Seismic input methods in coupled system of train-track-bridge

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Abstract. To research the influence of seismic input method on the seismic response of train-track-bridge system, four methods are adopted to input non-uniform seismic excitation, including direct solving method, relative motion method, large mass method and large stiffness method. Train-track-bridge dynamic analysis models under different seismic input methods are established. Taking rigid frame-continuous composite beam bridge with the span of (48+5×80+48) m as an example, the seismic responses of coupled system of train-track-bridge under different seismic input methods are compared. The results show that the seismic responses of vehicle and bridge system from large stiffness method and direct solving method are the same, derailment coefficients and the rates of wheel load reduction from large mass method are bigger than that from direct solving method, the maximum deviation reaches 44.0% and 26.4%; the derailment coefficients, the rates of wheel load reduction and bridge displacements from relative motion method are smaller than that from direct solving method with maximum deviation of 32.5%, 12.8% and 51.9% respectively. As large stiffness method only requires the input of dynamic displacement time-history, so it is more convenient than direct soling method.

1. Introduction

China faces the Pacific seismic belt in the east and lies in Eurasian seismic belt in the west with distribution of seismic zone. The possibility that the high-speed railway bridge is in earthquake-prone areas is high, the influence that the earthquake research has on safe running of trains on high-speed railway bridge is inevitable. As for the engineering sites where the long-span bridge lies, the spatial variability of seismic oscillation is obvious [1], the bearing force displacements that the structure experiences at different supporting nodes might be different. Thus non-uniform excitation model of seismic oscillation input must be adopted when studying the dynamic response of the long-span bridge under earthquake and the safe running of the train.

At present, scholars have adopted different methods in vehicle-bridge system to realize non-uniform seismic excitation input [2-6]. Due to the difference of function mechanism of different seismic input methods, the seismic responses of the same system with the same input may be different. So far, the studies on input methods of non-uniform seismic excitation in coupled system of train-track-bridge is scanty. On the basis of previous researches [7], based on train-track-bridge dynamic interaction theory, this thesis adopts direct solving method, relative motion method, large mass method and large stiffness method respectively to establish train-track-bridge dynamic analysis models under different seismic input methods, taking rigid frame-continuous composite beam bridge with the span of (48+5×80+48) m as an example, calculates the seismic responses of coupled system of train-track-bridge under different seismic input methods and discuss the influences of different seismic input methods have on seismic responses of coupled system of train-track-bridge.

2. Dynamic model of train-track-bridge system under earthquakes

The train-track-bridge dynamic analysis model with seismic function is a strong nonlinear and time-varying system composed of six parts, that is, train model, track model, bridge model, wheel-rail relation model, bridge-track relation model and seismic force boundary conditions, as shown in figure 1. The train in this study is a four-axle locomotive model with 35 degree of freedom, and the ballasted track structure is considered into the track. The train also goes through three-tier elastic supports brace summer simulation, the bridge adopts finite element model of spatial bar system. The detailed parameters of the track and train is shown in reference [8]. In the calculation, bridge-track relation is taken as the function of state variables of bridge and track motion. The coupled relation model of ballasted track and bridge is shown in reference [9]; supposing the contact between bridge and track is rigid, and the detachment is allowed, Hertz's nonlinear elastic contact theory should be adopted to solve the normal contact. Kaller's Linear creep theory should be adopted to solve the tangential force, and both should be nonlinearly revised by Shen Zhiyun-Hedrick-Elkins theory [10].
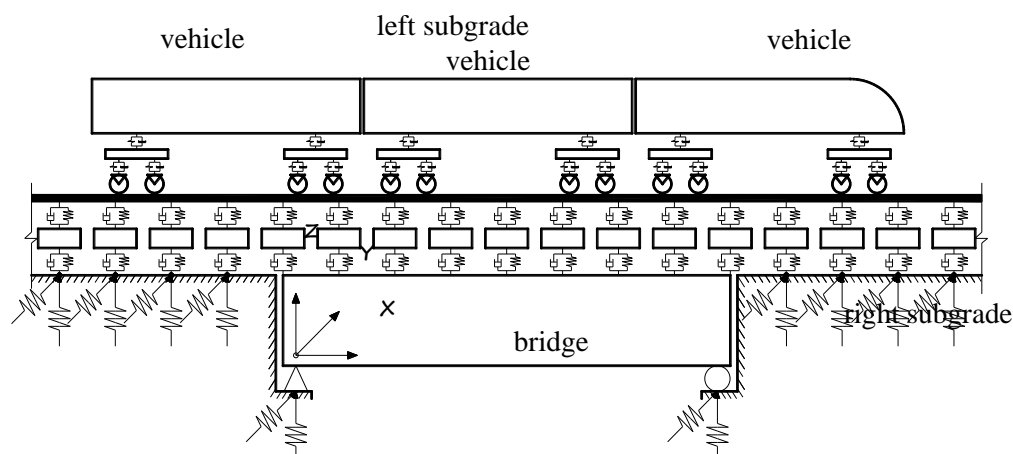

