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Research paper

Deformation control standards for shield tunneling under high-speed railway tunnels that meet driving safety and stability requirements

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Abstract: The safety and stability of high-speed railway operations are highly sensitive to tunnel deformation caused by shield tunneling. This study addresses the deformation control standards for shield tunneling under high-speed railway tunnels, focusing on ensuring driving safety and stability. Tunnel deformation, including settlement, uplift, bending, and misalignment, poses significant risks to train dynamics, passenger comfort, and operational safety. A dynamic analysis of the vehicle-track interaction system is conducted, examining key indicators such as wheel-rail force, wheel load reduction rate, vertical acceleration, and Sperling index under various deformation wavelengths and amplitudes. The results reveal that shorter wavelengths (10–20 m) amplify deformation impacts, affecting stability and comfort. Longer wavelengths exhibit reduced dynamic effects but still demand careful monitoring. Proposed deformation control thresholds are wavelength-specific, ensuring safe and smooth train operation while minimizing maintenance costs. These findings provide practical guidance for designing and managing high-speed railway tunnels subjected to shield tunneling, contributing to improved safety, comfort, and infrastructure durability.

Keywords: high-speed railway tunnels, tunnel deformation control, shield tunneling, train dynamics, ballastless tracks

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1. Introduction

Tunnel settlement can not only cause damage to the lining structure and track structure, but also severely jeopardize the safety of train operations. Accidents of train derailment caused by uneven settlement occur from time to time [1]. Foreign scholars have investigated the interaction between tunnel deformation and track structure in shield tunneling, particularly focusing on uneven settlement. They have employed the composite beam theory to calculate the deformation of the track structure. Additionally, MATLAB was utilized to analyze the load-bearing capacity of the track structure, and the influence of factors such as fastener stiffness on track settlement was studied [2]. Furthermore, research has been conducted on the impact of shield tunneling construction on existing tunnels, where the deformation of the track structure and tunnel structure was considered equivalent. However, during this research, the differences in deformation between the two were neglected, and the allowable deformation values of tunnels under various factors were analyzed. Nevertheless, the control standards for the impact of tunnel deformation on train safety and comfort are still underexplored. To ensure the safety of high-speed railway operation, it is necessary to strictly control the deformation of high-speed railway tunnels, which makes reasonable tunnel deformation control limits an important control standard in the design and long-term operation of high-speed railways [3–6]. Low control standards make it difficult to ensure the safe and smooth operation of trains; If the control standards are too high, it will increase the workload and maintenance costs of railway engineering. At present, deformation control of high-speed railway tunnels often only focuses on the amplitude of tunnel deformation, without considering the influence of deformation type and deformation wavelength [7–9]. In addition, existing studies have rarely considered the impact of uneven settlement of high-speed rail tunnels on driving safety and stability when setting settlement control limits. Based on this, this study comprehensively analyzes the influence of high-speed rail tunnel deformation on the dynamic response of the vehicle track system, and proposes control limits for various types of deformation of high-speed rail tunnels applicable to CRTS II slab ballastless tracks after analysis.

Currently, commonly used deformation monitoring techniques in practical engineering include fiber-optic sensing technology and 3D laser scanning technology, among others. These technologies all have their own advantages and disadvantages, but they can all be used for the detection of tunnel settlement deformation. For example, fiber-optic sensing technology has the advantages of high sensitivity and accuracy, strong resistance to electromagnetic interference, and high durability. However, it is complex to install, expensive, and difficult to interpret the data. 3D laser scanning technology can perform non-contact measurement, which can improve efficiency. However, it is sensitive to the environment and has complex data processing requirements [10–12].

2. Analysis of the impact of high-speed rail tunnel deformation and driving speed on train operation

This section analyzes the dynamic effects of deformation types and wavelengths on the vehicle-track system, providing a theoretical basis for the subsequent threshold setting.

2.1. The influence of tunnel deformation factors on driving

(i) Type of deformation [13]

The deformation of tunnels, including settlement deformation, uplift deformation, bending deformation, and misalignment deformation, has multiple impacts on the safety of high-speed train operation.

(1) Settlement deformation: This deformation may cause uneven settlement of the internal structure of the tunnel, affecting the overall stability and structural integrity of the tunnel. Trains passing through settlement areas may experience severe impacts and vibrations, which can cause discomfort to passengers and even further damage to tunnel structures, increasing safety risks.
(2) Uplift deformation: The uplift deformation of the tunnel may lead to a decrease in tunnel clearance, affecting the pass ability of trains. In addition, the raised part may collide with the train, causing safety accidents. Even small bumps and deformations can have a significant impact on driving safety while driving at high speeds.
(3) Bending deformation: Bending deformation may cause distortion of the internal structure of the tunnel, affecting the stability of the tunnel. Trains passing through such deformation areas may experience additional lateral forces, which could lead to train derailment or equipment damage.
(4) Misalignment deformation: Misalignment deformation usually refers to the stepped deformation that occurs at the bottom or sidewall of a tunnel. This kind of deformation may cause severe vibrations during train operation, affecting the smoothness of train operation, and in severe cases, may lead to train derailment.

In all these cases, the magnitude, rate, and location of deformation will affect the safety of high-speed train operation. Therefore, regular inspection and maintenance of tunnels, as well as the use of advanced monitoring technology to prevent and control deformation, are crucial for ensuring the safety of high-speed train operation.

