Jiaotong University, Beijing 100044, China
²State Key Laboratory for Track Technology of High-speed Railway, China Academy of Railway Sciences Corporation Limited, Beijing, 100081, China

E-mail: kuyu1994@163.com

Abstract. In order to explore the dynamic stress distribution, attenuation characteristics of subgrade under high-speed train load, a three-dimensional solid model was established by the ABAQUS finite element software, and the dynamic stress characteristics of subgrade of high-speed railway were calculated and analyzed. The research results show that: The distribution of additional dynamic stress on the surface of subgrade is close to elliptical, and the distribution on the cross section is similar to saddle-shaped; the peak value of stress appears below the rail. The additional dynamic stress of the subgrade has no superposition effect between the front rear bogie and the rear front bogie of the two trains. The additional dynamic stress distribution of the subgrade surface can be regarded as four stress waves that do not overlap each other. When the contact degradation shape of the subgrade gravel and the track structure concrete base is assumed to be rectangular, the aspect ratio is between 2 and 3.3. With the deterioration of the contact state, the maximum additional dynamic stress of the surface layer of the subgrade is 120 kPa.

1. Introduction

With the construction and operation of ballastless tracks of high-speed railway in China, the subgrade disadvantage of ballastless track are gradually revealed, one of them being the contact loss on the roadbed surface. Cai et al. [1] comparatively analyzed and studied the mechanical properties of three contact conditions: normal state, slab end void, and slab edge void under the same temperature gradient load. Ren et al. [2] used the coupled dynamics theory to analyze forces acting on the car body and track structures under different void lengths, and put forward suggestions on the limit of void range under the base plate. Zhang et al. [3] used the non-linear spring element to simulate the void area, analyzed the track structure and subgrade stress under different void length conditions, and studied the relationship between the void length and the service life of track structure according to the fatigue performance of concrete.

At present, the research on subgrade contact loss is mostly based on the analysis of the change of subgrade soil properties and external loads. There are few studies on the mechanism of contact loss and the law of deterioration development. The contact state between the surface layer of subgrade bed directly reflects the transmission of upper load downward and the support of subgrade soil to track structure. Therefore, it is necessary to study the contact state between track structure and subgrade soil.
2. Establishment of analytical model

The vehicle-track-subgrade coupling analysis model is shown in figure 1.

![Figure 1. Vehicle-track-subgrade coupling analysis model.](image)

Using the ABAQUS finite element software, a three-dimensional dynamic analysis model of coupled non-linear system is established, which includes vehicle-rail-track slab-CA mortar layer-concrete base-surface layer of subgrade and bottom layer of subgrade.

| Parameter | Unit weight (kN/m³) | Elastic modulus (GPa) | Poisson’s ratio | Rayleigh damping coefficient α/s⁻¹ | β/s |
|-----------|---------------------|-----------------------|-----------------|-----------------------------------|-----|
| Rail      | 78                  | 206.0                 | 0.3             | 0.0328                             | 0.0031 |
| Slab track| 24                  | 35.5                  | 0.1             | 0.0983                             | 0.0092 |
| Base plate| 24                  | 30.0                  | 0.1             | 0.0983                             | 0.0092 |
| CA mortar layer | 18          | 0.1                   | 0.4             | 0.0983                             | 0.0092 |

| Parameter | Thickness /m | Unit weight (kN/m³) | Compression modulus (MPa) | Poisson’s ratio | Cohesive force (kPa) | Internal friction angle (°) | Rayleigh damping coefficient α/s⁻¹ | β/s |
|-----------|--------------|---------------------|---------------------------|-----------------|----------------------|-----------------------------|-----------------------------------|-----|
| Subgrade surface | 0.4          | 19.5                | 190.0                     | 0.3             | 32.0                 | 75                          | 0.2620                             | 0.0244 |
| Subgrade Bottom     | 2.3          | 19.0                | 100.0                     | 0.3             | 26.0                 | 25                          | 0.2293                             | 0.0214 |

