Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
© 2019 Associazione Geotecnica Italiana, Rome, Italy, ISBN 978-0-367-14328-2

The influence of seismic waves spectrum characteristics and subgrade height to the running safety of high-speed railway

H. Li, H. Zhang & B. Liu
Beijing Jiaotong University, Beijing, China

ABSTRACT: High-speed railways are fast and have a large capacity. Once derailed or overturned in an earthquake, the loss of life and property is enormous. Therefore, it is necessary to study the running safety vehicles under the seismic excitation. Firstly a simplified multi-rigid vehicle-track-embankment coupled dynamics model is established. This in order to analyze and discuss the running safety and derailment mechanism of the high-speed railway under the seismic excitation and Verify the correctness of numerical model calculation by comparing with Nishimura‘s test results. Subsequently, a sine wave has been adopted to analyze the vehicle-track model frequency response by time history method and frequency domain method. Inputting nine typical measured seismic waves to further study the influence of seismic spectrum characteristics on vehicle-track system. Finally, the influence of different subgrade heights on vehicle running safety under the seismic excitation is discussed.

1 INTRODUCTION

China’s high-speed railway has developed rapidly and its running kilometer has been increasing. It has exceeded 20,000 kilometers so far. By 2025, the high-speed railway will reach 38,000 kilometers, covering most major cities. However, China is a country with many earthquakes. Most of the high-speed railways are under the threat of high-intensity earthquakes, such as the Beijing-Tianjin inter-city railway, the Beijing-Guangzhou high-speed railway, the Beijing-Shanghai high-speed railway etc, have passed the earthquake-stricken area. Therefore, the issue of earthquake prevention and disaster reduction of high-speed railways has always been valued.

In order to solve the threat of earthquake to the safety running of high-speed railways, scholars from various countries have done a lot of researches. Miyamoto believes that it is necessary to carefully study the mechanism of derailment under earthquake, and use more direct parameters to distinguish the mechanism of derailment. They applied a five-cycle sine wave to the track plate as a seismic load and analyzed the dynamic response of the vehicle-track, including wheel lift and traverse. They obtained the critical amplitude curve of the safety running of the vehicle, by taking 30mm wheel lift as the derailment limit, and verified the numerical analysis results by simulating the full-size vibration table test of the vehicle track. The critical amplitude curve can be applied to the design of the vehicle track structure. Author Ling Liang and Xiao Xinbiao also used five cycles of sine waves to analyze the dynamic response of high-speed trains under the earthquake. They proposed two new high-speed train derailment evaluation criteria, namely the position of wheel-rail contact point and the amount of wheel lift. Studies above all believe that the speed of the vehicle has little effect on the running safety boundary of the vehicle under earthquake, and the spectral characteristics of the seismic wave have a great influence on it. Luo Xiu, Ling Liang believe that when the seismic excitation frequency is low, it is prone to overturn derailment. When the seismic excitation frequency is instead high, it is prone to jump derailment. Xu Peng, Wu Xingwen also believe that the cause of the derailment of the train is related to the frequency of the seismic wave, and the low-frequency seismic wave has a greater impact on the safety of the vehicle. When the seismic wave frequency is in the range of 0.5 Hz-1 Hz, it is easy to resonate with the upper or lower center roll of the vehicle body, which affects the running safety of the vehicle. Nishimura simulated the running safety of the vehicles with a 13-degree-of-freedom semi-vehicle/track coupling model, and then used a rolling shaker to build a small model which was 1:10. They carry out the simulation test, and finally through the full-size rolling vibration table test of the vehicle track, and verified the simulation results and the 1:10 scale test results of the vehicle track are valid, which proves that the dominant role of the train derailment under the earthquake is the roll motion of the vehicle body and the wheel traverse under the effect of wheel-track creep. The derailment of high-speed trains takes “jumping derailment” as the main form, and the reason for derailment is related to the amplitude of seismic excitation, and has nothing to do with the speed of the vehicle. Li Ming fei discussed and analyzed the impact of the two sub-grades on the running safety of vehicles under earthquake. They are believed that the improved soil subgrade has less response than the ordinary soil subgrade. The improved soil subgrade is improved strength and density compared with the ordinary soil subgrade.

Based on above all, some of researches about the dynamic response of the vehicle track under the earthquake, the derailment mechanism and the amplitude and frequency characteristics of the seismic wave, on the running safety of the vehicle track have been done. However, the above literature does not consider the influence of the subgrade height and the spectral characteristics of the measured seismic waves on the running safety of the vehicle. Based on the numerical simulation of vehicle-track dynamic response under earthquake, this paper studies the effects of measured seismic waves with different spectral characteristics and different subgrade heights on running safety of vehicle track.

