Seismic response law of suspension bridge-track system of high-speed railway

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Abstract
Taking a suspension bridge of (84 + 84 + 1092 + 84 + 84) m high-speed railway as an example, a nonlinear dynamic simulation model of long-span suspension bridge-tracks system is established. The seismic response characteristics of CWR system of railway suspension bridge under the action of multi-dimensional seismic waves are analyzed. The effects of design parameters such as initial temperature load mode and viscous damper on the seismic response of the system are discussed. Calculation results showed that the longitudinal seismic excitation has great influence on the steel rail stress on the adjacent bridges on both sides and the longitudinal shear force at the pier bottom, and the transverse seismic excitation has great influence on the steel rail stress on the main truss of the suspension bridge, the vertical seismic excitation has a great influence on the internal forces of the main cable and sling; the initial temperature load has a significant influence on the internal forces of the main cable and sling; by reasonably setting the damping coefficient and speed index of the viscous damper, it can effectively reduce the displacement at the end of the main tower pier beam and the bending moment at the bottom of the pier.

Keywords
High-speed railway, suspension bridge, continuous welded rail, seismic response, viscous damper

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Introduction
Scholars from all over the country have carried out detailed research on the interaction between long-span railway bridges and tracks with different structural systems. Zhu et al.¹ studied the deformation adaptability between (35 + 40 + 60 + 300 + 60 + 40 + 35)m long-span double tower cable-stayed bridge and ballastless track; Li et al.² studied the dynamic response distribution of deck and floor of the (90 + 240 + 630 + 240 + 90)m long-span steel truss cable-stayed bridge; Handong³ studied the longitudinal force characteristics of ballastless track on (35 + 40 + 60 + 300 + 60 + 40 + 35)m long-span hybrid beam cable-stayed bridge under different loads; Yan et al.⁴–⁶ proposed using the load step method considering the loading history to calculate the bending force and braking force of simply supported beam bridge, continuous
beam bridge and single tower cable-stayed bridge of high-speed railway; The longitudinal force distribution law of CWR on kilometer railway suspension bridge under the action of temperature, vertical live load and train braking is studied, and the influence law of key design parameters such as temperature load mode on the force of the system is discussed; The effects of various factors on the collision effect and pier stress of three span 32 m simply supported box girder bridge on The Shanghai-Kunming Railway are also studied. These studies of the above scholars did not consider the response of long-span bridges under multidimensional earthquake. In terms of the interaction law between bridge and track structure under earthquake conditions, Li et al. studied the dynamic response of long-span continuous beam arch bridge with span arrangement of (56 + 139 + 56) m under multi-point and multi-dimensional earthquake action; Yu et al. studied the dynamic response characteristics of 156 m long-span simply supported steel truss bridge track system under longitudinal traveling wave effect and vertical earthquake, and discussed the influence law of temperature changes before earthquake on the seismic response of the system; Weiankui studied the longitudinal bridge-track interaction and seismic response analysis of CWR on three types of bridge, upper through type, middle through type and lower through type; Kaqian et al. studied the seismic performance of double tower composite long-span cable-stayed bridge with 470 m main span and the influence of viscous damper parameters on the seismic performance of the bridge; Gao Jun et al. studied the selection of friction pendulum bearing setting scheme of (50 + 50 + 224 + 672 + 174 + 50 + 50 + 50) m double tower double cable plane long-span cable-stayed bridge; Shen Yu et al. the accuracy and effectiveness of using the endurance time method to predict the seismic collision response of (120 + 235 + 235 + 120) m long-span three tower double cable plane low tower cable-stayed bridge considering the traveling wave effect. The above are the research of arch bridge and cable-stayed bridge, but the multi-dimensional seismic analysis of long-span suspension bridge needs to be supplemented.

