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Safety threshold of high-speed railway pier settlement based on train-track-bridge dynamic interaction

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This paper presents a method to determine the safety threshold of bridge pier settlement in high-speed railways. An analytical expression of the mapping relationship between the pier settlement and the rail deformation is derived theoretically for the double block ballastless track-bridge system. By adopting the superposition of the track random irregularity and the rail deformation caused by the pier settlement as the excitation inputs, the variations of vehicle dynamics indices with pier settlement are comparatively analyzed. Then, the safety threshold of the bridge pier settlement is obtained according to the limit of vehicle running safety and ride comfort indices of the high-speed trains. Results show that the dynamics indices of different trains have different sensitivities to the pier settlement, and the train CRH2C is the most sensitive one among all the types of Chinese high-speed trains. When passing through the bridges in common span with pier settlement at the speed of 250–350 km/h, the trains suffer the low-frequency excitations, and the vertical acceleration of car body is most sensitive to the pier settlement of all the dynamics indices. When the car body vertical acceleration just exceeds the allowable limit, the critical settlement value is 23.4 mm, which is much bigger than the pier differential settlement limit in the current code for Chinese high-speed railways.

high-speed railway, pier settlement, safety threshold , dynamic characteristics, train-track-bridge dynamic interaction

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1 Introduction

As one of the important infrastructures in high-speed railways, the bridge has a large proportion in Chinese high-speed railways. Bridges provide smooth and stable line conditions for the high-speed trains, to ensure the vehicle running safety and ride comfort [1]. However, it is hard to avoid the pier settlement in the process of bridge construction and operation, therefore, the pier settlement safety threshold becomes a key technical parameter in the design of high-speed railway bridges. If the safety value is too strict, the construction and maintenance cost of high-speed railways would be greatly increased. While if the value is too loose, the pier settlement would be too large, which makes the rail geometry quality abnormal and intensifies the train-track-bridge dynamic interaction, which eventually influence the vehicle ride comfort and even the running safety.

At present, there are many studies focusing on the train-track-bridge dynamic interaction [2–13]. Diana and Cheli [2] built a vehicle-bridge dynamic model in which the track flexibility and the wheel-rail interaction were considered, and the simulation results were compared with the test results. Bogaert [3] built a vehicle-bridge interaction model to calculate the acceleration of the vehicle and the bridge, in which the vehicle was modeled as a multi-rigid-body system. The results were compared with the test results to val-

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idate the vehicle-bridge model. Japanese Railway Technical Research Institute developed the procedure DIASTARS to calculate the dynamic interaction between the trains and foundations of the Shinkansen [4]. In the procedure, a more detailed nonlinear vehicle model was built and the simplified linear theory of rolling contact was adopted to calculate the wheel-rail creep force. Via a more complicated vehicle-bridge dynamic model, DZ14 committee of ERRI (European Rail Research Institute) studied the bridge dynamic responses to the track irregularity, and proposed some beneficial results into the standards [5,6]. Xia et al. [7,8] built a train-bridge dynamic model including rolling stocks and pier structures. The model was adopted to study the resonance mechanism and conditions of train-bridge system and to calculate the responses of bridges when trains pass through with a high speed. Zhai et al. [9–12] considered the train, the track, and the bridge as an integrated dynamic system, aiming to provide a method for analyzing and assessing the running safety and the ride comfort of high-speed trains passing through bridges. The complete train-track-bridge dynamic interaction model was established, and the computer simulation software TTBSIM (train-track-bridge interaction simulation software) was developed. This software had been validated by many onsite experiments [12]. Recently, Arvidsson and Karoumi [13] made a review and discussion of the key model parameters in train-bridge dynamic interaction. However, there are few literatures working on the pier settlement. Ismail and Jeng [14] developed a high-order neural network (HON) to simulate the nonlinear relationship between the load and the pier settlement. The results indicated a significant improvement in the accuracy of HON predictions over other models. Based on the three-dimensional theory, Zhao et al. [15] analyzed the pier settlement characteristics in the double-layered soft clay. The research showed that the settlement of the single-driven pile caused by the dissipation of pile-side excess pore water pressure is larger than that caused by the vertical load. Song et al. [16] built a vertical model of train-track-bridge system, and analyzed the influence of bridge pier settlement on the vertical vibration of freight car. The results showed that the car body acceleration was affected most by the pier settlement and the wheel unloading rate was the second one. So far, there are no researches about the influence of high-speed railway pier settlement on the vehicle running safety and ride comfort, nor the safety threshold of the pier settlement.

Based on the train-track-bridge dynamic interaction theory [9–12], a train-track-bridge coupled dynamics model including high-speed train and double block ballastless track is built in this paper. At the same time, the analytical expression of the mapping relationship between the pier settlement and the rail deformation in the coupled system is derived, and the rail deformation is calculated. Superposing the rail deformation with the track random irregularity, the excitation of the train-track-bridge system is obtained and utilized as inputs to the coupled dynamic system. The variations of vehicle dynamics indices with pier settlement are analyzed by using the coupled dynamics model, and the settlement safety threshold can be determined on the basis of the limit in the code for vehicle running safety and ride comfort in high-speed railways.