Figure 1. Dynamic model of train-track-bridge coupling system subjected to earthquakes

3. Case Study

3.1. Design parameter

The object of analysis is rigid frame-continuous composite beam bridge with certain span (48+5×80+48) m; design speed is 300km/h; double track; the site is located in field I, general layout is showed in figure 2. The single cell box girder with variable sections is adopted in the girder; bridge roadway width is 12.2m; depth of beam in the middle pivot is 7.0m; beam depth of mid-span center and side-span end is 4.0m. The conduct of emulating calculation adopts the finite element model of spatial bar system; the simulation of girder and pier adopts the spatial beam element; the top of movable pier and girder centroid are connected by master-slave degree of freedom; the top of rigid frame and girder centroid are consolidated by yoke; the boundary of pier bottom may be dealt with rigid frame consolidation without considering the impact of subgrade. The dead load of the second phase is 144.0kN/m; structural damping ratio is 2%; integration step of time-history is 0.1ms; track irregularity is simulated by German track spectrum with low interference.
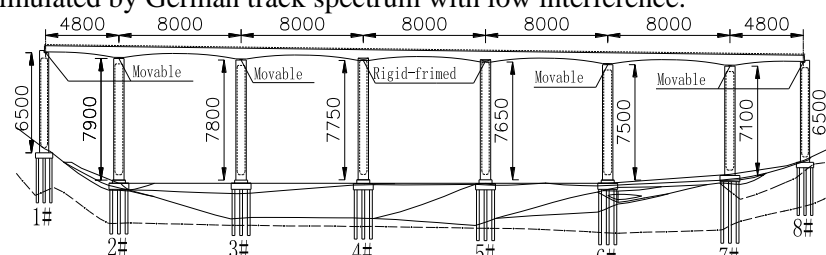