At present, when the new high-speed railway line crosses the Yangtze River, the Yellow River, and other large water areas, it puts forward higher requirements for the crossing capacity of the bridge. Among them, the railway suspension bridge is one of the options. Due to the flexible structural system and various components of suspension bridge, the bridge-track interaction is more complex after laying CWR on suspension bridge. Xie et al. and Yan have discussed in detail the nonlinear distribution characteristics of longitudinal force of CWR on high-speed railway suspension bridge, but the dynamic response law of CWR on Railway suspension bridge under earthquake has not been studied. In order to study the dynamic interaction characteristics of railway suspension bridge and track under earthquake, taking a (84 + 84 + 1092 + 84 + 84) m high-speed railway suspension bridge as an example, this paper establishes a refined simulation model of long-span suspension bridge-track system, analyzes the seismic response of suspension bridge CWR system under different seismic waves, and discusses the temperature load mode and influence law of the viscous damper parameters on the seismic response of the system.

**Engineering background**

Taking a (84 + 84 + 1092 + 84 + 84) m double tower continuous steel truss beam ground anchored suspension highway and railway combined bridge as an example, the North Tower is 203 m high, the south tower is 191 m high, and the bridge tower adopts box section. The main beam is a plate truss combined with steel truss beam and Warren truss. The cross section adopts the form of straight main truss with auxiliary truss. The spacing between the two main trusses is 30 m, the truss height is 16 m and the internode length is 14 m. There are two main cables in the whole bridge, which are composed of galvanized high-strength steel wires with a diameter of 1.3 m, and are connected to the top of the main tower through the main cable saddle. The transverse center distance between the two main cables is 43 m, the side span is 350 m, and the rise span ratio is 1/10. There are 154 slings in the whole bridge, with a spacing of 14 m. Double track passenger dedicated line and double track intercity railway are laid on the bridge, and the line spacing is 4.6 m. Rail expansion regulators are set at both ends of the main truss of the suspension bridge. The number of each pier of the bridge is shown at the pier bottom, and the structural elevation and section are shown in Figure 1.

**Simulation model of suspension bridge-track system of high-speed railway**

The analysis model of suspension bridge-track system is established. The steel truss section is simulated by beam element, the sling and main cable are simulated by rod element in tension, and the upper and lower deck are simulated by plate element. The top of the tower and the main cable, the end of the main beam and the ground, the sling and the main cable and the bridge deck are hinged. Six equivalent stiffness springs are used at the bottom of the bridge tower to simulate the pile group foundation. CHN60 type steel rail is adopted. According to UIC specifications, it is recommended to continue to extend the steel rail at both ends.
of the concrete continuous beam bridge (170 m here), and the distance between four track lines is 4.6 m. The vertical stiffness of rail fastener is taken as 60 MN/m.

See formula (1) for the relationship between longitudinal force and displacement of the line

$$r = \begin{cases} 7.5u & u \leq 2\text{mm No load} \\ 15.0 & u > 2\text{mm No load} \\ 11.6u & u \leq 2\text{mm loaded} \\ 23.2 & u > 2\text{mm loaded} \end{cases}$$  \hspace{1cm} (1)$$

Where: $r$ is the longitudinal resistance of the track and $u$ is the relative displacement of rail fastener.$^{16}$

See formula (2) for the value of horizontal resistance of the line.

$$r = \begin{cases} 4.5u & |u| \leq 2\text{mm} \\ 9 & |u| > 2\text{mm} \end{cases}$$  \hspace{1cm} (2)$$

Where: $r$ is the longitudinal resistance of the track and $u$ is the relative displacement of rail fastener.$^{5}$

Establish the following verification model, as shown in Figure 2.

The calculation example of C.5 continuous beam bridge in appendix of UIC774-3-2001$^{15}$ is analyzed with the verification model, and the results are shown in Table 1.

The maximum error between the calculated results and the UIC value is only 0.72%, which proves that the model can be used to study the beam rail interaction.

