

Running safety of high-speed train on rigid frame bridge subjected to earthquakes

H J Lei¹ and J Z Huang¹

¹School of Civil Engineering, FuJian University of Technology, Fuzhou 350118, China.

Abstract. To research the running safety when high-speed train running over a high-pier rigid frame bridge subjected to earthquakes, a coupling vibration model is set up based on the train-track-bridge dynamic interaction theory. In this model, the seismic action is solved by the relative motion method and the ballast track is simulated by the elastic point support model with three layers. As an example, a high-pier rigid frame bridge with spans of (88+168+88) m is modelled, and the dynamic responses of vehicle and bridge system under El Centro seismic wave are calculated. The analysis results show that the dynamic responses of the high-pier rigid frame bridge present weakly coupled in plane and out plane, moreover the running safety of the train is decreased along with the increase of seismic amplitude and train speed. In addition, the most threat direction to the running safety of the train on bridge is transverse, and the running safety threshold of ICE3 subjected to 7 degree, 8 degree and 9 degree frequent seismic is 275, 250 and 225 km/h.

1. Introduction

Earthquake induced ground movements may cause intense bridge vibrations, which would affect the safety of bridge structures and the running trains. In the southwest mountainous area of China, the topography is varied and complicated, where the new railways will inevitably span many deep canyons and a lot of bridges with high peers are constructed. And, at the same time, earthquake frequently occur in mountainous area, which greatly increases the probability of trains on bridges when an earthquake occurs. So, as to the bridges with high peer in mountainous area, it is significant to research the running safety of trains on bridge when an earthquake occurs. The dynamic behavior of train-bridge coupling systems subjected to earthquake has been studied by many researchers ^[1-7]. Up to now, as to the bridges with high peer in mountainous area, there have not been publications on the coupling vibration of seismic-train-track-bridge system and the running safety of trains with the track model taken into account.

In this paper, based on the theory of train-track-bridge dynamic interaction, a dynamic model of train-track-bridge systems under seismic excitations is established. A high-pier rigid frame bridge with spans of 88+168+88 m is taken as a case study. By input El Centro seismic wave, the directions of seismic input on the dynamic responses of vehicle and bridge system are studied. Then, as to the frequent seismic of 7, 8 and 9 degree, the running safety of a high-speed train running over the bridge is analyzed and the running safety threshold is obtained.

2. Dynamic Model of Train-Track-Bridge System under Earthquakes

The dynamic analysis model of train-track-bridge system under earthquakes can be regarded as a spatial dynamic system composed of the vehicle model, the track model, the bridge model and the



boundary conditions of seismic. Seismic ground motions at the supports of the bridge are taken as the external excitations, which act on the track subsystem through the conditions of displacement harmony and static equilibrium on the interface of the bridge subsystem and the track subsystem. Then, the earthquake action acts on the train subsystem through wheel/rail contact relationship. The dynamic equation of train-track-bridge system under earthquakes can be expressed as

$$\begin{cases} \mathbf{M}_v \ddot{\mathbf{u}}_v + \mathbf{C}_v \dot{\mathbf{u}}_v + \mathbf{K}_v \mathbf{u}_v = \mathbf{P}_{tv} \\ \mathbf{M}_t \ddot{\mathbf{u}}_t + \mathbf{C}_t \dot{\mathbf{u}}_t + \mathbf{K}_t \mathbf{u}_t = \mathbf{P}_{vt} + \mathbf{P}_{bt} \\ \mathbf{M}_b \ddot{\mathbf{u}}_b + \mathbf{C}_b \dot{\mathbf{u}}_b + \mathbf{K}_b \mathbf{u}_b = \mathbf{P}_{tb} + \mathbf{P}_{gb} \end{cases} \quad (1)$$

where the \mathbf{M} , \mathbf{C} and \mathbf{K} denote the mass, damping and stiffness matrices, respectively; $\ddot{\mathbf{u}}$, $\dot{\mathbf{u}}$ and \mathbf{u} the acceleration, velocity and displacement vectors, with the subscripts v, t, and b representing the vehicle, track and bridge subsystem, respectively; \mathbf{P}_{tv} and \mathbf{P}_{vt} are the interaction force vector of the vehicle subsystem and the track subsystem each other, which are determined by the geometric constraint relationship on the interface of wheel/rail [8]; \mathbf{P}_{bt} and \mathbf{P}_{tb} are the interaction force vector of the bridge subsystem and the track subsystem each other, which are determined by the relations of interaction between the bridge subsystem and the track subsystem [9]; \mathbf{P}_{gb} is the earthquake load vector at the supports of the bridge, which is determined by the boundary conditions of seismic.

