Analysis of Influence of Track Deformation on Running Safety of High Speed Trains after Earthquake

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Abstract

In order to explore the impact of track deformation on the running safety of high-speed trains after earthquake, the vehicle-rail coupling model is established according to the principle of multi-body dynamics , the track irregularity and track deformation are regarded as external excitations, the Newmark-β method is used to solve the train dynamic balance equation, and the three indicators of the CRH2 train (derailment coefficient, wheel load shedding rate, lateral wheel-rail force) under the conditions of speeds of 200km/h, 250km/h and 300km/h are calculated using MATLAB programming , four deformation modes of the track (vertical deformation in one direction, lateral deformation in one direction, high and low undulation deformation, serpentine bending deformation) are considered in the analysis. The findings are as follows:(1) In the case of the same track deformation form, the change of the three indicators of the train increases with the increase of the deformation of the track, and increases with the increase of the running speed, but there is fluctuation.(2) Under the same train speed, the influence of vertical deformation of the track on the wheel load shedding rate is greater than the lateral deformation, and the lateral deformation of the track has more influence on the lateral wheel-rail force and the derailment coefficient than the vertical deformation. At the same time, it is found that the vertical high and low undulation deformation has more influence on the three indicators than the vertical one direction deformation, and the lateral serpentine bending deformation has more influence on the three indicators than the horizontal one direction deformation. (3) Under the condition that the train running speed is 200km/h, 250km/h and 300km/h, the limit of the four types of track deformation that poses a threat to train running safety is obtained.

Keywords: track deformation; Newmark-β method; high-speed railway; train running safety

1. Introduction

At the end of 2018, the operating mileage of high-speed rail exceeded 29,000 kilometers In China, accounting for more than two-thirds of the world's high-speed rail operating mileage, exceeding the sum of other countries. In 2019, it is planned to ensure the production of a new high-speed rail line of 3,200 kilometers. Such a large high-speed railway network line has extremely high requirements for track deformation and smoothness. According to the requirements of the "Code for Design of High Speed Railway" [1], the deformation range of the ballastless track is in the millimeter level, and the deformation requirements for the ballastless track are also high. Many high-speed railways in China are distributed in the seismic zone. Once an earthquake occurs, it will cause serious deformation of the track. Therefore, it is necessary to investigate the impact of track deformation on running safety after an earthquake.

Scholars have done some research on the impact of track deformation on running safety after earthquakes. Miura, Shigeru [2] summarized the possible accidents in railway operations. They believed that the main reasons for the accidents were track damage factors and vehicle damage factors. The track damage factors were mainly caused by the track deformation caused by the earthquake. And the characteristics of track deformation and running safety of the train under earthquake are discussed. Miyamoto T et al. [3] used a numerical simulation method to establish a vehicle-track coupling model, and applied lateral and vertical sine waves of a certain amplitude to the rail foundation to simulate seismic waves, and the dynamic characteristics of the vehicle under this excitation were obtained. Yang Kun [4], considering the five influencing factors of traveling speed, pier height, track irregularity, seismic wave strength, track fasteners and bridge support parameters, the vehicle-track-bridge coupling dynamics was established using ABAQUS software. The model makes regular analysis and research on the coupled system under the action of earthquakes, and draws suggestions for the safe operation of trains under earthquakes. Su Liping [5] established a three-dimensional dynamic finite element model of ballasted track structure using ANSYS, analyzed the dynamic response of the track under the earthquake and the safety of running, and obtained the main form of track deformation after the earthquake. With the increase of the earthquake intensity, the change trend of the three indicators of driving is calculated. Ke Xinmeng [6] used MIDAS and ADAMS software to establish a calculation model of the bridge subsystem and the track subsystem under earthquakes, and obtained the influence of the peak acceleration of the seismic wave on the running safety, and established the vehicle derailment under the earthquake Security domain.

Although many scholars have studied the impact of track deformation on running safety during and after an earthquake, there is a lack of research on the relationship between track deformation and running safety in consideration of different vehicle speeds.

2. Model

2.1 Vehicle model

Locomotives and vehicles have a wide variety and complex structures. It is difficult to accurately simulate the movement behavior of train components, and it is necessary to simplify the train model assumption [7]. The simplified model adopted in this paper is the widely used four-axle passenger train CRH2 model. The degrees of freedom of the car body, bogie, and wheel set are considered in the model calculation. See Table 1 for details. The model has 31 degrees of freedom.