2 Method for analyzing the pier settlement safety threshold based on the train-track-bridge dynamic interaction

The pier settlement induces a vertical displacement of the two beam bodies nearby the pier, leading to a corresponding displacement of the track structure and a deformation of the rail. The rail deformation caused by the pier settlement results in an additional track irregularity, and it has a large effect on the vehicle running safety and ride comfort when the trains pass through at a high speed. Adopting the high-speed train-track-bridge dynamic interaction model, the dynamic responses of the high-speed trains running across the pier settlement area are analyzed. The safety threshold of the pier settlement can be determined according to the limit in the current code for running safety and ride comfort indices of high-speed trains.

The study of the pier settlement safety threshold based on the train-track-bridge dynamic interaction theory can be carried out as the following steps.

(1) Build the high-speed train-track-bridge dynamic interaction model.

(2) Deduce the mapping relationship between the settlement and the rail deformation, and calculate the rail deformation caused by pier settlement.

(3) Superpose the rail deformation and the track random irregularity to obtain the excitation inputs of the system.

(4) Analyze the dynamic responses of the vehicles by adopting the model in step 1).

(5) Determine the pier settlement safety threshold according to the current code for vehicle dynamics.

Clearly, steps (1) and (2) are the key problems to study the pier settlement safety threshold. The dynamic model instep 1) is introduced in this section, and step (2) will be presented in Section 3 in detail.

In the train-track-bridge dynamic interaction theory [9–12], the train, the track and the bridge are regarded as an integrated dynamic system, in which the train and the track are coupled by the wheel-rail interactive relationship, and the track and the bridge are linked through the track-bridge interaction. The high-speed train-track-bridge dynamic interaction model adopted in this paper contains three sub-models of the train, the track and the bridge [11]. The vehicle model is established based on the multi-body system dynamics. The model of a high-speed train consists of seven rigid bodies, including the car body, bogies, and wheelsets, as well as primary and secondary suspensions. Five degrees of freedom (DOFs) are taken into consideration for each rigid body, describing the vertical, lateral, roll, yaw and pitch motions. In total, each vehicle model has 35 DOFs. For double block ballastless track model, the sleeper blocks and the concrete base are considered in the mass of the bridge. This is because the sleeper blocks are precast into the slab directly and there is no elasticity between the slab and the concrete base on the bridge deck. The rail is modeled as a continuous rail beam discretely supported by fasteners, and three DOFs of the rail are taken into account, including vertical, lateral and torsional vibrations [1,11]. The bridge structures are modeled with the finite element method. For different types of bridge structures, the spatial beam element, the spatial pole element, the plate element and other special elements are used for modeling specific components. The bridge calculated in this paper is the simply supported girder bridge, which is modeled with the spatial beam elements. In the high-speed train-track-bridge dynamic interaction model, the wheel-rail spatially dynamic coupled model [11] is adopted to calculate the wheel-rail contact geometry and contact forces. For the track-bridge dynamic interaction model, the track-bridge interaction forces are different when different types of track structures are adopted. The expression of the track-bridge interaction force for double block ballastless track is shown in ref. [17]. Figure 1 shows the high-speed train-track-bridge dynamic interaction model adopted in this paper.

Based on the train-track-bridge dynamic interaction theory and a large number of previous studies on the train-bridge coupled vibration, the train-track-bridge interaction simulation software (TTBSIM) is developed by four institutions in China, including Southwest Jiaotong University, Beijing Jiaotong University, China Academy of Railway Sciences and Central South University [11]. Using this software, the vertical and lateral dynamic responses of the train-track-bridge system can be obtained in the cases of different trains passing through different bridges. In this paper, TTBSIM is used for calculating the dynamic responses of the coupled system with different pier settlements.

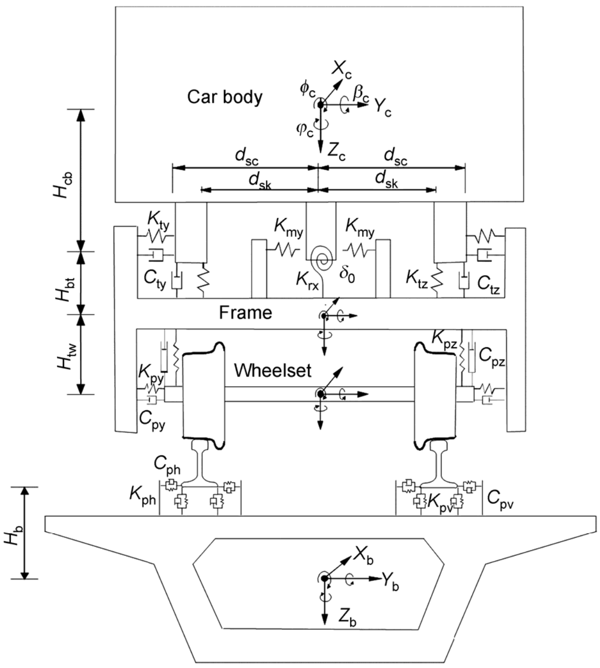

Figure 1 High-speed train-track-bridge dynamic interaction model.