The system adopts Rayleigh damping, the damping ratio is taken as 0.05, and the damping coefficient $\alpha$ and $\beta$ are taken according to formula (3):

$$\alpha = 2h \frac{w_1 w_2}{w_1 + w_2} \quad \beta = 2h \frac{1}{w_1 + w_2}$$  \hspace{1cm} (3)$$
$w_1$ and $w_2$ are the first-order frequencies and the first-order frequencies that contribute the most to the longitudinal vibration mode of the structure. The established finite element model is shown in Figure 3.

**Seismic response of suspension bridge-track system**

**Influence of different seismic waves**

According to the standard, the peak ground acceleration is set as 0.57g and the characteristic period of ground acceleration response spectrum is 0.35 s. El-Centro seismic wave, Taft seismic wave and Hollywood seismic wave are used for time history response analysis respectively, as shown in Figure 4.

It can be seen from Figure 4 that the rail stress, additional internal force of main cable and additional internal force of sling in the middle part under the excitation of Hollywood seismic wave are significantly greater than those under the excitation of El-Centro seismic wave and Taft seismic wave. On the contrary, the additional stress of the sling on both sides excited by Taft seismic wave exceeds that generated by Hollywood seismic wave. The influence of Hollywood seismic wave on the bottom shear of piers 5, 6, 7, 8, 9, and 10 is much greater than Taft seismic wave and El-Centro seismic wave, but under the excitation of Hollywood seismic wave and Taft seismic wave. The bottom shear forces of 1, 2, 3, 4, 11, 12, 13, and 14 piers are similar. Therefore, when checking the stress and strain of different parts, appropriate seismic waves should be considered.

**Influence of different seismic excitation directions**

This section discusses the influence of seismic excitation in different directions of the same seismic wave on the seismic response of long-span suspension bridge-track system. Select El-Centro seismic wave, set the maximum acceleration of seismic wave to 0.57g, and set longitudinal, transverse and vertical seismic excitation respectively. Figure 5 is the stress of the system under seismic excitation in three directions.

It can be seen from Figure 5 that the positions of rail stress excited by seismic waves in different directions are different. Under the longitudinal seismic excitation, the rail stress of continuous beams on both sides is the largest, but the rail stress on the main truss of suspension bridge is relatively the smallest; Under lateral seismic excitation, the rail stress on the main truss of suspension bridge is the largest, but the rail stress of continuous beams on both sides and the peak value of rail stress at the junction of continuous beam and subgrade are relatively minimum; The vertical seismic excitation is in the middle state.

Under vertical seismic excitation, the additional internal force of main cable and sling is the largest, especially at both sides and mid span. The additional internal force of the main cable is the smallest under the seismic excitation in the transverse direction, while the additional internal force of the suspender is the smallest under the seismic excitation in the longitudinal direction.
Under the longitudinal seismic excitation, the longitudinal shear force at the pier bottom is the largest. Except for No. 5 and No. 10 piers, the pier bottom shear force is the smallest under vertical seismic excitation, the pier bottom shear force of other piers is the smallest under transverse seismic excitation.

Therefore, when designing and checking the long-span high-speed railway suspension bridge, the longitudinal seismic excitation should be considered when controlling the rail stress on the continuous beams on both sides and the longitudinal shear force at the pier bottom; Lateral seismic excitation should be considered when controlling the rail stress on the main truss of suspension bridge; Vertical seismic excitation should be

Figure 4. System stress under different seismic waves: (a) rail stress envelope, (b) maximum internal force of main cable, (c) maximum internal force of sling, and (d) maximum longitudinal shear force at pier bottom.

Figure 5. System stress under different direction of seismic wave: (a) rail stress envelope, (b) maximum internal force of main cable, (c) maximum internal force of sling, and (d) Maximum longitudinal shear force at pier bottom.
considered when controlling the additional internal force of main cable and sling.

**Effect of initial temperature load mode on seismic response**

According to the Code for Design of Railway Continuous Welded Rail, two, considering the temperature change of steel main truss is ±25°C, concrete continuous beam is ±15°C and main cable sling is ±40°C, the working conditions are shown in Table 2.