Figure 2. General Layout of Rigid-continuous Composite Beam Bridge

Taking the horizontal component L09291 of San Fernando earthquake (1971/02/09 14:00) in foreign representative earthquake record as the input, record station is 127 Lake Hughes #9. To eliminate the "zero drift" phenomenon of seismic wave speed and displacement time-history, the original acceleration needs to conduct a band pass filtering treatment. The band pass width is 0.5-35.0Hz, the treated acceleration a_g, speed v_g and displacement d_g is showed in figure 3.
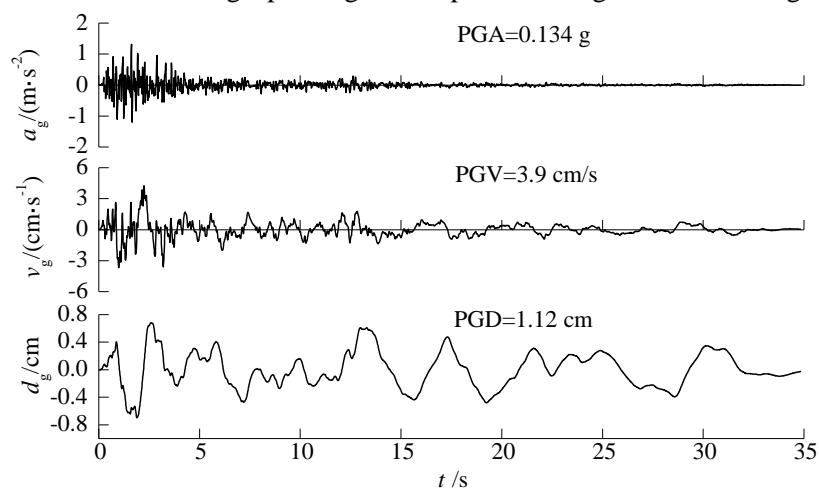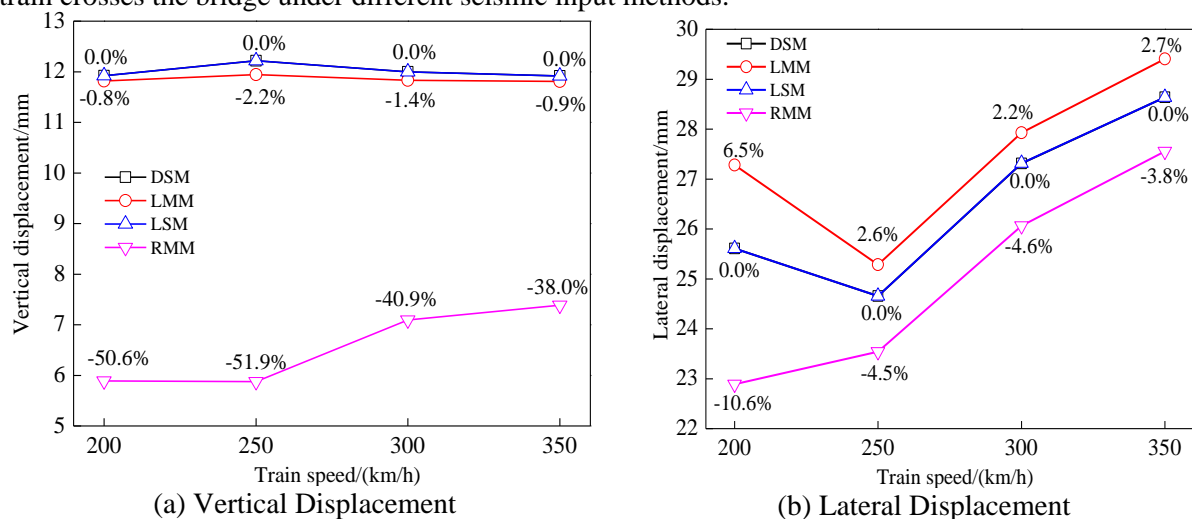

Figure 3. Inputting time-history of seismic wave

The above seismic wave is input simultaneously along lateral and vertical in all supporting nodes of sub-grade and bridge. The direct solving method (DSM), large mass method (LMM), large stiffness method (LSM) and relative motion method (RMM) may be adopted respectively in calculating the seismic response of axle system when single-track high-speed train crosses the bridge with the speed of 200, 250, 300 and 350km/h.

3.2. Dynamic responses analysis of bridge.
The maximum value difference between bridge's displacement and acceleration response under different seismic input methods is being studied. Figure 4 are the changing curves of the maximum value of bridge's mid-span displacement with the change of train speed when single-track high-speed train crosses the bridge under different seismic input methods.

(a) Vertical Displacement   (b) Lateral Displacement

Figure 4. Displacement Amplitude of Bridge's Mid-span with Train Speed

As can be seen from figure 4, the maximum values of vertical displacement solved by large mass method under different train speed are lower on average relative to direct solving method, and the maximum deviation is 2.2%; while the maximum values of horizontal displacement are larger on average, and the maximum deviation is 6.5%. The maximum values of lateral and vertical displacement solved by large stiffness method are completely the same with direct solving method. The maximum values of lateral and vertical displacement solved by relative motion method are lower on average relative to direct solving method, and the maximum deviations are up to 51.9% and 10.6% respectively. By comparing the relative error of vertical and lateral displacements under different train speeds, we could see that there aren't big changes on the relative errors of the three methods with the increase of train speed.

Thus it can be seen that, the bridge response waveforms obtained by using different seismic input method are similar, but there are some differences between maximum values. Of these differences, the bridge response obtained by using large mass method has little deviation compared with that obtained from direct solving method, with only 6.5% for the largest displacement and only 3.6% for acceleration. The bridge response under the large stiffness method is identical to that gained by using direct solving method. The bridge displacement obtained by using relative motion method is smaller than that obtained by using direct solving method, while the accelerations are larger, so do the deviations. The maximum deviation for displacement and acceleration reaches to 51.9% and 17.6% respectively. As a result, seismic input method exerts a larger influence on the dynamic response for bridge subsystem in the coupled system of train-track-bridge.

3.3. Analysis of train's dynamic responses

Under different seismic input method, the differences in maximum value of train's dynamic response are studied. Figure 5 show that the maximum value changing curves of the derailment coefficient and the wheel load reduction rate, change with train speed.