2 VEHICLE-TRACK DYNAMICS MODEL

2.1 *Vehicle-track model*

The numerical model consists of the body - bogie - wheel pair - tracks - fastener - track plate which is from the top to the bottom of model . According to the vehicle-track dynamics theory, a single vehicle of a high-speed train can be simplified to consist of a body, a frame, a wheel pair, primary suspension and secondary suspension. The wheel-set and the bogie are connected by the primary suspension, while the body and the bogie are connected by the secondary suspension. The spring-damping unit is used to simulate the fastener between the track and the track plate. The model diagram is shown in Figure 1.

In the dynamic model, the inner diameter of the wheel is 845mm, the outer diameter is 915mm, the thickness is 145mm, the rail adopts the standard 60 rail, the rail height is 176mm, the lower width is 150mm, the upper width is 73mm, and the waist thickness is 16.5mm. The rail spacing is determined to be 1435 mm according to the specification, and the axle between the wheels is 100 mm. The track plate is laid under the track, 2.5m long and 260mm thick,

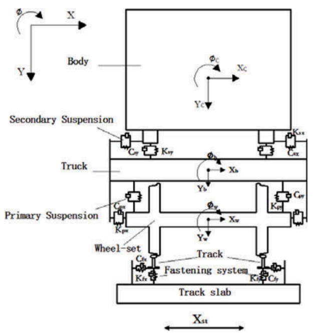


Figure 1. Vehicle-track dynamics model

which is a concrete structure. The track, track plate and fastener system are all linear elastic constitutive models. The parameters are shown in Table 1. the dynamic parameters of each component of the track superstructure in Table 2.

2.2 *Wheel-track contact setting*

In this model,The contact pair is applied to simulate the interaction between the wheel and the track. The wheel-track spatial dynamic contact force model includes the wheel-track tangential force calculation model and the wheel-track normal force calculation model. The wheel-track tangential force is calculated by the "penalty function" which is a certain class of algorithms for solving constrained optimization problems, and the friction coefficient[15] of the wheel-track contact surface sets to 0.3; the wheel-track normal force is the relationship between the normal load and the local deformation at the wheel-track contact, using "Hertz" contact method to analyze the model, and the schematic diagram of wheel-rail contact is shown in Figure 2.

2.2.1 *"Hertz" contact*

Hertz first used the mathematical elastic mechanics method to derive the calculation formula for the contact problem. The assumptions are: the material is considered to be homogeneous, isotropic, completely elastic; the friction of the contact surface is negligible, the surface is the ideal smooth surface, and the Hertz contact formula is as follows:

$$N(t) = \begin{cases} \left[\frac{1}{G_{wr}} Z_{wrnc}(t)\right]^{3/2}, Z_{wrnc}(t) > 0 \\ 0, \qquad\qquad\qquad Z_{wrnc}(t) \leq 0 \end{cases} \tag{1}$$

Among them, G_{wr} is the wheel-track contact constant ($m/N^{2/3}$), $G_{wr}=3.86R^{-0.115}\times10^{-8}$; $Z_{wrnc}(t)$is the penetration amount of the wheel-track contact point, which can be determined according to the following formula:

Table 1. Track system parameters

Name	Thickness/m	Young's modulus/GPa	Poisson's ratio	Density/kg/m^3
Track	0.176	206	0.3	7800
Track-plate	0.19	35.5	0.1	2400

Table 2. Track superstructure parameters

Name	Parameter	符号	Unit	Value
Body	Mass	M_c	kg	13000
Bogie	Mass	M_b	kg	3200
Wheel-set	Mass	M_w	kg	1800
Primary suspension	Horizontal stiffness	K_{px}	kN/m	7700
	Vertical stiffness	K_{py}	kN/m	60000
	Vertical damping	C_{pz}	kN·s/m	20
Secondary suspension	Horizontal stiffness	K_{sx}	kN/m	380
	Vertical stiffness	K_{sy}	kN/m	12000
	Horizontal damping	C_{sx}	kN·s/m	30
	Vertical damping	C_{sy}	kN·s/m	25
Fastener	Horizontal stiffness	K_{fx}	kN/m	8000
	Vertical stiffness	K_{fy}	kN/m	59000
	Horizontal damping	C_{fx}	kN·s/m	65
	Vertical damping	C_{fy}	kN·s/m	280