Table 1 – Vehicle component degrees of freedom

Component	Ups and downs	Lateral swing	Side scroll	Nod forward	shake head
Car body	Z_c	Y_c	θ_c	Φ_c	Ψ_c
Bogie (i=1,2)	Z_{bi}	Y_{bi}	θ_{bi}	-	Ψ_{bi}
Wheel（i=1,2,3,4）	Z_{wi}	Y_{wi}	θ_{wi}	-	Ψ_{wi}

2.2 Vehicle-track model

The track model adopts pillow-buried ballastless track [8].The wheel-rail normal force is solved by Hertz nonlinear elastic method, and the wheel-rail creep force is calculated by Kaller linear creep force. According to Shen-Hedrick-Elkinss theory, the above results are processed nonlinearly. The vehicle-track coupling model is shown in Figure 1.

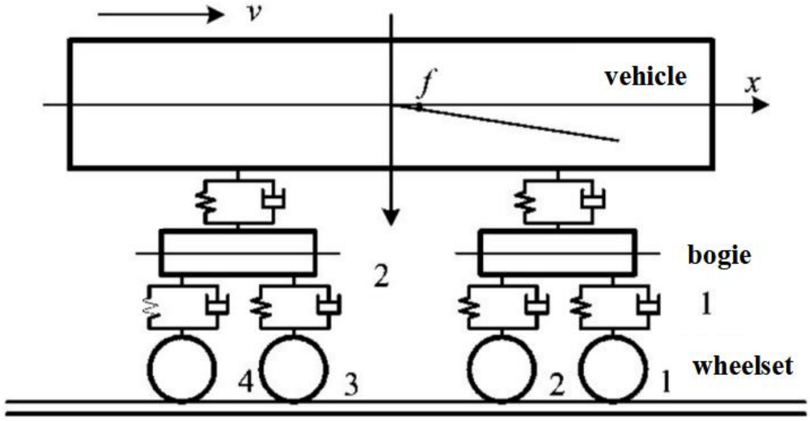

Fig.1 – Vehicle-track coupling model

Vehicle's dynamic balance equation:

$$[M][\ddot{U}]+[C][\dot{U}]+[K][U]=\{P\} \quad (1)$$

In Eq. (1), [M], [C] and [K] are train mass, damping, stiffness matrix, $[\ddot{U}]$ is the acceleration vector of the train, $[\dot{U}]$ is the speed vector of the train, $[U]$ is the vector of train displacement, {P} is external load caused by excitation of track irregularity and track deformation.

3. Simulation of track irregularity and track deformation

The state of the track determines the safety of the high-speed rail train. Under the normal operation of the train, the irregularity of the rail reaches a certain value, which may cause the derailment of the train. The track deformation considered in this paper is mainly composed of two parts: track irregularity and rail deformation.

3.1 Track irregularity simulation

The track irregularity power spectral density function can be simulated by numerical methods. At present, the most commonly used methods include quadratic filtering method, white noise filtering method, triangular series method, and frequency domain method [9,10].

This article uses the triangular series method for simulation, which can be simulated by formula (2):

$$\omega(x)=\sqrt{2}\sum_{k=1}^{N}\sqrt{S(\omega_K)\Delta\omega}\cos(\omega_k t+\varphi_k) \quad (2)$$

In Eq. (2), x is coordinate of position point, $\omega(x)$ is sequence of irregular track samples, ω_k (k = 1,2, ..., N) is selected frequency, ω_1 and ω_N are the upper and lower limits of the frequency value, $S(\omega_K)$ is power spectral density function, $\Delta\omega$ is frequency interval, φ_k is phase of the k-th frequency, its value range is [0,2].

Irregular curves of vertical left and right orbits and horizontal left and right orbits are obtained by using triangular series method.

3.2 Track deformation simulation

Assuming that the railway section line is a straight line, a 500-meter-long railway section is selected. Based on the track irregularity simulation, an arc with a certain chord length is added to the middle to simulate the four types of track deformation under actual conditions (Vertical in one direction, lateral in one direction, high and low undulation, serpentine bending), Taking vertical track deformation as an example, a schematic diagram of additional track deformation is shown in Figure 2.