| Parameter | Body | Bogie | Wheel |
|-----------|------|-------|-------|
| Weight (kg) | 39364 | 5630  | 1843  |
| Rolling inertia (kg·m²) | 92394 | 2650  | 1200  |
| Pitching inertia (kg·m²) | 1723415 | 2100  | 170   |
| Yawing inertia (kg·m²) | 2495967 | 3000  | 1200  |

| Parameter | Primary suspension | Secondary suspension |
|-----------|--------------------|----------------------|
| Longitudinal damping (Ns/m) | 0                   | 2000000              |
| Horizontal damping (Ns/m)   | 0                   | 60000                |
| Vertical damping (Ns/m)     | 30000               | 45000                |
| Longitudinal stiffness (Ns/m) | 10000000          | 2000000              |
| Horizontal stiffness (Ns/m) | 50000000           | 2000000              |
| Vertical stiffness (Ns/m)   | 2399600            | 885800               |

The Drucker-Prager ideal elastic-plastic constitutive model is used for the surface layer and the bottom layer of the subgrade. The parameters of each part are shown in Table 1 [4]. The modulus of...
soil given in table 2 is the compressive modulus, which relationship with the elastic modulus is not easily determined under the effect of many factors. In this paper, the elastic modulus is 6.5 times higher than the compressive modulus [5]. The train parameters are listed in table 3.

3. Additional dynamic stress characteristics of subgrade

3.1. Time distribution

Exploring the additional stress of subgrade soil under train load, the vertical dynamic stress of the subgrade soil under the train load is taken as the additional dynamic stress of the subgrade. Selecting a section in the middle of the subgrade as a typical example to analyze the characteristics of subgrade stress, and draw the three-dimensional curve of dynamic stress on the surface of the subgrade as shown in figure 2. It can be seen that, when the train model passes at a speed of 300 km/h, the dynamic stress of the subgrade surface appears four peaks in time, corresponding to four bogies, and the peak stress range is between 30 and 45 kPa. The maximum dynamic stress of subgrade surface is 44.2 kPa.

![Figure 2. 3-D dynamic stress map of subgrade surface.](image)

![Figure 3. Dynamic stress time-history curve of subgrade.](image)

From figure 3, it can be seen that there are obvious stress peaks on the surface of the subgrade when the train passes by. The four stress peaks correspond to the four bogies of the train respectively. Between the second and third stress peaks, the dynamic stress on the surface of the subgrade decreases rapidly to 2.7 kPa. It can be seen that there is no obvious stress superimposed influence between the adjacent bogies of the front and rear vehicles. The maximum stress value of the section is 37.3 kPa.

3.2. Space distribution

From 3.1, it can be seen that there is no superposition effect between the front and rear bogies of the two trains and the front bogies of the rear car. Therefore, the additional dynamic stress distribution on the surface of the subgrade can be regarded as four stress waves which do not interfere with each other. The peak stress value is between 30 and 45 kPa.

From figure 4 can be seen that the spatial distribution of additional dynamic stress on the surface of subgrade concentrates in the range of 3 m between the concrete base and the surface of subgrade on the cross-section, and its longitudinal influence range is 5-7 m. The peak value of additional dynamic stress still appears directly below the rail, it has two peaks.

From the above calculation, it can be concluded that the surface of subgrade bed is in low stress state under ideal condition, but from the reaction in engineering practice, subgrade bed will still show many disadvantage, including mud pumping soils, contact loss, extrusion deformation etc. In this paper, based on the analysis of the additional dynamic stress characteristics of the subgrade, the contact loss state of the subgrade surface is artificially set up, and its evolution law is analyzed.
4. Contact degradation of the surface of subgrade

Based on the analysis of additional dynamic stress of subgrade in last section, the different contact states between concrete base of high-speed railway track structure and graded gravel of subgrade surface are compared and analyzed. From figure 4, can be concluded that under ideal condition, the maximum additional dynamic stress of subgrade surface appears at the position below the rail, so this position is taken as the initial position of subgrade surface Graded Macadam crushing failure. In the ABAQUS finite element model, contact failure at this location is simulated by deleting elements and corresponding contacts. As shown in figure 5, a non-contact area with a length of 0.5×0.15 m is set. The contact condition is named as contact condition 1.