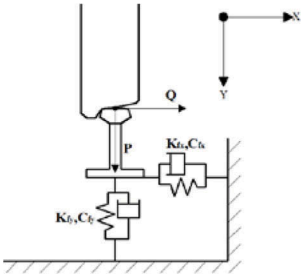


Figure 2. Schematic diagram of wheel and track contact

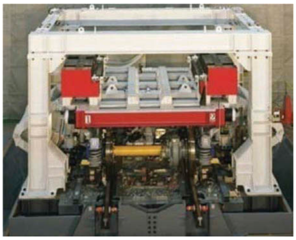


Figure 3. Nishimura full-scale testing plant

$$\begin{cases} \delta Z_L = Z_w(t) - (\Delta Z_{Lwt} - \Delta Z_{w0}) \\ \delta Z_R = Z_w(t) - (\Delta Z_{Rwt} - \Delta Z_{w0}) \end{cases} \quad (2)$$

Where, ΔZ_{Lwt}, ΔZ_{Rwt}, is the minimum vertical spacing of the left and right wheel track at time t; ΔZ_{w0} is the minimum vertical spacing of the wheel rails at time 0; $Z_w(t)$is the vertical displacement of the wheel to the centroid at time t. Through the geometric relationship between the normal compression of the wheel and track to obtain the compression in the normal direction of the left and right side wheel track.

$$\begin{cases} \delta Z_{Lc} = \frac{\delta Z_L}{\cos\cos(\delta_L + \phi_w)} \\ \delta Z_{Rc} = \frac{\delta Z_R}{\cos\cos(\delta_R - \phi_w)} \end{cases} \quad (3)$$

2.3 *Verification of dynamic numerical model*

The parameters of vehicle-track model above all are given by the Japanese scholar Nishimura. Nishimura uses a bogie and half-car body to carry out a full-scale vibratory test. The derailment mechanism and the function of the anti-derailment guard are studied. The model test is shown in the Figure 3. In this test, the vehicle is in static state. Comparing with Nishimura's vehicle vibratory test results to verify the accuracy of the vehicle-track calculation model that established in this paper.

Five cycles of sinusoidal seismic waves is applied to the bottom of the vehicle-track dynamics model to analyze the seismic time-history response, plotting the wheel lift, the horizontal contact force of the wheel-track and the vertical contact force of the wheel-track with the seismic excitation. and comparing with Nishimura's vehicle-track testing plant results. The comparison results are shown in the Figure 4.

Figure 4 shows the comparison results of Nishimura's test and calculation, (a) Nishimura test wheel lift, (b) calculation wheel lift, (c) Nishimura test horizontal contact force, (d) calculation horizontal contact force, (e) Nishimura test vertical contact force, (f) calculation vertical contact force (g) five cycles of sinusoidal seismic waves are shown. In the left, the rigid line indicates the Nishimura's test results as seen (a) (c) (e), and in the right, the rigid line indicates the numerical results as seen in (b) (d) (f). According to their periodicities and peak values the wheel lift, the horizontal contact force and vertical contact force show good agreement with the numerical calculations as seen in (a)-(f), which indicates the vehicle-track numerical model established in this paper has certain correctness and provides a theoretical basis for the subsequent research.

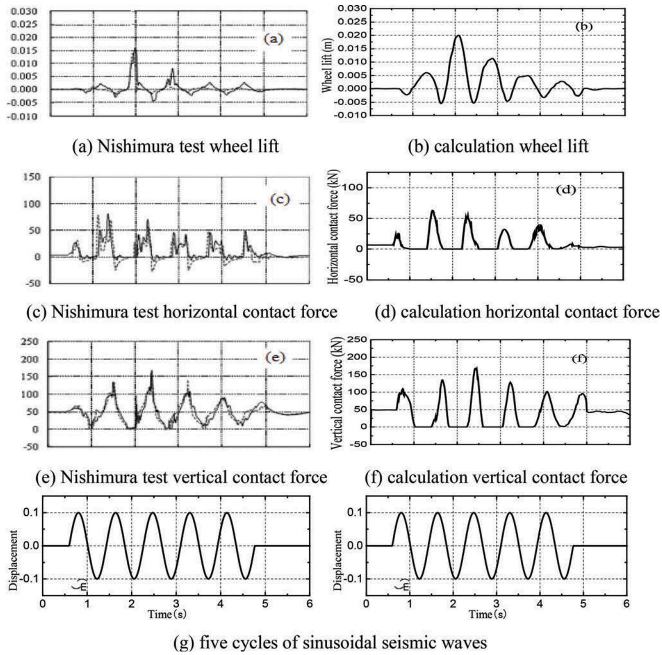


Figure 4. The time history of wheel motions (Nishimura's test and calculation, input:1.2Hz 100mm)