(ii) Deformable wavelength

The impact of tunnel deformation wavelength on the safety of high-speed train operation is mainly reflected in the following aspects:

(1) Dynamic response influence: The measured wavelength of arch deformation on ballastless track in the tunnel is mainly between 3 and 30 m, and the amplitude is between 0 and 8 mm. When the wavelength of the upper arch does not exceed 6 m, the peak value of the wheel rail force is relatively large; When the wavelength of the upper arch is around 12 m, the peak value of the vertical acceleration of the vehicle body is relatively large. Especially the deformation of the upper arch with a wavelength of about 6 m has a significant impact on the safety of high-speed driving, and there is a certain risk of derailment.
(2) Vibration characteristics: The deformation at the bottom of the tunnel, especially short wave deformation, has a significant impact on the dynamic characteristics of vehicles and track structures. The vibration characteristics of the vehicle track system decrease with increasing wavelength, so it is recommended to control the wavelength above 25 m. At the same time, the power indicators of vehicles and tracks increase significantly with the increase of amplitude, which affects driving stability and track operation. It is recommended to control the amplitude below 20 mm.

(iii) Deformation amplitude

The influence of the deformation amplitude of tunnel deformation on the safety of high-speed train operation is mainly reflected in the following aspects:

(1) Wheel rail force variation: The measured wavelength range of arch deformation on ballastless tracks in tunnels is mainly 3-30 m, and the amplitude range is mainly 0-8mm. When the wavelength of the arch does not exceed 6m, the peak value of the wheel rail force is relatively large, which may lead to increased wheel rail wear and affect driving safety.
(2) Vehicle vibration: When the wavelength of the upper arch is around 12 m, the peak value of the vertical acceleration of the vehicle body is relatively large, which will increase the vibration during train operation, affect passenger comfort, and may cause fatigue damage to the train structure.
(3) Risk of derailment: The deformation of the upper arch with a wavelength of about 6m has a significant impact on the safety of high-speed driving and has a certain risk of derailment, which requires special attention.
(4) Dynamic response: The amplitude of arch deformation on ballastless tracks in high-speed rail tunnels has a significant impact on the vehicle's dynamic response. When the deformation amplitude is large, the dynamic response of the vehicle will also increase, which may lead to a decrease in vehicle stability.
(5) Driving safety and stability: When the lateral deformation of the tunnel is $\leq$ 25 mm or the vertical deformation is $\leq$ 35 mm, the evaluation indicators for train driving safety and stability are within the limits. But when the deformation amplitude exceeds these limits, it may have adverse effects on the safety and stability of train operation.

2.2. The impact of train speed factors on train operation

Driving speed is one of the important factors affecting the safety of high- speed train operation [14]. The increase in train speed will bring higher requirements to the power performance, braking system, structural strength, and operational stability of the train. The following is the impact of driving speed on the safety of high-speed train operation:

(1) Power performance

With the increase of driving speed, the requirements for the power performance of trains also increase. The train needs a more powerful power system to maintain high-speed operation, and at the same time, the stability and guidance performance of the train need to be strengthened when passing through bends at high speed.

(2) Braking system

High speed trains need to slow down or stop in a short period of time in emergency situations, so the braking system must be strong and reliable enough. The higher the train speed, the greater the deceleration required for braking, and the design and material selection of the braking system need to meet these requirements.

(3) Structural strength

Trains are subject to greater aerodynamic forces during high-speed operation, which can cause additional pressure on the body structure. Therefore, the train structure must have sufficient strength and stiffness to withstand these forces.

(4) Operational stability

High speed trains need to maintain stability during operation to avoid dangerous situations such as derailment. The increase in train speed requires higher requirements for the geometry of the track, stability of the track bed, and interaction between the wheel and rail.

2.3. Calculation conditions and loading modes

(1) Calculate operating conditions [15]

This section mainly analyzes the effects of curved settlement deformation, curved uplift deformation, angular deformation, and staggered deformation of high-speed railway tunnels on the dynamic response of train operation. The main analysis indicators include wheel rail vertical force, wheel load reduction rate, vertical acceleration of the vehicle body, and Sperling index. The influence of different tunnel deformation wavelengths and amplitudes on the safety and stability of trains is compared. The vehicle speed is 350 km/h, and the influence of track roughness is considered. The calculation length of the model is 300 m.

(2) Loading mode

The tunnel deformation types analyzed in this section are divided into curved settlement deformation, curved uplift deformation, angled deformation, and staggered deformation. By setting the deformation wavelength and amplitude, the vertical force between the wheel and rail, wheel load reduction rate, vertical acceleration of the vehicle body, and Sperling index under different working conditions are compared to explore the influence of deformation wavelength and amplitude on driving safety and stability.

Based on the above analysis, Section 3 will quantify the specific impact of deformation parameters on train operation safety through a dynamic model.

3. Evaluation of train safety and stability under deformation conditions after shield tunneling under high-speed railway construction

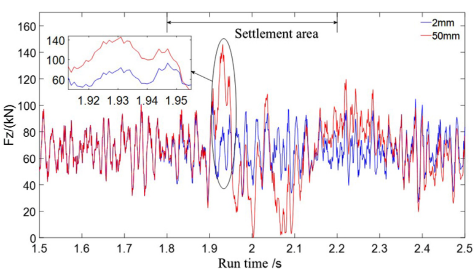
Shield tunneling beneath a high-speed railway tunnel will cause deformation of the tunnel structure. As previously analyzed, deformation of high-speed railway tunnels and train operating speed can affect train operation. When deformation or interlayer damage occurs in the track structure, on the one hand, the geometric state of the rail surface changes, intensifying the wheel-rail interaction. On the other hand, interlayer debonding occurs beneath the slab, and the contact stiffness between the track slab and the underlying structure changes. This leads to parametric excitation under the condition of non-uniform stiffness. All these factors will affect train performance and the service performance of the structure. Therefore, it is necessary to conduct research on the coupled dynamic analysis model and dynamic response characteristics of the vehicle-track-tunnel system under the deformation conditions caused by shield tunneling. This section is based on the vehicle-track coupled dynamic model independently developed, and the influence of deformation parameters is analyzed through numerical simulation.