3 Mapping relationship between the pier settlement and the rail deformation

To study the influence of bridge pier settlement on dynamic characteristics of high-speed trains and to determine the pier settlement safety threshold, the mapping relationship between the pier settlement and the rail deformation should be ascertained and the excitation inputs of the system must be calculated firstly. Chen et al. [18,19] studied the mapping relationship between the pier settlement and the rail deformation in the unit slab track system and the longitudinal connected ballastless track system. By adopting the method in refs. [18,19], the mapping relationship between the pier settlement and the rail deformation in the double block ballastless track system would be calculated in this paper.

3.1 Analysis of the rail deformation caused by the pier settlement

For the double block ballastless track-bridge system with pier settlement, the two beam bodies nearby the pier with settlement generate vertical displacements due to the gravity of the structures. Meanwhile, the concrete base and the roadbed slab on the bridge deck have the same vertical displacement. Consequently, the fastener systems installed on the slab move downward, resulting in the rail deformation, as shown in Figure 2.

3.2 Basic equation

In deriving the analytical expression of the mapping relationship between the pier settlement and the rail deformation, the bridge and the rail are considered as simply supported beams. Some basic assumptions are proposed.

(1) In the force analysis for each part, the relative deformation is calculated by placing the origin of coordinates in the static equilibrium position under the effect of gravity, thus the action of gravity is ignored in deriving the expression.

(2) The restraint effect of the rail on the bridge is ignored as the vertical bending stiffness of the rail is much smaller than that of the bridge.

(3) The settlements are the same along the lateral direction of the track, thus, the effect of pier settlement on the rail lateral deformation is ignored.

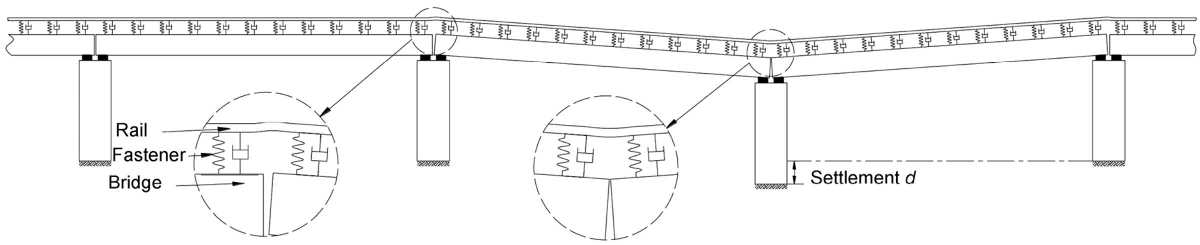

Figure 2 Rail deformation caused by pier settlement in the double block ballastless track-bridge system.

3.2.1 Rail displacement

Based on the assumptions, there are only fastener forces acting on the rail, as shown in Figure 3, where $F_{r,i}$ is the ith fastener force. Assuming that the number of bridge spans is $2M$, and the number of the fasteners installed on each span is N, therefore, the total number of fasteners is $2MN$. Define the origin of the calculated coordinates on the left side of the rail. The x-axis is along the axial direction of the rail and the z-axis works along with the vertical direction.

Based on the deflection formula of the simply supported beam, the rail displacement $z_{r,i}$ at the ith fastener can be expressed as

$$z_{r,i} = \sum_{j=1}^{i} \frac{F_{r,j}(l-x_j)}{6E_r I_r l}\left[\frac{l}{l-x_j}(x_i-x_j)^3-(2lx_j-x_j^2)x_i-x_i^3\right] + \sum_{j=i+1}^{2MN}\frac{F_{r,j}x_i(l-x_j)}{6E_r I_r l}(2lx_j-x_j^2-x_i^2), \tag{1}$$

in which

$$\begin{cases} x_j=(j-0.5)l_f, \\ l=2Ml_b, \end{cases} \tag{2}$$

where x_j is the coordinate of the jth fastener; l is the calculated length of the rail; l_f is the fastener spacing; l_b is the length of one bridge; E_r and I_r are the elastic modulus and the section inertia of the rail, respectively.