Based on the previous studies, the input module of the seismic force is increased and a new program is formed for solving the dynamic responses of train-track-bridge coupling system under earthquakes, Train-Track-Bridge-Seismic Analysis System (TTBSAS) [10].

3. Case Study

3.1. Design parameter

In this paper, a high-pier rigid frame bridge, with spans of 88+168+88 m, design speed of 250km/h, double line space of 5.0m and on the Changsha-Kunming high-speed railway in China, is taken as a research example, the general arrangement as shown in Figure 1.

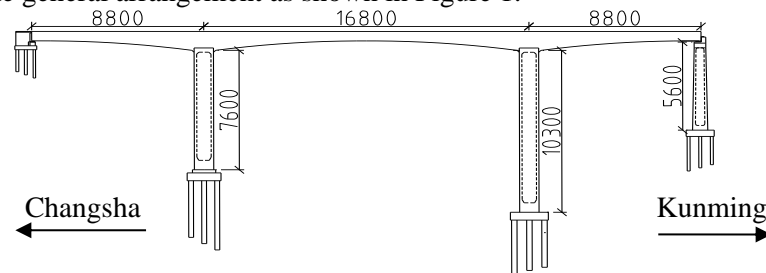


Figure 1. General layout of main bridge (Units: cm)

The total length of the bridge is 466m and the wide is 12m. The main bridge with the length of 344m is designed as a five-span one-coupling of 88+168+88 m prestressed concrete rigid frame bridge. The thin-walled hollow pier that section dimension is 10×9m and thickness of the wall is 1.1m is once variable slope with transverse outer slope of 15:1 and transverse within slope of 10:1. The highest pier is 103m in height. The concrete grade of main beam and pier are respectively C55 and C35. The secondary dead load is 144kN/m.

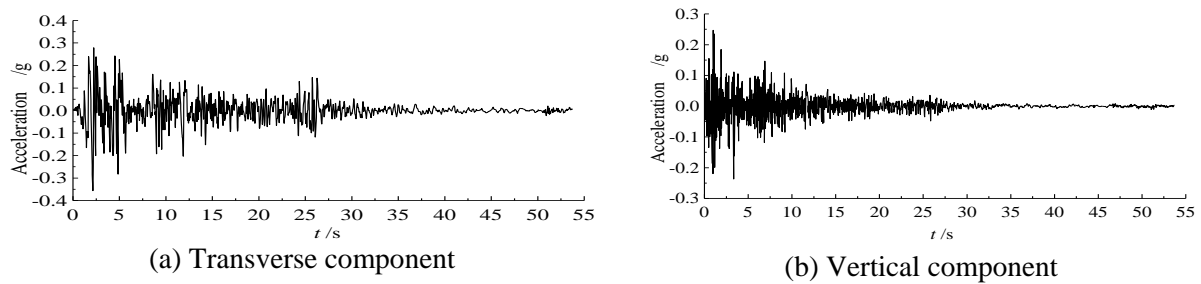


Figure 2. Input earthquake waves

The earthquake action can be input the coupling system. In our research, a classical earthquake record named El Centro is taken as the input earthquake wave, which is occurred in 1940 and the recording station is located in EL CENTRO ARRAY #9, the waves as shown in Figure 2.

3.2. Influence of the directions of seismic input

To investigate dynamic response of seismic coupling system with the changes of the directions of seismic input, normalized El Centro seismic wave of 0.14g is inputted respectively along the longitudinal X, lateral Y, vertical Z, three all XYZ and calculate the dynamic response of the system when ICE3 high-speed train travers the bridge with the design speed of 250km/h on the single-line, the maximum statistical results as shown in Table 4. Among them, the number 1 to 4 denotes the four calculated conditions, respectively; C is the short name of the calculated conditions.

Table 1. Maximum dynamic response of the vehicle and bridge in different seismic wave directions

C	dv	dt	av	at	Q/P	$\Delta P/Q$	Q
1	28.72	0.87	0.2483	0.0039	0.1443	0.3848	10.9
2	9.27	63.04	0.0234	0.4225	1.0205	0.6019	99.1
3	13.78	0.86	0.3211	0.0039	0.1417	0.3757	10.7
4	31.12	63.10	0.3146	0.4212	0.9113	0.5538	80.6

Table 1 shows : (1) Vertical displacement: The vertical displacement of working condition 1 is close to the working condition 4's and is a little less than the working condition 4's, and the vertical displacements of other working conditions are much smaller than the working condition 4's. Therefore, the longitudinal ground motion and the vertical ground motion contribute to the vertical displacement of high-pier rigid frame bridge, and the longitudinal ground motion contributes more than the vertical ground motion.