The deformation type analyzed in this section is curved settlement deformation. By setting the deformation wavelength to 10 m, 20 m, 30 m, 40 m, and 50 m, the deformation amplitude is set to 2 mm, 4 mm, 6 mm, 8 mm, 10 mm, 20 mm, 30 mm, 40 mm, and 50 mm for each deformation wavelength. Compare the wheel rail vertical force, wheel load reduction rate, vehicle vertical acceleration, and Sperling index under different operating conditions, and explore the influence of deformation wavelength and amplitude on driving safety and stability.

3.1. Wheel rail vertical force and wheel load reduction rate

Fig. 1 shows the time history curve of the vertical force and wheel load reduction rate of the first wheel of a high-speed vehicle passing through the tunnel settlement zone under different settlement amplitudes when the tunnel curve settlement wavelength is 10 m.

In Fig. 1(a), as the vehicle passes through the curved settlement area of the tunnel, the wheel rail interaction gradually strengthens and produces three severe fluctuations. When the first wheel of the vehicle enters the settlement trough on a downhill slope, the vertical force of the rail shows a fluctuating characteristic of decreasing increasing decreasing; When driving uphill out of the settlement trough, the vertical force between the wheel and rail shows a fluctuating characteristic of increasing decreasing increasing; Affected by the gradual entry of subsequent wheelsets into the raised area, the vertical force between the wheel and rail continued to fluctuate after the first wheelset exited the raised area, but the fluctuation amplitude gradually decreased and approached the normal fluctuation amplitude of the road section. When the vehicle passes through the areas with settlement amplitudes of 50 mm and 2 mm in the tunnel, the maximum increase in vertical force between the first wheel and rail compared to the normal section of 100 kN is 40 kN and 0 kN, respectively. This indicates that the 50 mm settlement amplitude has a strong superimposed effect on the unevenness of the existing track, while the 2 mm settlement amplitude can be ignored. When the settlement amplitude increases from 2 mm to 50 mm, the maximum wheel rail vertical force of the first wheelset increases from 100 kN to 140 kN, with an increase of about 40%.



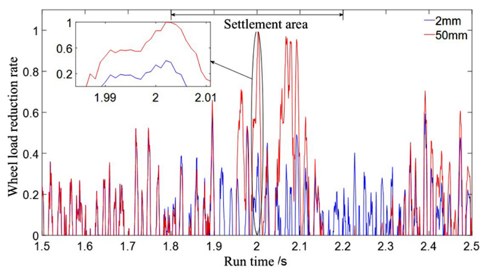


Fig. 1. Time history of wheel rail vertical force/wheel load reduction rate under curved settlement deformation of tunnel; (a) Time history of vertical wheel rail force with a wavelength of 10 m, (b) Time history of wheel load reduction rate at a wavelength of 10 m

In Fig. 1(b), when the vehicle passes through the curved settlement zone of the tunnel, its wheel load reduction rate shows a characteristic of first increasing and then decreasing. When the vehicle passes through the areas with settlement amplitudes of 50 mm and 2 mm in the tunnel, the first wheelset reaches its maximum wheel load reduction rate at the settlement center, which is 1.0 (limit of wheel load reduction rate) and 0.38, respectively, indicating that the 50 mm curved settlement amplitude will affect driving safety. When the settlement amplitude increases from 2 mm to 50 mm, the maximum wheel load reduction rate of the first wheelset increases by about 163%.

As shown in Fig. 2, the power spectral density of vertical force between the wheel and rail at settlement wavelengths of 10 m and 100 m are presented respectively. It can be seen from the figure that an increase in tunnel settlement amplitude will significantly increase the power spectral density of vertical force within 5-10 Hz, reduce the smoothness of the track, and thus affect the safety and comfort of passengers.

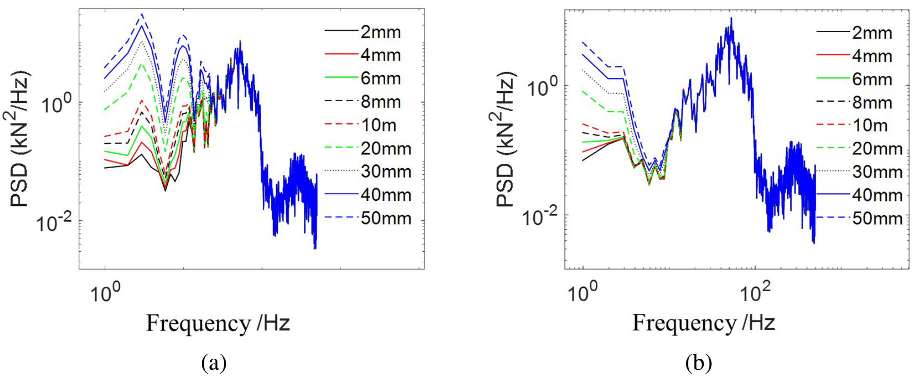
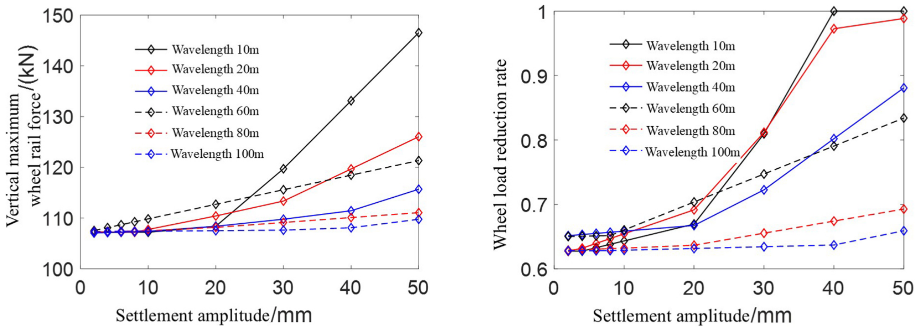