According to eq. (1), the rail displacement at all the fasteners can be obtained, and the rail displacement matrix can be described as

$$\boldsymbol{Z}_r = \boldsymbol{A}\cdot\boldsymbol{F}_r, \tag{3}$$

where $\boldsymbol{Z}_r$, $\boldsymbol{F}_r$ and $\boldsymbol{A}$ are the rail displacement matrix, the fastener force matrix and the relation matrix between the fastener force and the rail displacement, respectively. The matrix $\boldsymbol{A}$ is written as

$$\boldsymbol{A}=\begin{bmatrix} A_{1,1} & A_{1,2} & \cdots & A_{1,j} & \cdots & A_{1,2MN} \\ A_{2,1} & A_{2,2} & \cdots & A_{2,j} & \cdots & A_{2,2MN} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{i,1} & A_{i,2} & \cdots & A_{i,j} & \cdots & A_{i,2MN} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{2MN,1} & A_{2MN,2} & \cdots & A_{2MN,j} & \cdots & A_{2MN,2MN} \end{bmatrix}, \tag{4}$$

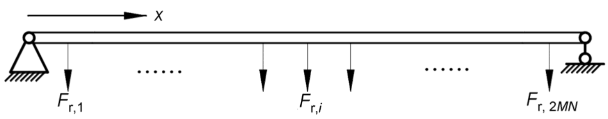

Figure 3 Force analysis of the rail.

$$A_{i,j}=\begin{cases} \dfrac{l-x_j}{6E_r I_r l}\left[\dfrac{l}{l-x_j}(x_i-x_j)^3-(2lx_j-x_j^2)x_i-x_i^3\right], \\ (i \geqslant j), \\ \dfrac{x_i(l-x_j)}{6E_r I_r l}(2lx_j-x_j^2-x_i^2), \\ (i<j). \end{cases} \tag{5}$$

3.2.2 Bridge displacement

Assuming that the middle pier has a settlement d, only the middle two beam bodies have vertical displacements. Figure 4 shows the displacement of the Mth span beam. The symbol θ is the turn angle of the beam; l_{b0} is the distance between the adjacent two bridge bearings along the longitudinal direction in the same bridge; l_{b1} is the distance between the bridge bearing and the beam-end. A coordinate system for the bridge is defined, and the origin is coincided with the left endpoint of the bridge.

According to the geometrical relationship shown in Figure 4, the vertical displacement of the Mth span beam body can be expressed by

$$z_b(x_b^M) = d(x_b^M - l_{b1})/l_{b0}, \tag{6}$$

where x_b^M is the coordinate of the calculation point in the Mth span.

In a similar way, the displacement of the $(M+1)$th span beam can be described as

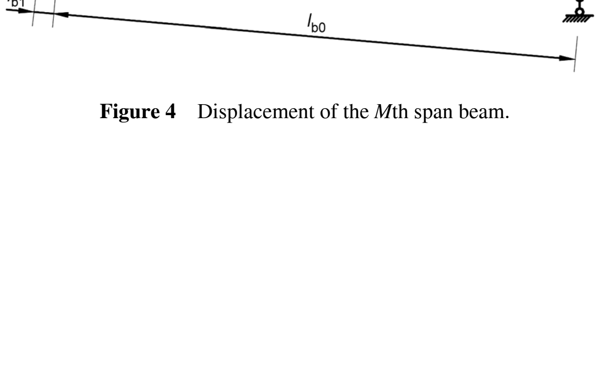

Figure 4 Displacement of the Mth span beam.

$$z_b(x_b^{M+1}) = d(l_{b0} + l_{b1} - x_b^{M+1}) / l_{b0}. \tag{7}$$

In accordance with eqs. (6) and (7), the bridge displacement matrix is expressed as

$$\boldsymbol{Z}_b = \boldsymbol{B} \cdot d, \tag{8}$$

where $\boldsymbol{Z}_b$ and $\boldsymbol{B}$ are the bridge displacement matrix and the relation matrix between the pier settlement d and the bridge displacement, respectively. The matrix $\boldsymbol{B}$ is given as following:

$$\boldsymbol{B} = [B_1\ B_2\ \cdots\ B_i\ \cdots\ B_{2MN}]^{\mathrm{T}}, \tag{9}$$

$$B_i = \begin{cases} 0, \\ (i = 0 \sim (M-1)N), \\ \{[i-(M-1)N-0.5]l_f - l_{b1}\}/l_{b0}, \\ (i = (M-1)N+1 \sim MN), \\ \{l_{b0} + l_{b1} - [i-(M-1)N-0.5]l_f\}/l_{b0}, \\ (i = MN+1 \sim (M+1)N), \\ 0, \\ (i = (M+1)N+1 \sim 2MN). \end{cases} \tag{10}$$

3.2.3 Fastener force

The fastener systems are modeled as linear springs. Thus, the ith fastener force can be described as

$$F_{r,i} = k_p(z_{b,i} - z_{r,i}), \tag{11}$$

where k_p is the spring stiffness of a fastener.

The fastener force matrix can be expressed as

$$\boldsymbol{F}_r = k_p(\boldsymbol{Z}_b - \boldsymbol{Z}_r). \tag{12}$$

3.3 Analytical expression of the mapping relationship

Dealing with eqs. (3), (8) and (12) simultaneously, the fastener force matrix F_r can be obtained as

$$\boldsymbol{F}_r = (\boldsymbol{E} + k_p\boldsymbol{A})^{-1} k_p \boldsymbol{B} d, \tag{13}$$

where $\boldsymbol{E}$ is a unit matrix.

It can be known from eq. (13) that the fastener forces are in direct proportion to the pier settlement d as the matrixes A and B are constant in a certain track-bridge system.