(2) Vertical acceleration: The vertical acceleration of working condition 3 is close to the working condition 4's and the others are less than the working condition 4's. Therefore, the vertical ground motion is the main factor causing the vertical acceleration of high-pier rigid frame bridge;

(3) Lateral displacement and lateral acceleration: The lateral displacements and lateral accelerations of working condition 2 and 4 are almost identical, and the others are much smaller. Therefore, the lateral ground motion is the main factor causing the lateral vibration of bridge;

(4) Running safety indexes: The vehicle derailment coefficient, reduction rate of wheel load, rail lateral force of working condition 2 are larger than the working condition 4's, and they are far larger than the working condition 1's and 3's. Therefore, the lateral ground motion is the main factor that threatens the running safety of train for a high-pier rigid frame bridge, and threatens the ICE3 high-speed train greatest while inputted separately.

3.3. Running safety of train

From the above analysis, the lateral ground motion threatens the ICE3 high-speed train greatest while inputted separately for a high-pier rigid frame bridge. The frequent earthquakes of 7、8、9 fortification intensity are selected for analysis with reference to Code for Seismic Design of Railway

Engineering (GB 50111-2006) for the ICE3 high-speed train. El Centro seismic wave is inputted only along the lateral direction of the bridge corresponding that the peaks of horizontal earthquake acceleration are respectively 0.05g, 0.10g, 0.14g. The analysis speed changes from 200km/h to 350km/h at intervals of 25km/h. The maximum dynamic response of the mid-span of the main girder of the high-pier rigid frame bridge is shown in Table 2, when the ICE3 high-speed train traverses the bridge with the design speed of 250km/h under different seismic fortification intensities.

Table 2 shows that the vertical displacement and vertical acceleration of bridge change a little under different seismic fortification intensities, and the lateral displacement and lateral acceleration increase with the seismic fortification intensity. The variation of dynamic response of the bridge is consistent with above, and it shows a weak coupling feature of the dynamic response of in-plane and out of plane of the bridge under earthquakes. In the 7, 8, 9 fortification intensity area, the lateral displacements of main beam are respectively 24.6mm, 48.5mm, 67.7mm, and lateral vibration with large amplitude of high-pier rigid frame bridge is induced by seismic load.

Table 2. Maximum dynamic response of the bridge in different seismic fortification intensity

Amplitude	/	7	8	9
	0.00g	0.05g	0.10g	0.14g
dv	7.12	7.10	7.13	7.15
dt	0.66	24.57	48.49	67.72
av	0.02	0.02	0.02	0.02
at	0.01	0.16	0.33	0.45

The variation curves between running safety index of ICE3 high-speed train and speed are shown in Figure 3 under different seismic fortification intensities.

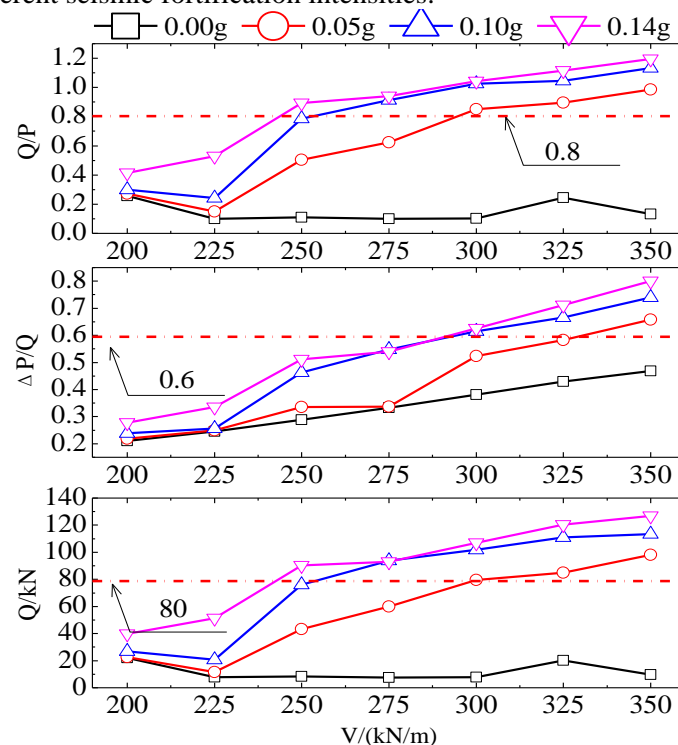


Figure 3. Running safety indexes for speed in different seismic fortification intensity

Figure 3 shows, as the seismic fortification intensity and seismic load increase, the vehicle derailment coefficient, reduction rate of wheel load, rail lateral force and other safety indexes increase as well. The growth rate of running safety of train gradually decreases with the increase of speed.