3 INFLUENCE OF SEISMIC WAVE SPECTRUM CHARACTERISTICS

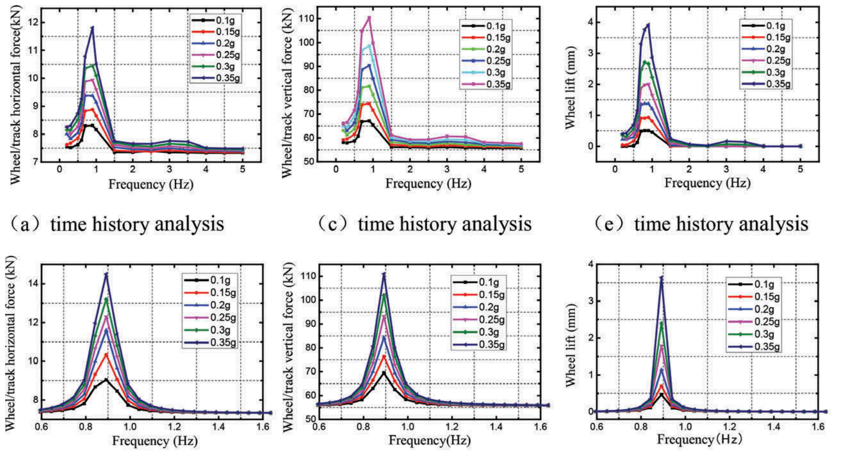
3.1 *Sine wave spectrum characteristics*

The intensity, frequency and duration of seismic waves have an important impact on the vehicle-track system, and the spectral characteristics of seismic waves are particularly significant. In order to study the derailment mechanism of vehicle-track under different spectral seismic waves, Time history method and frequency domain method are used to analyze the dynamic response of the vehicle-track models under different frequencies of seismic wave. The seismic wave adopts the acceleration sine wave, and its acceleration peaks are 0.1g, 0.15g, 0.2g, 0.25g, 0.3g, 0.35g respectively. According to the vehicle system dynamics theory, the rigid body mode of the vehicle system is mainly concentrated in the low frequency range. Therefore, the frequency range is selected from 0.1 Hz to 5 Hz. Summarizing the results calculated statistically by time history method and frequency domain method, and Obtaining the frequency response relationship under the two analysis conditions which are horizontal contact force, the vertical contact force and the wheel lift-up Figure.

It can be seen from Figure 5(a)-(f) that the time history method results is close to frequency domain method results. When the time history method is used, the derailment index has a response peak near 0.9 Hz. In the frequency domain method, the derailment index reaches the response peak near 0.89Hz; in the high frequency range (greater than 1.5Hz), the derailment index is not obvious with the increase of the seismic wave frequency. The modal analysis of the vehicle-track model shows that the rolling self-vibration frequency of the vehicle body is 0.87 Hz, which indicates that when the sinusoidal seismic wave frequency is close to the self-vibration frequency of the vehicle body roll, resonance will be generated,Thus each derailment indicator reached the peak response.

3.2 *Measured seismic wave spectrum characteristics*

Nine typical measured seismic waves are used to the vehicle-track model for dynamic response analysis. The nine kinds of seismic wave accelerations are normalized, and the peak values of



(a) time history analysis (c) time history analysis (e) time history analysis

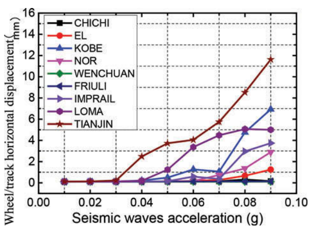
(b) frequency domain analysis (d) frequency domain analysis (f) frequency domain analysis

Figure 5. Frequency response of horizontal contact force vertical contact force and wheel lift

the seismic wave accelerations are adjusted to 0.01 g, 0.02 g, …… 0.1 g. The above-mentioned seismic waves are sequentially input to the bottom of the vehicle-track model to perform time-history analysis calculation. The horizontal relative displacement of the wheel-track contact point and wheel lift of the model under the action of seismic waves is calculated, and the peak of seismic wave acceleration at each level is taken as the abscissa. The maximum response value of horizontal relative displacement of the wheel-track contact point and wheel lift is plotted on the ordinate, as shown in Figures 6 and 7.