Under this contact condition, the cloud figure for calculating the additional dynamic stress on the surface of subgrade is shown as figure 6. It can be seen that the spatial distribution of the additional dynamic stress on the surface of subgrade is similar to that under ideal contact condition when the train bogie passes by. Laterally, the area of additional dynamic stress on the surface concentrates within 3 m of the contact between the concrete base plate and the roadbed surface; vertically, the influence range of the train bogie is approximately 7 m. There is obvious stress concentration around the non-contact area.

As can be seen from figure 7(a), except for the obvious stress "hollow" in the non-contact area, its distribution law is basically the same as that in the ideal contact state. Figure 7(b) shows that the peak stress range of the section is still between 25 and 45 kPa, which indicates that the additional dynamic stress of the roadbed does not increase obviously at the initial stage of contact deterioration under contact condition 1. The larger stress value mainly occurs on both sides of the non-contact area. According to the magnitude of the additional stress value of the subgrade, it can be judged that the expansion trend of the non-contact area is to expand to both sides.
Based on the calculation results of contact condition 1, it can be seen that the additional dynamic stress on the surface of subgrade mainly occurs on both sides of the non-contact area. On this basis, the non-contact area is expanded to both sides, and the elements on both sides are deleted to form a non-contact area with a length of 0.5×0.5 meters and a width of 0.5 meters. The contact condition is named contact condition 2, as shown in figure 8.

**Figure 8.** Failure schematic diagram of subgrade contact position.

Under this contact condition, the additional dynamic stress calculation cloud of the surface of subgrade as shown in figure 9. It can be seen that with the lateral expansion of non-contact area, when the train bogie passes through the bad contact area, the stress concentration appears in the longitudinal direction of non-contact area, with no obvious stress concentration on both sides of non-contact area.

**Figure 9.** Additional dynamic stress nephogram of subgrade surface.

Figure 10. Additional dynamic stress map of subgrade surface. (a) Broken line comparison diagram and (b) Time history diagram.
A broken line comparison chart of dynamic stress distribution between non-contact area section and its adjacent full contact section subgrade is shown in figure 10(a). In the non-contact section, the maximum stress value appears on both sides of the non-contact area, and the dynamic stress in the non-contact area decreases significantly, showing a hollow platform; on the full contact section, the maximum stress value is still in the position just below the rail. The position of maximum dynamic stress in figure 10(a) is taken to construct the time history curve in figure 10(b).

It can be seen that the peak stress range of this section is between 40 kPa and 60 kPa, which indicates that the peak additional dynamic stress of subgrade increases with the deterioration of contact state under condition 2. The larger stress value mainly appears in the front and back of the non-contact area. According to the magnitude of the additional stress value of the subgrade, it can be judged that the expansion trend of the non-contact area is along the longitudinal direction of the subgrade.

On the basis of contact condition 2, according to the above calculation results, it is judged that the expansion trend of non-contact area extends along the longitudinal direction of subgrade. A non-contact area with a length of 1 × 0.5 meters in width is made by deleting the unit, and the contact state is named contact condition 3, as shown in figure 11.

As shown in figure 12, the calculation cloud chart of contact condition 3 shows that the stress around the non-contact area is larger, and the stress area is mainly distributed along the longitudinal direction of the subgrade. Draw a broken line comparison chart of dynamic stress distribution of subgrade surface as shown in figure 13(a).