Fig. 2. Vertical force power spectrum of wheel rail under curved settlement deformation of tunnel; (a) Vertical force power spectrum of wheel rail at a wavelength of 10 m, (b) Vertical force power spectrum of wheel rail at a wavelength of 100 m

As shown in Fig. 3, the curves of the maximum vertical wheel rail force and wheel load reduction rate in different tunnel settlement amplitudes/settlement wavelengths are presented. It can be seen that overall, the maximum values of the vertical wheel rail force and wheel load reduction rate increase with the increase of tunnel settlement amplitude. When the settlement amplitude is less than 20 mm, the maximum values of the wheel rail force and wheel load reduction rate do not change significantly; When the settlement amplitude is greater than 20 mm, the maximum values of wheel rail force and wheel load reduction rate change significantly. When the settlement amplitude reaches 50 mm, the maximum values of wheel rail force at all wavelengths are reached, but they are all below the limit of 170 kN, making it relatively safe. The wheel load reduction rate also reaches its maximum value. However, when the wheel load reduction rate is 1, it may cause the vehicle to derail. Overall, as the settlement wavelength increases from 10 m to 100 m, the maximum vertical wheel rail force and maximum wheel load reduction rate also increase. The difference in extreme values of wheel rail force at a settlement wavelength of 10 m is significantly greater than that at other settlement wavelengths, indicating that changes in settlement amplitude at a settlement wavelength of 10 m have a greater impact on changes in vertical wheel rail force; When the settling wavelength is 10 m and 20 m, the wheel load reduction rate fluctuates greatly in various working conditions, and even reaches 1. Therefore, the settling wavelength of 10–20 m is a sensitive wavelength, and the occurrence of such settling wavelengths should be given more attention during construction or testing to improve the safety and comfort of driving.



(a) (b)

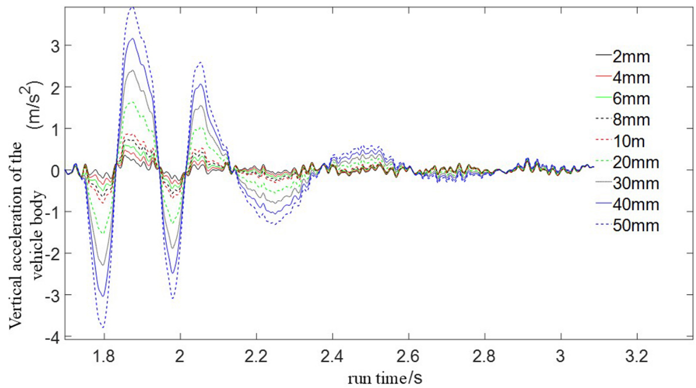
Fig. 3. Maximum vertical force/wheel load reduction rate of wheel rail under curved settlement deformation of tunnel; (a) Maximum vertical force of wheel rail under various operating conditions, (b) Maximum wheel load reduction rate under various operating conditions

3.2. Vertical acceleration and Sperling index

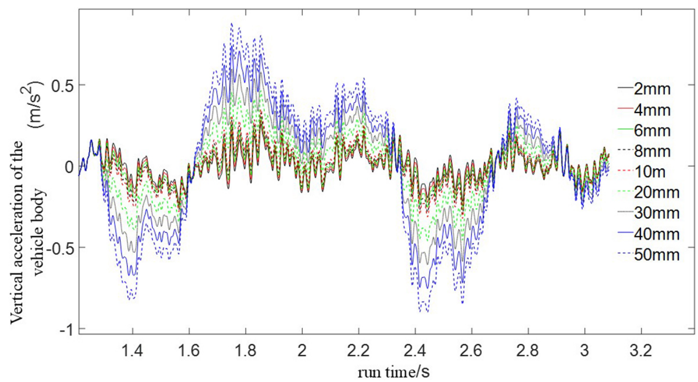
Fig. 4 shows the time history of vertical acceleration of high-speed vehicles passing through the tunnel settlement zone under different settlement amplitudes when the tunnel curve settlement wavelength is 10 m and 100 m. When the vehicle passes through the curved settlement area of the tunnel, the vertical acceleration of the vehicle forms two sets of significantly fluctuating time history curves, and quickly reaches the peak, indicating that the influence of the curved settlement deformation of the tunnel on the acceleration of the vehicle is greater than that of the random unevenness of the track. When the vehicle exits the curved settlement area of the tunnel, the fluctuation amplitude of the vertical acceleration time history curve of the vehicle gradually decreases and approaches the normal fluctuation amplitude of the road section.