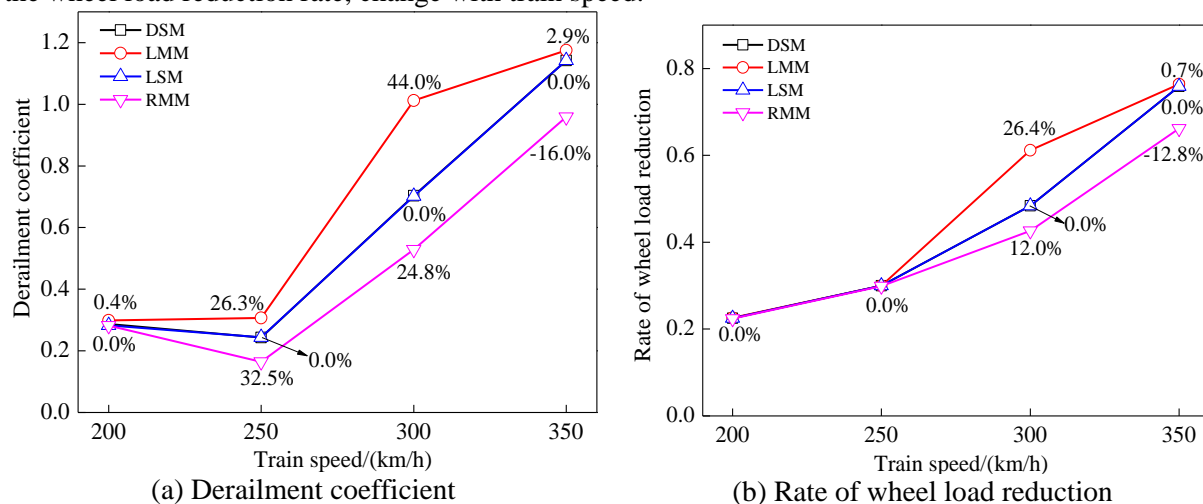(a) Derailment coefficient   (b) Rate of wheel load reduction

Figure 5. Train's rate of wheel load reduction amplitude with train speed

As can be seen in figure 5, under different speed, the maximum values of derailment coefficient and wheel load reduction rate, gained by using large mass method, are all larger than those gained by using direct solving method, with the maximum deviation of 44.0% and 26.4% respectively. The maximum value of derailment coefficient gained by using large stiffness method is almost the same as that gained by using direct solving method, with the maximum deviation of only 1.4%, and the maximum value of wheel load reduction rate is the same as that gained by using direct solving method. The maximum values of derailment coefficient and wheel load reduction rate gained by using relative motion method are all smaller than those gained by using direct solving method, with the maximum deviation of 32.5% and 12.8% respectively. Thus it can be seen that, seismic input method exerts a

greater influence on train's dynamic response, especially on derailment coefficient and rate of wheel load reduction.

4. Conclusions

(1) The influence of seismic input method on bridge dynamic response and waveform of vehicle dynamic response is little, while the influence on its amplitude is larger.

(2) Train dynamic response, especially train's derailment coefficient and rate of wheel load reduction will be over-estimated when inputting seismic excitation by using large mass method. Under the calculation condition of this paper, when train speed is between 200km/h and 350km/h, the derailment coefficient and the rate of wheel load reduction gained by using large mass method are all larger than those gained by using direct solving method, with the maximum deviation of 44.0% and 26.4% respectively.

(3) Train's dynamic response and bridge displacement will be under-estimated when inputting seismic excitation by using relative motion method, which may cause the calculation results towards insecurity. Under the calculation conditions of this paper, when the speed is between 200km/h and 350km/h, the derailment coefficient, rate of wheel load reduction and bridge displacement gained by using relative motion method are all smaller than those gained by using direct solving method, with the maximum deviation of 32.5%, 12.8% and 51.9% respectively.

(4) In coupled system of train-track-bridge, inputting seismic excitation by large stiffness method is completely identical to that gained by direct solving method. Because only seismic oscillation displacement time-history needs to be inputted when using large stiffness method, that its calculation is much simpler compared with direct solving method. As a result, in the coupled system of train-track-bridge, large stiffness method is the optimal method to input non-uniform seismic excitation.

Acknowledgments

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