Using the analysis method considering the loading history described in reference, the system stress of long-span suspension bridge-track system excited by El-Centro seismic wave (0.57 g) under the condition of initial temperature load is studied, as shown in Figure 6.

It can be seen from Figure 6 that compared with the single action of earthquake, the influence of temperature rise and temperature drop conditions on rail stress under temperature load is the same, and the direction is opposite. The maximum increase range of rail stress at the junction of continuous beam and subgrade is 111.9%; The temperature drop of main cable and sling has a great influence on its additional internal force, while the temperature rise is relatively small. The maximum increase range of main cable internal force is 290.5%, and the maximum increase range of sling internal force is 384.9%; When the temperature rises at piers 1, 2, 5, 6, 8, and 11, the longitudinal shear force at the bottom of pier is significantly higher than that when the temperature drop; when the temperature drop at piers 4, 7, 9, 10, 13, and 14, the longitudinal shear force at the bottom of pier is significantly higher than that when the temperature rise; when the temperature rise and drop at piers 3 and 12, the influence of the working conditions of temperature rise and temperature drop is small; the maximum increase of the longitudinal shear force at the bottom of pier 14 is the largest, which is 97.0%.

Compared with the temperature change of only the main truss continuous beam, the simultaneous temperature change of the main truss, continuous beam, and main cable sling is 6°C, and that of continuous beam is 15°C, and that of main cable sling is 40°C.

| Working condition | Temperature load mode |
|-------------------|-----------------------|
| I                 | Temperature load is not considered |
| II                | The temperature rise of main truss is 25°C, and that of continuous beam is 15°C |
| III               | The temperature rise of main truss is 25°C, the temperature rise of continuous beam is 15°C, and the temperature rise of main cable sling is 40°C |
| IV                | The temperature drop of main truss is 25°C, and that of continuous beam is 15°C |
| V                 | The temperature drop of main truss is 25°C, that of continuous beam is 15°C, and that of main cable sling is 40°C |

**Figure 6.** System stress under different temperature load modes: (a) rail stress envelope, (b) maximum internal force of main cable, and (c) maximum internal force of sling, and (d) maximum longitudinal shear force at pier bottom.
main cable, and sling has a significant impact on the rail stress, the internal force of the main cable and sling, and has little impact on the longitudinal shear force at the bottom of the pier. Therefore, when calculating the rail stress and the internal force of the main cable and sling, the temperature changes of the main cable and sling should be considered together; When calculating the longitudinal shear force at the pier bottom, the temperature change of main cable and sling can be properly ignored.

**Effect of viscous damper on seismic response of suspension bridge-track system**

Viscous damper is made according to the principle of throttling resistance when the fluid passes through the orifice. It is a damper related to the moving speed of the piston. The damping force generated is calculated according to formula (4).

\[ F = CV^a \]  

(4)

\( F \) is the damping force (kN), \( C \) is the damping coefficient (kN·(s/m)^a), and \( a \) is the speed index.

The speed index \( a \) and the damping coefficient \( C \) in the calculation formula have an influence on the performance of the damper, especially the former. The effects of speed index \( a \) and damping coefficient \( C \) on long-span suspension bridge-track system are considered respectively. The selected working conditions are shown in Table 3.

Maxwell model is used to simulate the viscous damper, which is set at the pier top where the main truss is located (Pier 5–10).

Under the longitudinal seismic excitation of El-Centro wave (0.57 g), the beam end displacement and pier bottom bending moment of No. 7 pier of the main tower pier of the long-span suspension bridge-track system are shown in Figure 7.

It can be seen from Figure 7 that when the damping coefficient \( C = 1000–7000 \), the beam end displacement of the pier decreases with the increase of the damping coefficient \( C \), but when \( C = 10,000 \), the beam end displacement is larger than that when \( C = 7000 \). When the speed index \( a = 0.2–0.8 \), the beam end displacement increases with the increase of speed index \( a \). The minimum displacement is obtained when \( C = 7000 \) and \( a = 0.2 \), and the minimum displacement is 41.3 mm.