The rail deformation at any position can be expressed as a function of all the fastener forces, as shown in eq. (14). The equation describes the mapping relationship between the pier settlement and the rail deformation.

$$z_r(x) = \sum_{j=1}^{N_f(x)} \frac{F_{r,j}(l-x_j)}{6E_rI_rl}\left[\frac{l}{l-x_j}(x-x_j)^3 - (2lx_j - x_j^2)x - x^3\right] + \sum_{j=N_f(x)+1}^{2MN} \frac{F_{r,j}x(l-x_j)}{6E_rI_rl}(2lx_j - x_j^2 - x^2), \tag{14}$$

in which

$$N_f(x) = \mathrm{INT}\left(\frac{x-0.5l_f}{l_f}\right) + 1, \tag{15}$$

where x is the coordinate of the observation point; $N_f(x)$is the number of fasteners within the length of x; INT(x) represents the rounding of x. All the fastener forces in eq. (14) are in direct proportion to the pier settlement d, and so is the rail deformation $z_r(x)$.

4 Dynamic evaluation of the pier settlement safety threshold for high-speed railways

4.1 Parameters used in calculation

There are various tracks and operating trains in Chinese high-speed railways. For elucidation, the line and the train conditions of the Wuhan-Guangzhou high-speed railway are chosen to calculate the pier settlement safety threshold. The method proposed in this work is also valid to obtain the safety threshold of the pier settlement in other line conditions.

In this paper, the vehicle parameters of the four kinds of trains (CRH2C, CRH3, CRH380A, CRH380B) serving in the Wuhan-Guangzhou high-speed railway are selected to determine the settlement safety threshold, respectively. Three speeds are considered, i.e. 250, 300 and 350 km/h.

The double block ballastless track with 60 kg/m rail and the matched fasteners are adopted in the track model for their extensive use in the Wuhan-Guangzhou high-speed railway.

The 32 m-span simply supported girder bridge is adopted predominantly in the Wuhan-Guangzhou high-speed railway bridges, and the 24 m-spam is an auxiliary one. The quantity of the simply supported girder bridges within a representative length of 37.5 km is summarized in ref. [20]. It shows that the total number and the total length of the 32 m-span simply supported girder bridge are 378 and 12906 m, respectively, while those of the 24 m-span are 62 and 1488 m, respectively. In the calculation, the bridges with 32 and 24 m-span are adopted. The secondary dead load is set to be 160 kN/m according to the actual weight of the structures including the track and the accessory structure.

The irregularity excitation at the wheel-rail interface comprises two parts, including the random irregularity and the rail deformation caused by the pier settlement. The average PSD of ballastless track irregularities of Chinese high-speed railway is adopted as the track random irregularity, as shown in Figure 5. The rail deformation caused by the pier settlement is related to the settlement value. According to ref. [21], the calculated settlement d is set to be 5, 10, 15, 20, 25, 30 mm, respectively. By using eq. (14), the rail deformations under different pier settlements in the 24 and 32 m-span bridge systems are calculated, shown in Figure 6.

4.2 Analysis of the pier settlement safety threshold in the 24 m-span bridge system

The previous research [16] indicates that the pier settlement mainly has effects on the vehicle dynamic responses, while it has negligible influences on the responses of track and bridge. Among all the dynamics indices, the vertical acceleration of car body and the wheel unloading rate are most sensitive to the pier settlement. Therefore, the two indices are used for analyzing the dynamic response and evaluating the safety threshold of the pier settlement.

Taking the rail deformation caused by the pier settlement (shown in Figure 6(a)) as the excitation inputs, the vehicle dynamic responses are calculated when the trains pass through the 24 m-span bridge pier settlement area. Figures 7 and 8 show the effects of different settlements on the vertical acceleration of car body and the wheel unloading rate, respectively.

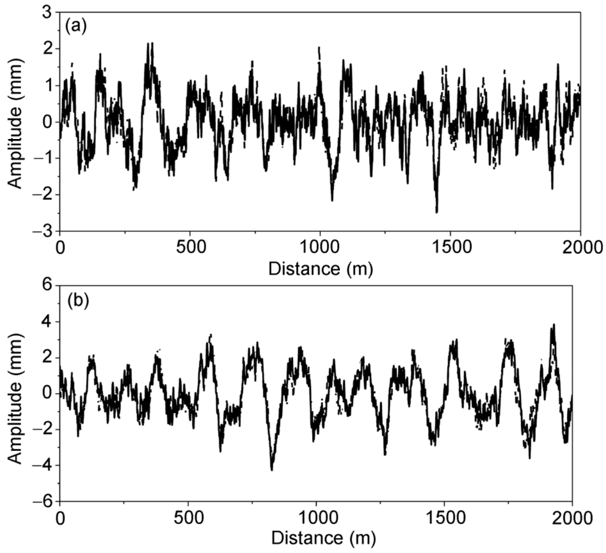

Figure 5 Time domain curve of the track random irregularity. (a) Alignment irregularity; (b) vertical profile irregularity.