It can be seen from the figure that when the seismic wave acceleration is below 0.03g, the horizontal relative displacement of the wheel and track is small. This is because the seismic wave acceleration is small at begin, resulting in the wheel-set and the track stay the centering position, with the increase of each seismic wave acceleration, the horizontal relative displacements of the wheel and rail are increased in different extents. The response caused by the Tianjin wave is the most significant. The predominance frequency statistics of each seismic wave are shown in the following Table 3.

It can be seen from the statistical results that the predominance frequency of each seismic wave is mainly concentrated in the low frequency range of 10 Hz. From the above, it can be seen that the rolling self-vibration frequency of the vehicle body is 0.87 Hz. From Table 2-1, the predominance frequency of the Tianjin wave is 0.73 Hz. They are close to each other, which results in the horizontal relative displacement and the wheel lift value is the most significant under the action of the Tianjin seismic wave. In summary, it can be judged that when the predominance frequency of the seismic wave is close to the rolling self-vibration frequency of the vehicle body, resonance is easy to occur, and the damage is larger.



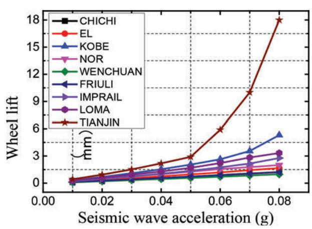


Figure 6. Wheel/track horizontal displacement Figure 7. Wheel lift

Table 3. The amplitude frequency characteristics of each seismic waves

seismic wave	Loma	Kobe	Tianjin	Chichi	Northrighe	Imperial	El-centro	Friuli	wenchuan
predominance frequency (Hz)	0.512	0.6	0.73	1.12	1.25	1.34	1.47	2	6

4 INFLUENCE OF SUBGRADE HEIGHT

In order to study the influence of different subgrade heights of high-speed railways on the running safety of trains under the action of different seismic waves, based on the above vehicle-track numerical model, the subgrade is added under the model. The subgrade is mainly composed of CA mortar, support layer, surface layer of subgrade bed and bottom layer of subgrade bed. According to the “High-speed Railway Design Code”, the following three working conditions are calculated: Case (1): no subgrade part; Case(2): with subgrade part, and the height of surface layer of subgrade bed is 0.4m, the height of bottom layer of subgrade bed is 2.3m; Case (3): with the subgrade part, and the height of surface layer of subgrade bed is 0.8m, the height of bottom layer of subgrade bed is 3.2m. The main parameters are shown in Table 4.

The model calculation diagram is shown in the Figure 7 . The other parameters of the model are shown in the first section. The seismic waves are input from the bottom of the subgrade. Using El-centro wave and Kobe wave to the model for the seismic response analysis.

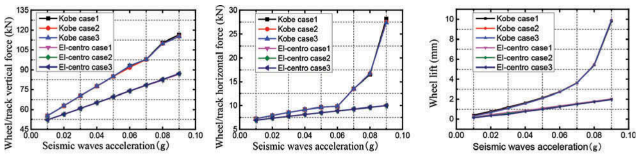
4.1 *Dynamic response of different subgrade heights under earthquake action*

The Kobe wave and the EL-centro wave are selected to analyze and calculate these three cases. The above seismic waves are sequentially input to the bottom of the model for time history analysis. Calculating the vertical contact force of the wheel-track the horizontal contact force of the wheel-track, the wheel lift under the action of seismic waves at all levels, taking the peak of the seismic wave acceleration at each level are as the abscissa, and the maximum response value of the wheel lift, the horizontal contact force of the wheel-track and the vertical contact force of the wheel-track is plotted on the ordinate, as shown in the Figure 8.

It can be seen from the figure that under the action of two kinds of seismic waves, the curves of the three cases are basically the same, and it can be found that when the seismic wave acceleration is within the range of (0-0.1g), the height of the subgrade changes within a certain range, the wheel lift, the horizontal contact force of the wheel-track and the vertical contact force of the wheel-track under the action of seismic waves have little effect.