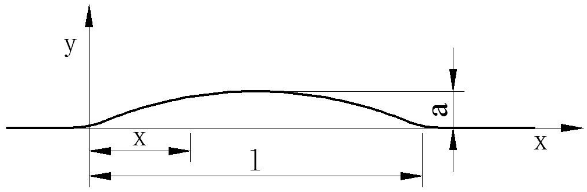

Fig.2 – Schematic diagram of additional rail deformation

Additional arc function E(X), as shown in formula (3):

$$E(x)=\sqrt{(\frac{l^2+a^2}{2a}-(x-\frac{l}{2})^2}-\frac{l^2+a^2}{2a}+a \qquad (3)$$

In Eq. (3), E(x) is additional deformation, l is chord length of track deformation, a is the maximum deformation of the track.

4. Safety standards for running trains

At present, the most widely used methods for the safety evaluation of trains are the derailment factor, the wheel load reduction rate, and the maximum value of the lateral wheel-rail force for safety evaluation.

4.1 Derailment factor

The derailment coefficient is the ratio of the lateral force Q to the vertical force P between the wheel and the track, which is first given by Nadal. Since then, it has been widely used by various countries in the world. The regulations on derailment coefficients in China [11] are shown in formula (4).

$$\frac{Q}{P}\le 0.8 \qquad (4)$$

4.2 Wheel load reduction rate

The wheel load reduction rate is an auxiliary index derived from the Nadal formula and is used to evaluate the safety of train derailment, it is defined as the ratio of the wheel load shedding value ΔP on one side of the wheel load shedding ratio to the mean $\overline{P}$ of the static wheel weight of the same wheel. The regulation of wheel load reduction under dynamic load reduction conditions in China [1, 11] is shown in formula (5).

$$\frac{\Delta P}{P}\le 0.8 (\text{dynamic}) \qquad (5)$$

4.3 Lateral wheel-rail force

When the vehicle generates excessive lateral force on the track, the track spacing will increase, and serious conditions will cause the train to derail. The regulations on lateral wheel-rail force in China [1, 11] are shown in formula (6).

$$H \leq 10 + \frac{P_0}{3} \quad (6)$$

Where P_0 is vehicle weight.

According to the vehicle weight of the model adopted in this paper, it can be calculated that the lateral wheel-rail force should satisfy formula (7):

$$H \leq 47KN \quad (7)$$

5. Analysis of influence of track deformation on three indicators of train operation

According to the vehicle-track model introduced above, programming is performed using MATLAB software, and the three indicators of train operation are solved according to the flowchart shown in Figure 3, with reference to the requirements of the "railway design code" [12] for the track deformation amount, the chord length of the track deformation, and the speed of the train, the value range of each variable is formulated for research.

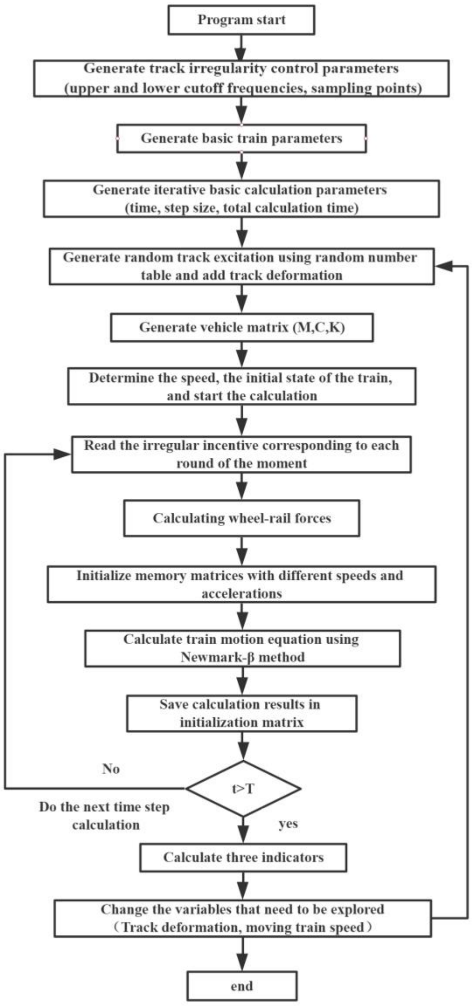

Fig.3 – program operation flow chart

5.1 Analysis of influence of track deformation at running speed of 200km/h on running safety

Set the vehicle speed to 200km/h and the chord length of the track deformation to 10m.By changing the values of the vertical deformation in one direction, lateral deformation in one direction, high and low undulation deformation, serpentine bending deformation of the tracks, the line graphs of the three indexes of the train as the deformation of the tracks increase are drawn, as shown in Figures 4 and 5.