The dynamic stress distribution and stress value of the bad contact section are similar to those of the bad contact section under condition 2, and there is an obvious stress "gap" in the non-contact area. There is obvious stress concentration in the adjacent full contact section below the rail, and the time history curve is drawn at the maximum of stress as shown in figure 13(b).
It can be seen from figure 13(b) that the peak value of additional dynamic stress of this section subgrade is between 60 and 120 kPa, which is much larger than the peak value of stress in condition 1 and 2. The expansion trend of non-contact area is the same as that of condition 2, and it still extends along the longitudinal direction of subgrade.

From the above three contact conditions, the deterioration trend of Graded Macadam on subgrade surface and concrete base of track under train load can be concluded: the first contact deterioration position of Graded Macadam is directly below the rail, and the non-contact area formed by contact deterioration extends transversely to both sides, after extending to 0.5 m, the trend of expansion expands along the longitudinal direction of roadbed, and then to 1.5 m, it shows lateral expansion. In this chapter, the area of contact deterioration is assumed to be rectangular, and its aspect ratio is 3.3 in condition 1, 1 in condition 2 and 2 in condition 3. It can be seen that when the contact deterioration shape of subgrade surface Graded Macadam with concrete base of track structure is assumed to be rectangular, its aspect ratio is between 2 and 3.3. With the deterioration of contact state, the maximum additional dynamic stress of Graded Macadam on subgrade surface is 120 kPa.

5. Conclusions
In order to reveal the contact dynamic behavior of ballastless track subgrade of high-speed railway in China, the finite element model for dynamic analysis of multi-train-ballastless track-subgrade coupling system is established considering the weight of structure. The additional dynamic stress of Subgrade under train load is analyzed and the following conclusions are drawn:

- When the upper train load is transferred to the surface of the subgrade through the track slab-CA mortar-concrete base and other track structures, it is shown that it is close to the elliptical stress increasing area. Its long axis is about 5-7 m along the longitudinal direction of the line, and its area is concentrated in the contact area between the surface of the subgrade and the concrete base.

- The stress on the surface of subgrade is mainly concentrated in the 3-meter-wide range of contact with concrete base plate. In the instant of train bogie passing, the distribution of additional dynamic stress on the surface of subgrade is similar to saddle-shaped distribution on the cross-section, and there is a peak value of stress under the rail. The maximum stress value of the selected cross-section is 37.3 kPa.

- There is no superimposed influence between the front and rear bogies of the two trains, so the additional dynamic stress distribution on the surface of the subgrade can be regarded as four stress waves which do not interfere with each other, and the peak stress is between 25 and 45 kPa.

- When the deteriorating contact shape between graded gravel and concrete base of track structure is assumed to be rectangular, the length-to-width ratio is between 2 and 3. With the deterioration of contact state, the maximum additional dynamic stress of Graded Macadam on subgrade surface is 120 kPa.

Acknowledgments
This work was financially supported by the Fundamental Research Funds of China Academy of Railway Sciences (Grant no. 2017YJ166) and the National Natural Science Foundation of China (Grant No. 51578055).

References
[1] Cai S Y, Que X T and Yang R S 2013 Effect analysis CA mortar disengaging on frame-type track slab’s warping Railway Standard Design 2013 21-4
[2] Ren J J, Yan X B, Xu G H and Xu K 2014 Effects of loss underneath concrete roadbed on dynamic performances of slab track-subgrade system Journal of Southwest Jiaotong University 49 961-6
[3] Zhang Z Y 2013 Analysis of the influence of the void of the base plate of unit slab track on the
track force Subgrade Eng. **2013** 64-7

[4] Xue F C and Zhang J M 2014 Spatial distribution of vibration accelerations in coupled rail-embankment-foundation system on high-speed railway under moving loads *Journal of Geotech. Eng.* **36** 2180-7

[5] Professional Committee of Soil Dynamics, Chinese Society of Vibration Engineering 1998 *Examples and Analysis of Engineering Application of Soil Dynamics* (Beijing: China Construction Industry Press) pp 193-20