In Fig. 4(a), when the settlement wavelength is 10 m and the vehicle passes through the tunnel settlement amplitude areas of 50 mm and 2 mm, the maximum vertical acceleration of the vehicle body is 3.6 m/s^2 and 0.1 m/s^2 , respectively, compared to the normal road section of 0.2 m/s^2 . This indicates that the superposition effect of 50 mm settlement amplitude on track roughness is strong, while the superposition effect of 2 mm settlement amplitude on existing track roughness can be ignored. When the settlement amplitude increases from 2 mm to 50 mm, the vertical acceleration of the vehicle body increases from 0.3 m/s^2 to 3.8 m/s^2 , with an increase of about 11.7 times.

In Fig. 4(b), when the settlement wavelength is 100 m, when the vehicle passes through the tunnel settlement amplitude areas of 50 mm and 2 mm respectively, the maximum increase in vertical acceleration of the vehicle body compared to the normal road section of 0.2 m/s^2 is 0.6 m/s^2 and 0.1 m/s^2 , respectively. This indicates that the 50 mm settlement amplitude has a certain impact on the superposition of track irregularities, while the 2 mm settlement amplitude can be ignored. When the settlement amplitude increases from 2 mm to 50 mm, the vertical acceleration of the vehicle body increases from 0.3 m/s^2 to 0.8 m/s^2 , with an increase of about 1.7 times.



(a)



(b)

Fig. 4. Various working conditions; (a) Various working conditions at a wavelength of 10 m, (b) Various working conditions at a wavelength of 100 m

According to the above analysis, under the condition of a settlement amplitude of 50 mm, when the settlement wavelength decreases from 100 m to 10 m, the vertical acceleration of the vehicle body increases from 0.8 m/s^2 to 3.8 m/s^2 , with an increase of about 3.75 times; The smaller the wavelength of the curved settlement, the larger the settlement amplitude, and the greater the adverse effect on the vertical acceleration of the vehicle body.

Figs. 5(a) and (b) show the variation of the maximum vertical acceleration and Sperling index of the vehicle body under different tunnel settlement amplitudes/wavelengths, respectively. It can be seen that the vertical acceleration at the center of mass of the vehicle body increases with the increase of tunnel settlement amplitude, and it basically increases linearly. The Sperling index of the vehicle body in the vertical direction also increases with the increase of tunnel settlement amplitude, but the growth rate gradually decreases; Overall, as the settling wavelength increases from 10 m to 100 m, the vertical acceleration and Sperling index of the vehicle body also increase with the same settling amplitude value. When the settling wavelength is above 60 m, the vertical acceleration of the vehicle body is within the limit value. When the settling wavelength is below 60 m and the settling amplitude reaches a certain value, the vertical acceleration of the vehicle body reaches the limit value of 1.7 m/s^2 . It can be seen that the vertical acceleration of the vehicle body under medium and long waves is more sensitive to changes in settling amplitude; At each settling wavelength, when the settling amplitude reaches a certain value, Sperling reaches the limit value of 3, exceeding the limit value of the passenger car qualification level in the "Code for Evaluation and Testing of Dynamic Performance of Locomotives and Rolling Stock" (GB 5599-2019). Therefore, more attention should be paid to tunnel settlement under medium to long waves, in order to improve the stability and safety of driving.

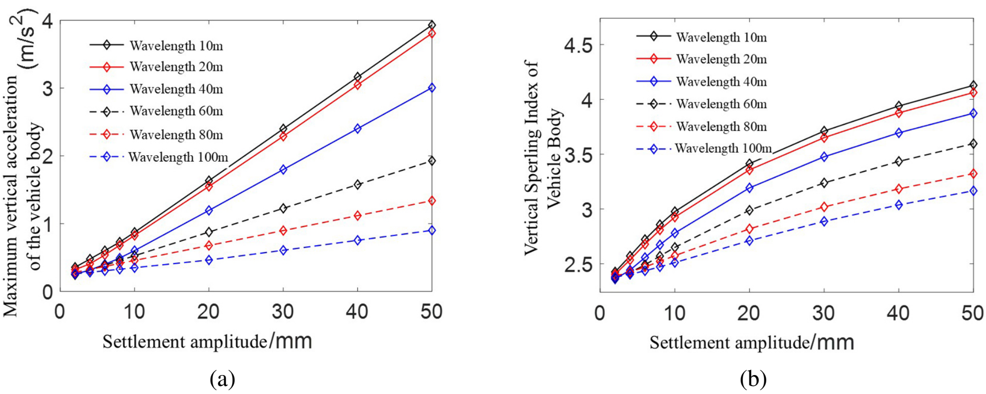


Fig. 5. Maximum vertical acceleration/sperling index of the vehicle body under curved settlement deformation of the tunnel; (a) Maximum vertical acceleration variation of the vehicle body under various operating conditions, (b) Vertical sperling index changes of vehicle body under various operating conditions

4. Deformation control standards for shield tunneling under high-speed railway tunnels that meet driving safety and comfort requirements