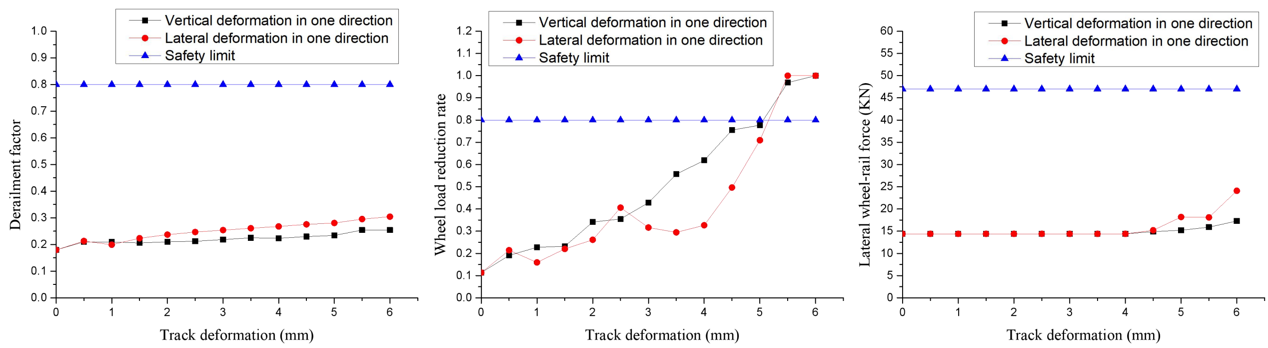

Fig.4 – The influence of the unidirectional deformation of the track at a speed of 200km/h on the three indexes of running train

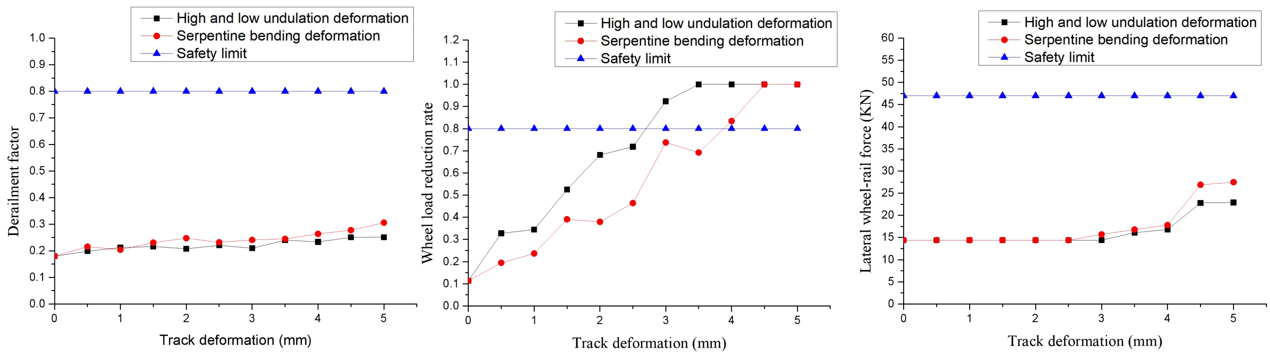

Fig.5 – The influence of the High and low undulation and serpentine bending of the track at a speed of 200km/h on the three indexes of running train

It can be seen from Figures 4 and 5 that at the speed of 200km/h, the values of the three parameters of the train increase with the increase of the track deformation, but there are fluctuations, and the calculation results in references [13, 14] also fluctuate. The main reason is the randomness of track irregularities. Among them, the derailment coefficient does not change much, and within the safety limit, the lateral deformation has a greater impact on the derailment coefficient than the vertical deformation. The change of wheel load reduction ratio is relatively obvious. The vertical deformation has a greater impact on the wheel load reduction ratio than the lateral deformation. When the vertical deformation in one direction and the lateral deformation in one direction are greater than 5.5mm, the high and low undulation deformation is greater than 3mm, and the serpentine bending is greater than 4mm, the wheel load reduction rate exceeds the limit, and the train is no longer safe. The influence of the lateral wheel-rail force is not great, and the lateral deformation has a greater impact on the lateral wheel-rail force than the vertical deformation.