Table 4. Parameter of subgrade part

Name	Height (m)	Young’s modulus (Gpa)	Poisson’s ratio	Density (kg/m^3)
Base plate	0.3	30	0.03	2400
CA mortar	0.05	0.2	0.4	2200
Surface layer	0.4 0.8	0.19	0.3	1950
Bottom layer	2.3 3.2	0.1	0.3	1850



(a)vertical force (b)horizontal force (c)wheel lift

Figure 8. Dynamic reponse of wheel and track

5 CONCLUSIONS

A 9-degree-of-freedom vehicle-orbit model has been established, and the dynamic response of the vehicles under the action of seismic waves has been calculating . The correctness of numerical model calculation by comparing with Nishimura's test results has been verified. Sine waves is used to analyze the vehicle-track model frequency response by time history method and frequency domain method. Nine typical measured seismic waves is inputted to study the influence of seismic spectrum characteristics on vehicle-track system. Finally, The influence of different subgrade heights on vehicle running safety under earthquake action is discussed. The main conclusions are as follows:

1. Though comparing the numerical simulation results with Nishimura's test results, it can be seen that the calculation results are basically consistent with Nishimura's test results which verifies the numerical calculation results are reliable.
2. The spectral characteristics of seismic waves have a great impact on the running safety of vehicles. When the excellent frequency of seismic waves is close to the natural vibration frequency of the rolling of the vehicle body, it is easy to generate resonance, which is very harmful, therefore when designing the vehicle track, try to make the rolling self-vibration frequency of the vehicle body to avoid the low-frequency area.
3. When the subgrade height changes within a certain range, the seismic wave has little effect on the wheel lift, the horizontal contact force of the wheel-track and the vertical contact force of the wheel -track.

REFERENCES

Miyamoto T, Ishida H, Matsuo M. Running safety of railway vehicle as earthquake occurs . Railway Technical Research Institute, Quarterly Reports, 1997,3 8(3):117–122.

Miyamoto T, Matsumoto N, Sogabe, et al. Full-scale Experiment on the Dynamic Behavior of Railway Vehicles against Heavy Track Vibration. Journal of Environment and Engineering, 2007,2(2): 419–428.

Miyamoto T, Ishida H. Numerical Analysis Focusing on the Running Safety of an Improved Bogie during Seismic Vibration. Quarterly Report of RTRI,2008, 49(3):173–177.

Ling liang, Xiao xinbiao, et al. Study on dynamic response and running safety boundary of high-speed train under seismic motions. JOURNAL OF THE CHINA RAILWAY SOCIETY, 2012, 34(10):16–22.

Luo Xiu.Study on methodology for running safety assessment of trains in seismic design of railway structures. Soil Dynamics and Earthquake Engineering, 2005, 25(2): 79–91.

Ling liang, Xiao xinbiao, et al.effect of spectrum characteristics of seismic wave on derailment of high-speed train. ENGINEERING MECHANICS, 2013,30(1):384–393.

Xu peng. Study on vibration of train-track-subgrade coupled system and running safety of train in earthquake. Chengdu:Southweat Jiaotong University. 2011.

Wu xingwen, Railway vehicle under the earthquake excitations[D]. Chengdu:Southweat Jiaotong University. 2016.

Nishimiira K,Terumichi Y, Morimura T,et al. Development of vehicle dynamics simulation for safety analyses of rail vehicles on excited tracks. Journal of computational and nonlinear dynamics,2009,4(1): 1–9.

Nishimura K,Terumichi Y, Morimura T, et al. Experimental study on the vehicle safety by earthquake track excitation with 1/10 scale vehicle and roller rig. Journal of System Design and Dynamics, 2010, 4 (1): 226–238.

Nishimura K,Terumichi Y,Morimura T,et al. Analytical Study on the Safety of High Speed Railway Vehicle on Excited Tracks. Journal of System Design and Dynamics, 2010, 4(1):211–225.

Kazuhiko NISHIMURA, Yoshiaki TERUMICHI, Tsutomu MORIMURA, et al. Experimental Study on the Vehicle Safety by Earthquake Track Excitation with 1/10 Scale Vehicle and Roller Rig.Journal of System Design and Dynamics.2010,4(1):226–238.

Kazuhiko Nishimura, Yoshiaki T, Tsutomu M, et al. Using Full Scale Experiments to Verify a Simulation Used to Analyze the Safety of Rail Vehicles During Large Earthquakes. Journal of Computational and Nonlinear Dynamics.2015,10:1–9.

Li mingfei, Research on the impact of the earthquake on the safety of running train on embankment. Beijing: Beijing Jiaotong University.2014.

Yoko smoked. Rolling friction between wheel and rail and its control. Foreign Rolling Stock, 2001, 38 (1): 36–40.