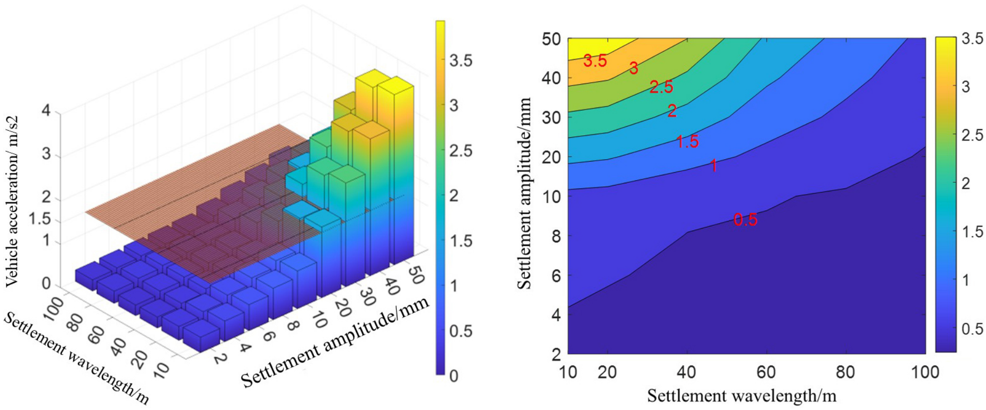
This section evaluates the driving safety and stability from three perspectives: driving safety, comfort, and dynamic interaction between the vehicle and the track. The wheel load reduction rate, vertical acceleration of the vehicle body, vertical force between the wheel and rail, and Sperling index of the vehicle body are taken to evaluate and control the driving safety and stability. The limit values of each index are as follows:

(1) Wheel load reduction rate: When vehicles pass through steel rail joints or uneven sections of the rail surface at high speeds, transient wheel load reduction may occur due to impact vibration. When the wheel load reduction is too large, it may cause derailment; The wheel load reduction rate is a safety indicator for vehicle operation. According to the current "High-Speed EMU Whole Vehicle Test Specification" and "Technical Specification for Dynamic Acceptance of High speed Railway Engineering" (TB10761-2012) in China, its limit value is set at 0.8.
(2) Vertical acceleration of the vehicle body: The degree of vehicle body vibration reflects the smoothness of vehicle operation, and the acceleration of vehicle body vibration is the most direct indicator of smoothness; In China's "Maintenance Rules for High speed Railway ballastless Track", the management level of track roughness is divided into four levels: regular maintenance (Level I), comfort level (Level II), temporary repair (Level III), and speed limit (Level IV). The management value of vertical acceleration of the vehicle body is also divided into four levels. This article selects the management value corresponding to the comfort level (Level II) as the evaluation index, which is 1.5 m/s^2 .
(3) Vertical force between wheel and rail: The dynamic force between wheel and rail is the most important indicator for measuring the dynamic interaction between the vehicle and the track; According to the "Test Specification for High speed EMU" and "Technical Specification for Dynamic Acceptance of High speed Railway Engineering" (TB10761-2013), the limit value of wheel rail vertical force is set at 170 kN.
(4) Sperling index of the vehicle body: The Sperling index of the vehicle body is mainly used to evaluate the stability of vehicle operation. Comparing it with the fatigue time evaluation, it is found that when the Sperling index is set to 3.0 (qualified for passenger cars), the standard is equivalent to a fatigue time of 5.6 hours. That is to say, according to the Sperling index set to 3.0, the vibration of the vehicle is limited, and its comfort level is relatively high.
(5) The dynamic deformation of the track structure is also an important indicator reflecting the degree of dynamic action of vehicles on the track; According to the Technical Specification for Dynamic Acceptance of High speed Railway Engineering (TB10761-2013), the maximum allowable vertical displacement of ballastless track rails is 2.0 mm.

In the subsequent analysis, based on the working conditions discussed in Section 6.3, three-dimensional and contour maps of various indicators will be drawn to determine the recommended values for deformation control.

4.1. Tunnel deformation control standards that meet the acceleration limit of the vehicle body

Fig. 6 shows the vertical acceleration values of the vehicle body when running on different tracks under various operating conditions. Fig. 6(a) is the corresponding bar chart, Fig. 6(b) is the corresponding contour map, and the area above 1.5 is the over limit area.



(a) (b)

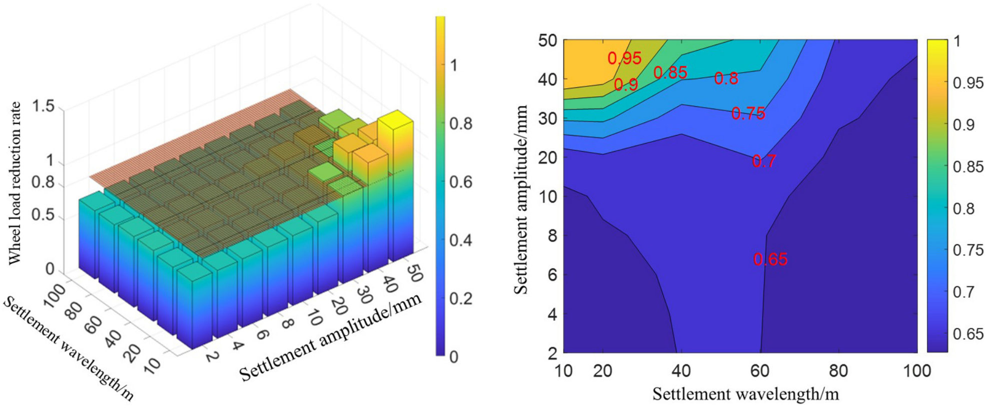
Fig. 6. Maximum acceleration of vehicle body under curved settlement deformation of tunnel; (a) Bar chart, (b) Contour map

The vertical acceleration management values corresponding to the four levels of regular maintenance, comfort, temporary repair, and speed limit are divided into 1.0, 1.5, 2.0, and 2.5 m/s^2. As shown in the figure, the corresponding vertical acceleration of the vehicle body has exceeded the limit significantly, indicating that the uneven curved settlement of the tunnel has a great impact on the smoothness of vehicle operation. As the amplitude of tunnel settlement increases, the acceleration of the vehicle gradually increases. When the settlement amplitude exceeds 20 mm, the vertical acceleration of the vehicle begins to exceed the limit. However, as the wavelength of tunnel settlement increases, the vertical acceleration of the vehicle significantly decreases. When the wavelength of tunnel settlement reaches 80 m, the vertical acceleration of the vehicle basically does not exceed the limit.