5.2 Analysis of influence of track deformation at running speed of 250km/h on running safety

Set the vehicle speed to 250km/h and the chord length of the track deformation to 10m.By changing the values of the vertical deformation in one direction, lateral deformation in one direction, high and low undulation deformation, serpentine bending deformation of the tracks, the line graphs of the three indexes of the train as the deformation of the tracks increase are drawn, as shown in Figures 6 and 7.

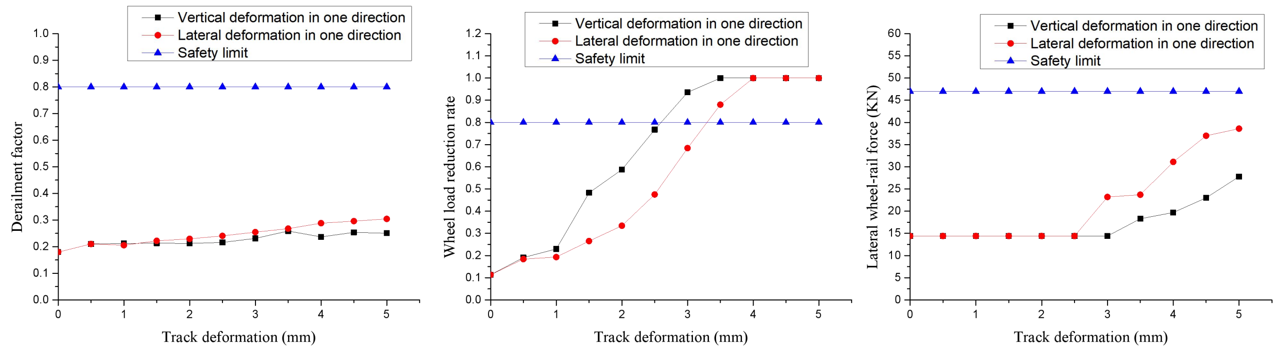

Fig.6 – The influence of the unidirectional deformation of the track at a speed of 250km/h on the three indexes of running train

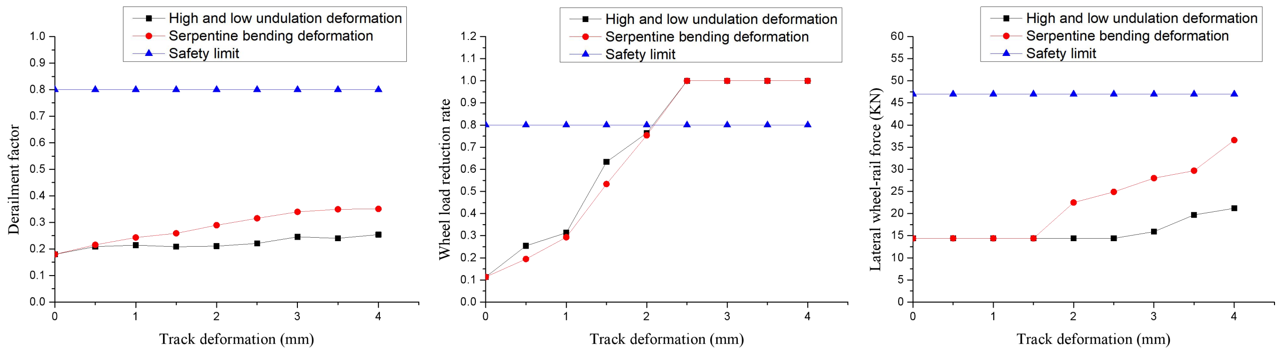

Fig.7 – The influence of the High and low undulation and serpentine bending of the track at a speed of 250km/h on the three indexes of running train