According to the limit value of running safety of train, the safe speed can be counted under different seismic intensities, and then the safety threshold is got when ICE3 high-speed train travers the high-pier rigid frame bridge under different seismic intensities as shown in Table 3.

Table 3. Safety speed of the bridge in different seismic fortification intensity

Seismic intensity	Safety speed (km/h)			Threshold (km/h)
	Q/P	$\Delta P/Q$	Q	
/	200~350	200~350	200~350	—
7	200~275	200~325	200~275	275
8	200~250	200~275	200~250	250
9	200~225	200~275	200~225	225

Table 3 shows that the limit value of safe speed of high-pier rigid frame bridge decreases with the increase of seismic intensity, and the limit value of safe speed under derailment coefficient is always minimum. Therefore, it is on the safe side that the running safety of train under the action of earthquake is judged by derailment coefficient directly for the high-speed rigid frame bridge. Taking the limit value of safe speed under the derailment coefficient as the threshold, the threshold of safe speed are respectively 275, 250 and 225km/h when ICE3 high-speed train travers the bridge at 7, 8, 9 fortification intensity under frequent earthquake.

4. Conclusions

(1) It shows a weak coupling feature of the dynamic response of in-plane and out of plane of the high-pier rigid frame bridge under earthquakes, and the vertical and lateral vibration produced respectively by longitudinal and vertical ground motion in-plane and lateral ground motion out of plane, but it shows a strong coupling feature of the dynamic response of train on the bridge.

(2) For high-pier rigid frame bridge, the lateral seismic wave is the main factor that threatens the running safety of the train on the bridge, and that the seismic wave is inputted only along the transverse direction of bridge is the biggest threat to the running safety of train.

(3) It is on the safe side that the running safety of train under the action of earthquake is judged by derailment coefficient directly for the high-speed rigid frame bridge. According to the calculation in the condition of the paper, the threshold of safe speed are respectively 275, 250 and 225km/h when ICE3 high-speed train travers the bridge at 7, 8, 9 fortification intensity under frequent earthquake.

Acknowledgments

This research was supported by the Natural Science Foundation of Fujian Province (Grant No. 2016J05108), the Natural Science Foundation of China (Grant No.51608120), the Education Scientific Research Project of Youth Teacher in the Education Department of Fujian Province (Grant No. JA15333) and the Scientific Research Foundation of School (Grant No. GY-14077).

References

- [1] Xia H, Han Y and Zhang N 2006 Dynamic analysis of train-bridge system subjected to non-uniform seismic excitations *Earthquake Engineering & Structural Dynamics* vol 35 (Beijing) pp 1563-1579.
- [2] Zhang N, Xia H and De Roeck G 2010 Dynamic analysis of a train-bridge system under multi-support seismic excitations *Journal of Mechanical Science and Technology* vol 24 (Seoul) pp 2181-2188.
- [3] Yang Y B and Wu Y S 2002 Dynamic Stability of Trains Moving over Bridge Shaken by Earthquakes *Journal Sound and Vibration* vol 258 (Amsterdam: Elsevier) pp 65-94.
- [4] Han Y, Xia H and Zhang N 2006 Dynamic Response Analysis of Train-Bridge System under Non-Uniform Seismic Excitations *China Railway Science* vol 27 (Beijing) pp 46-53.
- [5] Wang S L and Zhai W M 2011 Dynamic Responses of High-Speed Train-Track-Bridge System under Seismic Excitations *Journal of Southwest Jiaotong University* vol 46 (Chengdu) pp 56-62.

- [6] Deng Z M, Guo X Y and Zhang Z Y 2011 Coupled vibration of train-bridge system of steel truss bridge with seismic effect *Journal of Central South University: Science and Technology* vol 42 (Changsha) pp 184-191.
- [7] Lei H J, Li X Z and Liu D J 2014 Train running safety analysis of high-pier rigid frame bridge under earthquake action *Earthquake Engineering and Engineering Dynamics* vol 34 (Beijing) pp 87-93.
- [8] Shen Z Y, Hedrick J K and Elkins J A 1984 A comparison of alternative creep-force models for rail vehicle dynamic analysis 8th IAVSD Symp (Cambridge: Ma.) pp 591-605.
- [9] Zhai W M and Xia H 2011 *Train-Track-Bridge Dynamic Interaction Theory and Engineering Application* (Beijing: Science Press)
- [10] Lei H J 2014 *Coupling vibration and running safety of train-track-bridge system under non-uniform seismic excitations* (Chengdu: Southwest Jiaotong University).