Based on the contour map, the increase in tunnel settlement amplitude will seriously affect the comfort of passengers, and when the tunnel settlement increases to 20 mm, the vertical acceleration of the vehicle body increases significantly and exceeds the limit; The increase in wavelength of tunnel settlement can also affect ride comfort, and the deterioration effect of medium to long wave (10–40 m) settlement on vehicle vibration is most significant, even requiring speed limit management.

4.2. Tunnel deformation control standards that meet the limit of wheel load reduction rate

Fig. 7 shows the maximum wheel load reduction rate when the vehicle operates on different tracks under various operating conditions. As shown in Figs. 7(a) and (b), the maximum wheel load reduction rate caused by the cosine settlement deformation wavelength and amplitude of the tunnel on the ballastless track was calculated. Fig. 7(a) is a bar chart depicting the maximum wheel load reduction rate under various operating conditions, while Fig. 7(b) shows the corresponding contour map. The area above 0.8 is the over limit area.



(a) (b)

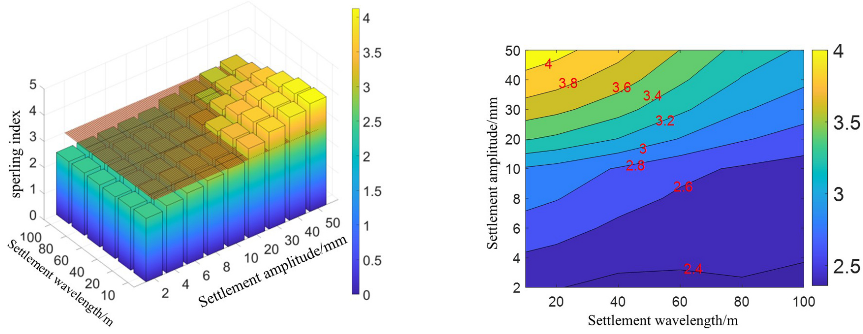
Fig. 7. Maximum wheel load reduction rate under curved settlement deformation of tunnel; (a) Bar chart, (b) Contour map

From Fig. 7(a), it can be seen that in the section where the settlement amplitude is less than 20 mm, the variation amplitude of the wheel load reduction rate is relatively small and within the limit. As the tunnel settlement amplitude continues to increase, the wheel load reduction rate also increases, and the increase amplitude is significantly larger. When the tunnel settlement assistance reaches 40 mm or more, the wheel load reduction rate equals 1, and the vehicle has already derailed; As the settlement wavelength expands, the impact on the wheel load reduction rate gradually decreases. When the settlement wavelength is within the range of 10–40 mm, the wheel load reduction rate may exceed the limit when the settlement amplitude is large. When the settlement amplitude reaches 50 mm, the wheel load reduction rate reaches 1, and even vehicle derailment may occur.

From Fig. 7(b), it can be seen that the wheel load reduction rate caused by uneven settlement wavelength in tunnels between 10 m and 40 m is more severe, but there is still a safety margin under this working condition. Moreover, uneven settlement with an amplitude greater than 40 mm in this wavelength range can cause the wheel load reduction rate to exceed the limit, and may even lead to derailment and pose safety hazards.

4.3. Tunnel deformation control standards that meet Sperling limits

Fig. 8 shows the Sperling index of the vehicle body corresponding to different tracks under various operating conditions. As shown in Figs. 8(a) and (b), the changes in the Sperling index of the vehicle body were statistically analyzed when the wavelength and amplitude of the cosine settlement deformation of the tunnel changed. Fig. 8(a) is a bar chart of the Sperling index of the vehicle body under various operating conditions, Fig. 8(b) is a contour map, and the area above 3 is the over limit area.



(a) (b)

Fig. 8. Sperling index corresponding to the vehicle body under the curved settlement deformation of the tunnel; (a) Bar chart, (b) Contour map

From Fig. 8(a), it can be seen that when the settlement amplitude is less than 10 mm, the Sperling index of the vehicle body increases with the increase of settlement amplitude, but the change amplitude is relatively low. When the settlement amplitude exceeds 20 mm, the Sperling index of the vehicle body increases significantly with the further increase of tunnel settlement amplitude, and even exceeds the limit; As the settlement wavelength increases, the amplitude of the Sperling index of the vehicle body does not change significantly in the medium to long wave range. However, when the settlement amplitude exceeds 20 mm, there will be a situation of exceeding the limit. When the wavelength exceeds 40 m, with further expansion of the settlement wavelength, the amplitude of the Sperling index of the vehicle body changes significantly, but the situation of exceeding the limit is significantly reduced.