It can be seen from Figures 6 and 7 that at the speed of 250 km/h, the changes of the three indexes of the train increase with the increase of the track deformation. Among them, the variation range of the derailment coefficient is not large, and the lateral deformation has a greater impact on the derailment coefficient than the vertical deformation. For wheel load reduction ratio, vertical deformation has a greater impact on wheel load reduction ratio than lateral deformation. When the vertical deformation in one direction is greater than 3mm, the lateral deformation in one direction is greater than 3.5mm, the high and low undulating deformation and the serpentine bending is greater than 2.5mm, the wheel load reduction rate exceeds the safety limit, and the train is no longer safe. The lateral wheel-rail force changes greatly, and the lateral deformation has a greater impact on the lateral wheel-rail force than the vertical deformation.

5.3 Analysis of influence of track deformation at running speed of 300km/h on running safety

Set the vehicle speed to 300km/h and the chord length of the track deformation to 10m.By changing the values of the vertical deformation in one direction, lateral deformation in one direction, high and low undulation deformation, serpentine bending deformation of the tracks, the line graphs of the three indexes of the train as the deformation of the tracks increase are drawn, as shown in Figures 8 and 9.

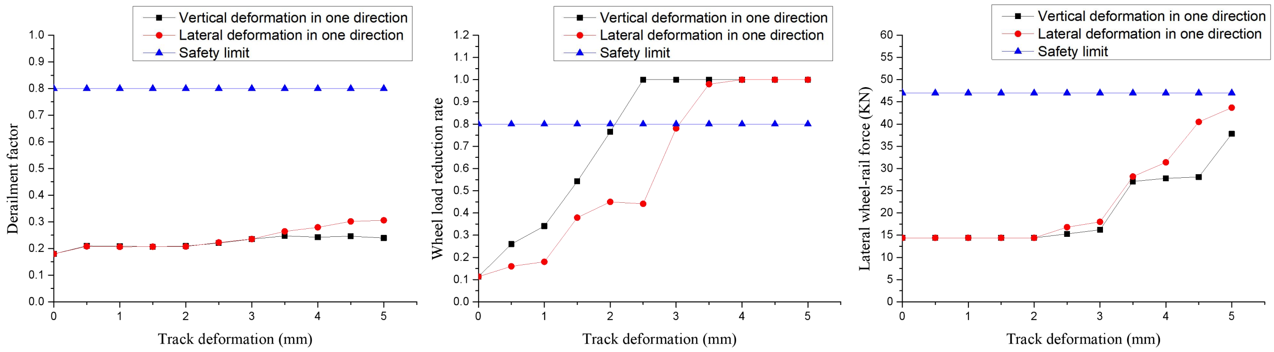

Fig.8 – The influence of the unidirectional deformation of the track at a speed of 300km/h on the three indexes of running train

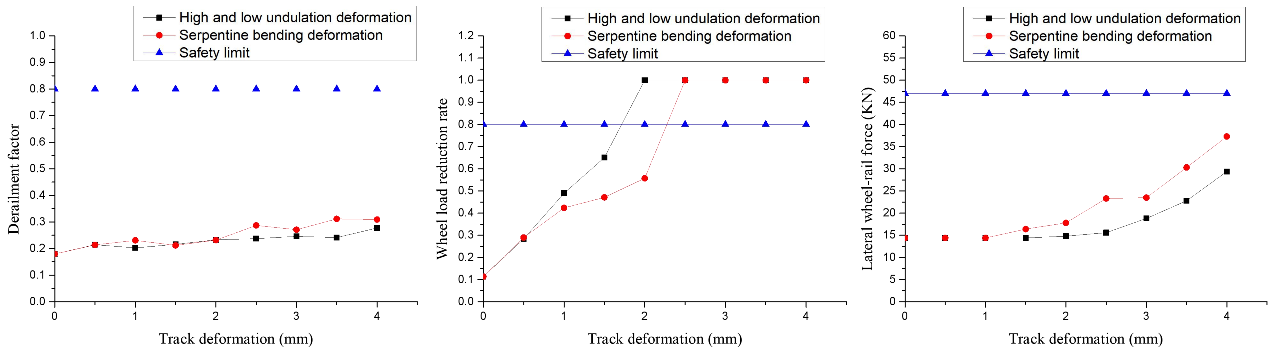

Fig.9 – The influence of the High and low undulation and serpentine bending of the track at a speed of 300km/h on the three indexes of running train