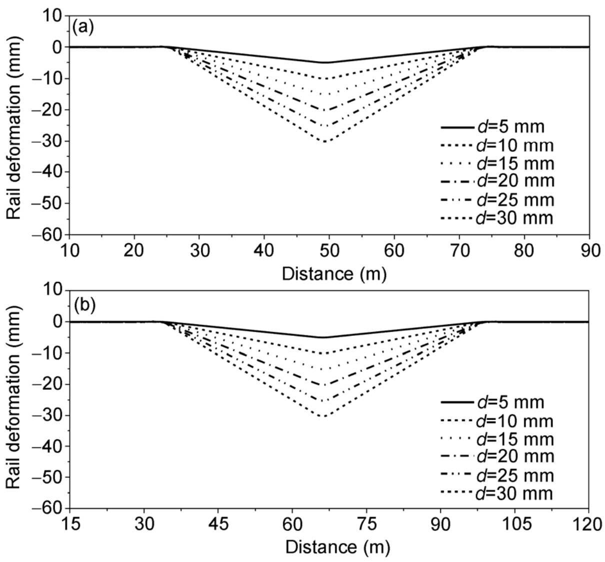

Figure 6 Rail deformation along with pier settlement. (a) 24 m-span; (b) 32 m-span.

It can be seen from Figure 7 that the car body vertical accelerations of different trains increase linearly as the pier settlement increasing from 5 to 30 mm. With larger pier settlements, the vertical accelerations of car body of CRH2C and CRH380A exceed the limit 0.13 g, as given in ref. [21]. When the acceleration exceeds the standard limit, the critical pier settlement for the train CRH2C is 23.4 mm, while that for CRH380A is 26 mm.

As the running speed increasing, the vertical acceleration of car body decreases. That is due to the fact that the excitation frequencies induced by trains running across pier settlement areas at a lower speed are much closer to the natural frequency of the car body. The length of the rail deformation areas are investigated with different settlements and the results are shown in Table 1. Table 2 lists the excitation frequencies caused by the trains passing through at different speeds. It can be known from Table 1 that due to the transition curve of rail in the edge of the pier settlement area, the length of the rail deformation area is slightly larger than the total length of the two beam bodies (i.e. the two beam bodies nearby the settlement pier). The length of the rail deformation area increases with the settlement increasing. That is because different pier settlements result in the different displacements of the beam bodies, and the rail also has different turn angles at the positions of the beam ends. As the rail is a continuous beam, different turn angle makes the length of the rail deformation different. So, the length of the rail deformation area differs with the value of settlement. Table 2 shows that the excitation frequency caused by the running trains changes from 1.13 to 1.87 Hz at the speed range of 250–350 km/h. The frequency shows an increase as the speed increases, while it decreases with the increase of the settlement value. At the speed of 250 km/h, the excitation frequency is closer to the natural frequency than other speeds, and this is why the vertical acceleration of car body is bigger than that at higher speeds.

As shown in Figure 8, the wheel unloading rate increases with the increase of the settlement and the running speed, and there is a linear variation between the wheel unloading rate and the pier settlement. When the trains move at the speed ranging from 250 to 350 km/h, the wheel unloading rates of all the trains are below the limit of 0.6 except the train CRH2C, whose wheel unloading rate exceeds the limit at speed of 350 km/h, and the critical settlement value is 25 mm.

It can be concluded that the pier settlement safety threshold is 23.4 mm judging by the indices of car body vertical acceleration and wheel unloading rate in the 24 m-span simply supported girder bridge system.

4.3 Analysis of the pier settlement safety threshold of the 32m-span bridge

The variations of the vertical acceleration of car body and

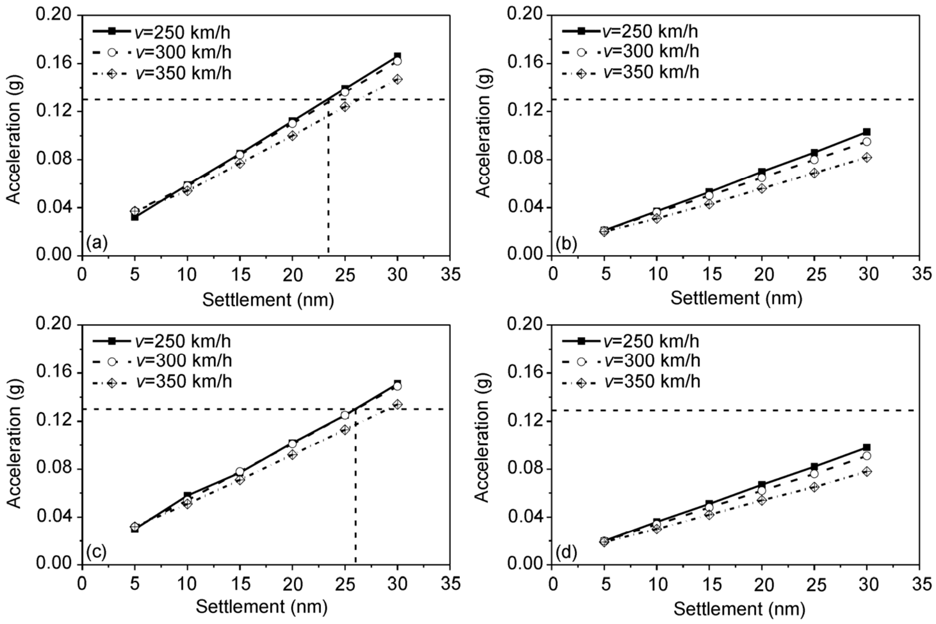

Figure 7 Vertical acceleration of car body along with pier settlement in 24 m-span simply supported girder bridge system. (a) CRH2C; (b) CRH3; (c) CRH380A; (d) CRH380B.