5. Conclusions

This study focuses on a high-speed vehicle ballastless track tunnel dynamic model considering uneven tunnel settlement. Five dynamic indicators - wheel load reduction rate, vehicle acceleration, wheel-rail vertical force, rail dynamic displacement, and vehicle vertical Sperling index - were analysed to investigate the vehicle-rail coupling system's response to curved settlement deformations. The study evaluated the impact of deformation amplitude and wavelength and derived control thresholds for CRTS-I-type slab ballastless tracks based on driving safety, stability, and dynamic effects. The specific conclusions are as follows:

1. Tunnel deformation intensifies wheel-rail dynamic interactions, increasing wheel-rail force, altering wheel load reduction rates, and fluctuating vehicle body acceleration, which mainly impacts passenger comfort rather than safety.
2. Deformation wavelength (10-20 m) significantly affects dynamic responses, including track displacement and vehicle acceleration, with shorter wavelengths amplifying the effects of deformation amplitude.
3. Compared to vehicle safety and dynamic effects, comfort is more affected by uneven tunnel changes, particularly in the 10–20 m wavelength range.

4. Proposed deformation amplitude limits include <10 mm for 10–20 m wavelengths, < 20 mm for 20–40 m, < 30 mm for 40–60 m, < 40 mm for 60–80 m, and < 50 mm for 80–100 m wavelengths. Shorter wavelengths necessitate stricter deformation controls.

References

[1] Y. Wang, Q.M. Gong, and M.F. Li, "The Calculation of the Supporting Stress of Track Plate in Ballastless High-Speed Rail Structure", *Applied Mechanics and Materials*, vol. 97–98, pp. 3–9, 2011, doi: 10.4028/www.scientific.net/AMM.97-98.3.

[2] X.G. Li and D.J. Yuan, "Response of a double-decked metro tunnel to shield driving of twin closely under-crossing tunnels", *Tunnelling and Underground Space Technology*, vol. 28, pp. 18–30, 2012, doi: 10.1016/j.tust.2011.08.005.

[3] W. Qian, T. Qi, Y. Zhao, Y. Le, and H. Yi, "Deformation characteristics and safety assessment of a high-speed railway induced by undercutting metro tunnel excavation", *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 11, no. 1, pp. 88–98, 2019, doi: 10.1016/j.jrmge.2018.04.014.

[4] W. Pan, Z. Gao, C. Zheng, and Z. Gong, "Analysis on the influence of cross tunnel construction on the deformation of the existing high-speed railway tunnel", *Geotechnical and Geological Engineering*, vol. 36, no. 6, pp. 4001–4013, 2018, doi: 10.1007/s10706-018-0553-4.

[5] X.M. Meng, et al., "Deformation of the Zhangjiazhuang high-speed railway tunnel: An analysis of causal mechanisms using geomorphological surveys and D-InSAR monitoring", *Journal of Mountain Science*, vol. 18, no. 7, pp. 1920–1936, 2021, doi: 10.1007/s11629-020-6493-5.

[6] Y. Liu, et al., "Characteristics of rail deformation caused by tunnel floor heave and corresponding running risk of high-speed train", *Construction and Building Materials*, vol. 346, art. no. 128385, 2022, doi: 10.1016/j.conbuildmat.2022.128385.

[7] X. Cui, et al., "Effect of Tunnel Floor Heave on the Deformation and Damage Behavior of Ballastless Track Structures in High-Speed Railways", *Transportation Geotechnics*, vol. 49, art. no. 101375, 2024, doi: 10.1016/j.trgeo.2024.101375.

[8] X. Wang, et al., "Structural deformation monitoring during tunnel construction: A review", *Journal of Civil Structural Health Monitoring*, vol. 14, no. 3, pp. 591–613, 2024, doi: 10.1007/s13349-023-00741-1.

[9] R. Fei, L. Peng, C. Zhang, J. Zhang, and P. Zhang, "Mechanical characteristics of twin tunnel undercrossing construction on existing high- speed railway tunnel", *Archives of Civil Engineering*, vol. 69, no. 1, pp. 403–420, 2023, doi: 10.24425/ace.2023.144180.

[10] J. Gómez, J.R. Casas, and S. Villalba, "Structural Health Monitoring with Distributed Optical Fiber Sensors of tunnel lining affected by nearby construction activity", *Automation in Construction*, vol. 117, art. no. 103261, 2020, doi: 10.1016/j.autcon.2020.103261.

[11] C. Zhou, et al., "Application of FBG sensor in health monitoring of engineering building structure: a review", *Sensor Review*, vol. 45, no. 1, pp. 129–145, 2025, doi: 10.1108/SR-06-2024-0572.

[12] N. Shen, et al., "A review of terrestrial laser scanning (TLS)-based technologies for deformation monitoring in engineering", *Measurement*, vol. 223, art. no. 113684, 2023, doi: 10.1016/j.measurement.2023.113684.

[13] Q. Yan, M. Sun, S. Qing, Z. Deng, and W. Dong, "Numerical investigation on the damage and cracking characteristics of the shield tunnel caused by derailed high-speed train", *Engineering Failure Analysis*, vol. 108, art. no. 104205, 2020, doi: 10.1016/j.engfailanal.2019.104205.

[14] Z. Wang, M.K. Li, Q. Zhang, Y. Wang, and W. Zhang, "High-speed train drivers' operation performance: Key factors, models, and management implications", *International Journal of Industrial Ergonomics*, vol. 97, art. no. 103482, 2023, doi: 10.1016/j.ergon.2023.103482.

[15] J. Zhang and J. Zhang, "Comprehensive Evaluation of Operating Speeds for High-Speed Railway: A Case Study of China High-Speed Railway", *Mathematical Problems in Engineering*, vol. 2021, no. 1, art. no. 8826193, 2021, doi: 10.1155/2021/8826193.

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