It can be seen from Figures 8 and 9 the changes in the values of the three indexes of the train increase with the increase of the speed, but there are also fluctuations. Among them, the variation range of the derailment coefficient is not large, and within the safety limit, the vertical deformation has a greater impact on the derailment coefficient than the lateral deformation. The wheel load reduction rate changes greatly. When the vertical deformation in one direction is greater than 2.5mm, the lateral deformation in one direction is greater than 3.5mm, the high and low undulation deformation is greater than 2mm, and the serpentine bending deformation is greater than 2.5mm, the wheel load reduction rate exceeds safety limits, trains are no longer safe. The lateral wheel-rail force changes greatly, and the lateral deformation has a greater influence on the lateral wheel-rail force than the vertical deformation.

6. Conclusions

(1) In the case of the same track deformation, the changes of the three index values of the train increase with the increase of the track deformation, and increase with the increase of the speed, but there are fluctuations.

(2) The vertical deformation of the track has a greater impact on the wheel load reduction ratio than the lateral deformation, and the lateral deformation of the track has a greater impact on the derailment coefficient and lateral wheel-rail force than the vertical deformation. The effect of vertical deformation on lateral wheel-rail forces is small.

(3) When the chord length of the track deformation is 10m and the train speeds are 200km/h, 250km/h, and 300km/h, the influences of changes in the amount of vertical deformation in one direction, lateral deformation in one direction, high and low undulating deformation, and serpentine bending deformation on driving safety were calculated, and the limit of the threat to driving safety was obtained. In all three cases, the wheel load reduction rate reached the safety limit first.

7. Acknowledgement

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8. References

[1] China Railway Design Corporation, China Railway Siyuan and Design Group Co., Ltd. (2014): *TB10621-2014 Code for Design of High Speed Railway*.

[2] Miura, Shigeru (1996). Deformation of track and the safety of train in earthquake. *Railway Technical Research Institute Quarterly Reports*, 37,139-146.

[3] Miyamoto, T., Ishida, H., Matsuo, M. (1997). Running safety of railway vehicle as earthquake occurs. *Quarterly Report of RTRI (Railway Technical Research Institute) (Japan)*, 38,117-122.

[4] Yang Kun (2010): Safety research on running response of vehicle-track-viaduct simple beam subjected to earthquake loading. (Doctoral dissertation, Beijing Jiaotong University).

[5] Su Liping (2015): Study on dynamic responses of ballasted track and running safety of train during earthquakes. (Doctoral dissertation,Lanzhou Jiaotong University).

[6] Ke Xinmeng (2014): Study on vehicle derailment safety under seismic action. (Doctoral dissertation, Southwest Jiaotong University).

[7] Xia He, Zhang Nan (2005). *Interaction between Vehicle and Structure Dynamics (2nd Edition)*, Beijing: Science Press.

[8] Zhai Wanming, Xia He (2011). *Train-Track-Bridge Dynamic Interaction Theory and Engineering Application*, Beijing: Science Publishing.

[9] Wang Yuanfeng, Wang Ying, Wang Dongjun (1997): A new simulation method for the irregularity of railway track. *Journal of the China Railway Society,* 19(6), 110-115.

[10] Chen Guo, Zhai Wanming (1999): Numerical simulation of stochastic process of railway track irregularity. *Journal of Southwest Jiaotong University*, 34(2), 138-142.

[11] China Academy of Railway Sciences (2013): *TB 10761-2013, Technical Code for Dynamic Acceptance of High-speed Railway Project*.

[12] China Railway Siyuan and Design Group Co., Ltd. (2017): *TB 10082-2017, Code for Design of Railway Track.*

[13] Guo Endong, Zhang Shuqiang, He Qian (2017): Seismic safety evaluation of high-speed trains considering the characteristics of track spectrum. *Journal of Railway Engineering Society*, 34(05), 32-37.

[14] Guo Endong, Li Raorao (2018): Analysis of the three indicators of high-speed railway run abilities during earthquake. *Journal of Railway Engineering Society*, 35(09), 14-20.