Table 1 Length of the rail deformation area in different pier settlements

Settlement (mm)	5	10	15	20	25	30
Length (m)	52.1	55.4	57.7	59	60.3	61.5

Table 2 Excitation frequencies caused by trains passing through the pier settlement area in different speeds (Hz)

Speed (km/h)	Settlement (mm)					
	5	10	15	20	25	30
250	1.33	1.25	1.20	1.18	1.15	1.13
300	1.60	1.50	1.44	1.41	1.38	1.36
350	1.87	1.75	1.68	1.65	1.61	1.58

the wheel unloading rate along with the pier settlement in the 32 m-span simply supported girder bridge system are almost the same with those in the 24 m-span bridge system. The critical pier settlement values when the two indices just exceed the limit in the Chinese code are listed in Table 3.

It can be seen from Table 3 that the car body vertical accelerations of the trains CRH2C and CRH380A exceed the Chinese allowable limit, and the critical pier settlements are 23.6 and 26.1 mm, respectively. For the index of wheel unloading rate, only that of the train CRH2C is beyond the limit, and the critical pier settlement safety threshold is 25.1

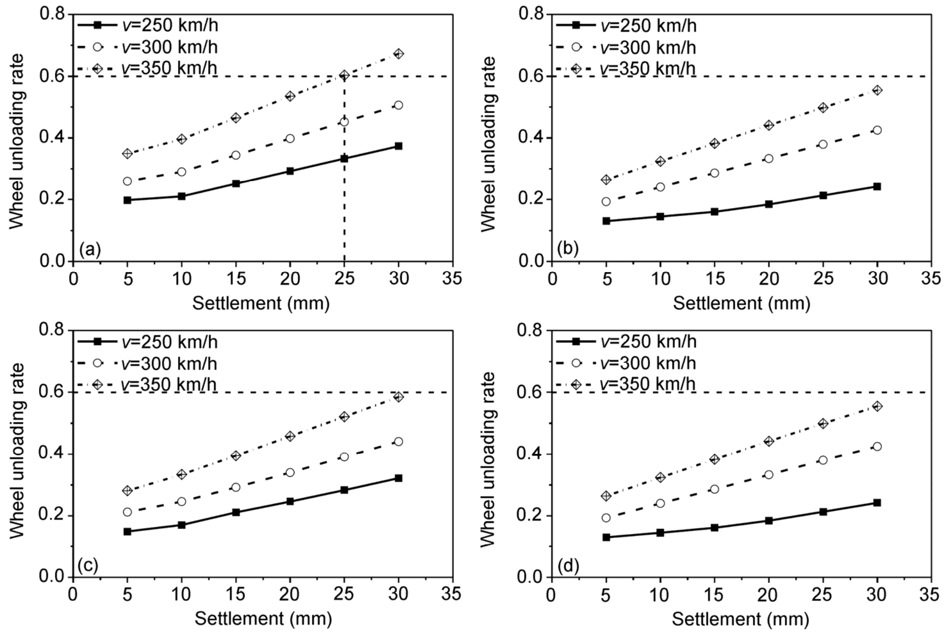

Figure 8 Wheel unloading rate changing with the pier settlement of the 24 m-span simply supported girder bridge system. (a) CRH2C; (b) CRH3; (c) CRH380A; (d) CRH380B.

Table 3 Critical settlement when indices just exceed the limit[a)]

Chinese high-speed trains	Critical settlement (mm)	
	Vertical acceleration of car body	Wheel unloading rate
CRH2C	23.6	25.1
CRH3	–	–
CRH380A	26.1	–
CRH380B	–	–

a) '–' means the index does not exceed the limit in the range of settlements calculated in this paper.

mm. Therefore, the pier settlement safety threshold is determined to be 23.6 mm in the 32 m-span simply supported girder bridge system.

In summary, based on the indices of vehicle running safety and ride comfort in the two kinds of bridge systems above, the safety threshold of the pier settlement is 23.4 mm for the simply supported girder bridges in common span.

5 Conclusions

A method of determining the pier settlement safety threshold for high-speed railways has been presented based on the train-track-bridge dynamic interaction in this paper. The analytical expression of the mapping relationship between the pier settlement and the rail deformation in the double block ballastless track-bridge system has been derived. According to the actual railway line and operation conditions in the Wuhan-Guangzhou high-speed railway, the dynamics indices of the vehicle running safety and ride comfort have been calculated when trains run through the pier settlement areas, and the pier settlement safety threshold has been obtained. From the studies, the following conclusions can be reached.