When the damping coefficient \( C = 1000–7000 \), the pier bottom bending moment decreases with the increase of damping coefficient \( C \), but when \( C = 10,000 \), the pier bottom bending moment is larger than that when \( C = 7000 \). When the damping coefficient \( C = 5000–10,000 \), when the damping coefficient \( C \) is fixed, the bending moment at the pier bottom when the speed index \( a = 0.4 \) is smaller than when \( a \) takes other values. The minimum bending moment at the pier bottom is obtained when \( C = 7000 \) and \( a = 0.4 \), and the minimum bending moment is 945.2 MN·m.

Through the above analysis, the most suitable parameter combination is obtained through the analysis and comparison of the response of suspension bridge-track system under seismic excitation with different damping parameters after setting viscous dampers.

| The damping coefficient \( C \) (kN·(s/m)^a) | 1000 | 3000 | 5000 | 7000 | 10,000 |
|--------------------------------------------|------|------|------|------|--------|
| The speed index \( a \)                    | 0.2  | 0.2  | 0.2  | 0.2  | 0.2    |
|                                            | 0.4  | 0.4  | 0.4  | 0.4  | 0.4    |
|                                            | 0.6  | 0.6  | 0.6  | 0.6  | 0.6    |
|                                            | 0.8  | 0.8  | 0.8  | 0.8  | 0.8    |
The working condition with the minimum displacement at the beam end is \( C = 7000 \) and \( a = 0.2 \), which is set as working condition I; The working condition with the minimum bending moment at the pier bottom is \( C = 7000 \) and \( a = 0.4 \), which is determined as working condition II. The comparison of the effects of the two working conditions is shown in Table 4.

It can be seen from Table 4 that the damping effect of viscous damper on long-span suspension bridge-track system is obvious, which can effectively reduce the displacement and stress under seismic excitation. Therefore, it can be considered to select viscous damper with reasonable parameters as the damping and seismic measures of long-span high-speed railway suspension bridge.

**Conclusion**

This paper mainly discusses the influence of different key influencing factors of the system on the seismic excitation of railway suspension bridge-track system, and discusses the stress-strain law of different components of the system. The main conclusions are as follows:

(1) Under the excitation of El-Centro seismic wave (the peak acceleration is set as 0.57g), the rail stress distribution of CWR on suspension bridge is relatively balanced, and the rail stress at the end of suspension bridge reaches the peak, up to 23.6 MPa.

(2) Different dimensional seismic waves have different effects on different parts of the long-span suspension bridge-track system. The longitudinal seismic excitation has a great impact on the rail stress on the continuous beams on both sides and the longitudinal shear force at the pier bottom, the transverse seismic excitation has a great impact on the rail stress on the main truss of the suspension bridge, and the vertical seismic excitation has a great impact on the internal forces of the main cable and sling.

(3) Compared with only considering seismic load, after considering temperature load, the internal forces of main cable and sling change significantly, and the maximum increases can reach 290.5% and 384.9%. The changes of rail stress and longitudinal shear force at pier bottom are relatively small. Compared with only considering the temperature changes of the main truss and continuous beam, considering the temperature changes of the main truss, main cable, sling and continuous beam at the same time has a significant impact on the rail stress.

(4) The speed index of viscous damper has great influence on the displacement of pier beam end and little influence on the bending moment at pier bottom; The damping coefficient has a great influence on the beam end displacement and the bending moment at the bottom of the pier. Through simulation calculation, the damping coefficient is 7000. When the speed index is 0.2, the displacement at the beam end is relatively small, and when the speed index is 0.4, the bending moment at the pier bottom is relatively small.

**Declaration of conflicting interests**

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**Data availability statement**

All data, models, and code generated or used during the study appear in the submitted article.

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