(1) Different kinds of high-speed trains have different sensitivities in dynamic responses to the bridge pier settlement. Among all the trains, the train CRH2C is most sensitive and the CRH380A is the second one, while the CRH3 and the CRH380B are relatively insensitive to pier settlement.

(2) At the speed of 250–350 km/h, the vertical acceleration of car body increases with the increase of the pier settlement, while it decreases as the speed increases. The wheel unloading rate increases with the increase of the pier settlement as well as the running speed.

(3) Low frequency excitations are generated when the high-speed trains run through the simply supported girder bridges in common span with pier settlement at the speed ranging from 250 to 350 km/h. The excitation frequency caused by the moving train at the speed of 250 km/h is closer to the natural frequency of the car body, resulting in the biggest vertical acceleration of car body at the speed of 250 km/h.

(4) The pier settlement safety threshold determined in this paper is 23.4 mm for the simply supported girder bridges in common span, neglecting the effects of other structural distortions, such as rotation angles at beam ends, creep of concrete and so on.

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1 Zhai W, Xia H. Train-Track-Bridge Dynamic Interaction: Theory and Engineering Application (in Chinese). Beijing: Science Press, 2011
2 Diana G, Cheli F. A numerical method of define the dynamic behavior of a train running on a deformable structure. Meccanica, 1988, Special Issue: 27–42
3 Bogaert V. Dynamic response of trains crossing large span double-track bridges. J Constr Steel Res, 1993, 24: 57–74
4 Wakui H, Matsumoyo N, Tanabe M. A study on dynamic interactions analysis for railway vehicles and structures-mechanical model and practical analysis method. Quarterly Report of Railway Technical Research Insitute, 1994, 35: 96–104
5 Specialists' Committee D214. RP5: Numerical investigation of the effect of track irregularities at bridge resonance-rail bridges for speeds>200 km/h. Technical Report, European Rail Research Institute, 1999
6 Specialists' Committee D214. RP9: Final report-Rail bridges for speeds>200 km/h. Technical Report, European Rail Research Institute, 1999
7 Xia H, Zhang N, Guo W W. Analysis of resonance mechanism and conditions of train-bridge system. J Sound Vib, 2006, 297: 810–822
8 Xia H, Zhang N. Dynamic analysis of railway bridge under high speed trains. Comput Struct, 2005, 83: 1891–1901
9 Zhai W M, Cai C B. Train/track/bridge dynamic interactions: Simulation and applications. Veh Syst Dyn, 2002, 37: 653–665
10 Zhai W M, Cai C B, Wang K Y, Numerical simulation and field experiment of high-speed train-track-bridge system dynamics. Veh Syst Dyn, 2004, 41: 677–686
11 Zhai W, Xia H, Cai C, et al. High-speed train-track-bridge dynamic interactions–part I: Theoretical model and numerical simulation. Int J Rail Transport, 2013, 1: 3–24
12 Zhai W, Wang S, Zhang N, et al. High-speed train-track-bridge dynamic interactions–part II: Experimental validation and engineering application. Int J Rail Transport, 2013, 1: 25–41
13 Arvidsson T, Karoumi R. Train-bridge interaction: A review and discussion of key model parameters. Int J Rail Transport, 2014, 2: 147–186
14 Ismail A, Jeng D S. Modelling load-settlement behaviour of piles using high-order neural network (HON-PILE model). Eng Appl Artif Intel, 2011, 24: 813–821
15 Zhao C, Leng W, Zheng G. Calculation and analysis for the time-dependency of settlement of the single-driven pile in double-layered soft clay. Appl Clay Sci, 2013, 79: 8–12

16 Song G, Gao M, Li G. Vehicle-bridge vertical system coupled vibration analysis under the uneven settlement of bridge pier and abutment (in Chinese). Chin Railway Sci, 2010, 31: 29–33
17 Wang S, Zhai W. Dynamic responses of high-speed train-track-bridge system under seismic excitations (in Chinese). J Southwest Jiaotong Univ, 2011, 45: 56–62
18 Chen Z W, Sun Y, Zhai W M. Mapping relationship between pier settlement and rail deformation of high-speed railways (I): The unit slab track system (in Chinese). Sci Sin Tech, 2014, 44: 770–777
19 Chen Z W, Sun Y, Zhai W M. Mapping relationship between pier settlement and rail deformation of high-speed railways (II): The longitudinal connected ballastless track system (in Chinese). Sci Sin Tech, 2014, 44: 778–785
20 Liu Z, Zeng M. Analysis on types and characteristics of bridge structures of Wuhan-Guangzhou railway passenger dedicated line (in Chinese). Railway Standard Design, 2013, 9: 54–58
21 TB10621-2009. Code for Design of High Speed Railway (in Chinese). Beijing: China Railway Publishing House, 2010