



# Vulnerability Analysis of Seismic High Speed Rail Simple Girder Bridges in Near-Fault Strong Seismic Zones

Xu Chen \*, Zhidong Duan, Liang Li

Lanzhou Jiaotong University, Lanzhou 730070, China

\*1062326223@qq.com

**Abstract.** In order to further study the vulnerability of simply supported girder bridges for high-speed railroads under the seismic effects in the near-fault strong seismic zone, a finite element model of simply supported girder bridges for high-speed railroads with a span of 6×32m is established based on the finite element software by considering pile-soil interactions and track constraints as an example. Stress and displacement response analysis of 15m pier height bridge rails was carried out to verify the accuracy of the model, and the effects of near-fault earthquakes on the sensitivity of 5m, 10m and 15m pier height simple supported girder bridges of high speed railroads were investigated. The results show that 0.3g can be used as the critical value for elastic-plastic damage of bridges with pier heights of 15m and below. When the PGA is located between 0.1g and 0.3g, the main damage forms of the pier and pile foundation of HSR simply supported girder bridge are slight damage and moderate damage. When the PGA is greater than 0.3g, the bridge piers and pile foundations start to show severe damage and complete damage. The effect of the near-fault earthquake on the piers is more significant, and the piers are damaged before the piles. The damage state of bridge piers under earthquakes should be emphasized in the actual project.

**Keywords:** near-fault earthquakes; high-speed rail simple girder bridges; pile-soil interaction; beam-rail integration; seismic vulnerability.

## 1 Introduction

Bridge structural damage is difficult to predict experimentally, and the application of numerical simulation for susceptibility analysis provides an effective analytical method for pre-earthquake damage prediction of bridges [1-3]. In recent years, bridges have achieved more results in the study of seismic response and susceptibility to damage near faults, such as:

Li Tinghui [4] analyzed the seismic susceptibility of bridge structures under three kinds of environmental erosion, namely, chloride erosion, freeze-thaw cycle, and scour, and obtained the seismic susceptibility model of simply supported girder bridges under different service times.

Kang Lin et al [5] developed a probabilistic seismic demand model using incremental dynamic analysis, performed susceptibility analysis of four typical girder bridges considering pile-soil interaction, and evaluated the seismic performance of the bridges using susceptibility curves.

Kuang Wenfei [6] established a refined model of multi-span simply supported girder-rail-contact network system and explored the influence of portal pier structure on the seismic susceptibility of the system.

Qu Juntong et al. [7] considered the traveling wave effect of earthquakes and dynamic water pressure, and analyzed the influence of side piers and middle piers on the susceptibility of bridges.

Dong Jun et al. [8] used the kernel density estimation theory to derive a method for calculating the seismic vulnerability of bridges and to establish a seismic analysis method for railroad bridges based on seismic risk assessment.

Existing bridge susceptibility studies are mainly focused on highway bridges, with relatively few railroad bridges. When vulnerability analysis of railroad bridges is carried out, simplified models are usually used, which may have problems such as insufficient calculation accuracy. In this paper, a refined model of simply supported girder bridges for high-speed railroads is established to investigate the effects of near-fault earthquakes on the susceptibility of simply supported girder bridges for high-speed railroads by considering pile-soil interactions as well as the restraining effect of the track on the girders.

## **2 Establishment of Refined Full Bridge Finite Element Model**

### **2.1 Bridge Overview**

In this paper, three kinds of pier height two-lane high speed railroad simple supported girder bridges of 6, 10 and 15m are taken as the research object. The span arrangement is 6×32m, and the track type is CRTS I ballastless track. The piers are round end type 2×6m solid piers with equal height arrangement. The pile foundation is drilled end bearing piles with C30 concrete; The base plate and sleepers of the track are made of C30 concrete; The fastener connects the rail to the track plate, and the fastener model is WJ-7; The track slab, bottom slab, and bridge deck are filled with CA mortar; Friction pendulum bearings are used to connect the girders to the abutments.

### **2.2 Model Building**

Parametric modeling using finite element software Ansys, considering the constraint effect of the rail on the beam, using Beam188 unit to simulate the beam body, abutment, track plate, base plate and rail, with nonlinear spring unit Combin39 to simulate the resistance of the fastener, linear spring unit Combin14 to simulate the vertical stiffness of the fastener, vertical stiffness is taken as 35kN/mm [9]. The friction pendulum support [10] is simulated using a nonlinear spring Combin39 cell. The bridge model diagram is shown in Figure 1.

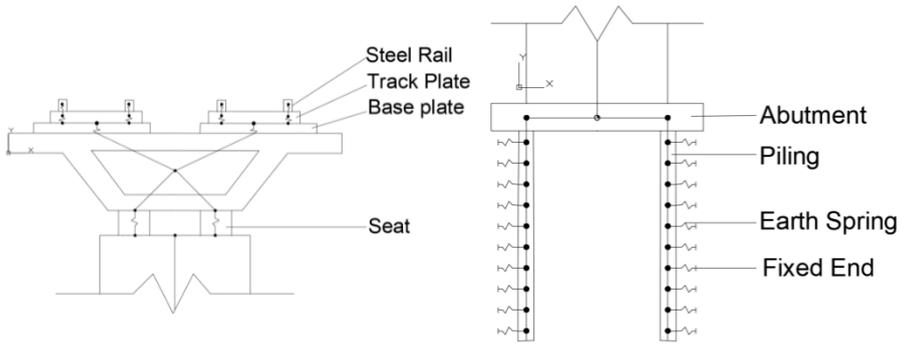


Fig. 1. Bridge modeling diagram

### 3 Vulnerability Analysis

#### 3.1 Ground Vibration Selection

A minimum of 10-20 seismic records are required to meet the accuracy requirements when using incremental dynamic analysis to calculate bridge susceptibility [11]. In order to exclude the interference of other factors, ten near-fault ground shaking records were selected from the Chi-Chi earthquake in Taiwan, and their information is shown in Table 1

Table 1. Recorded information for near-fault

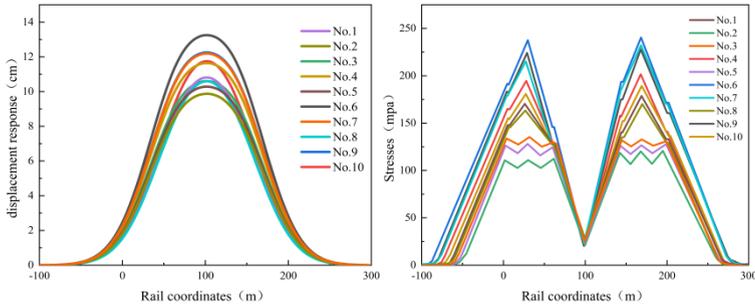
Number	station	fault distance	PGA/m <sup>2</sup> /s	PGV/(m/s)	PGD/m	PGV/PGA
1	TCU051	7.64	0.1602	0.0549	0.0753	0.3427
2	TCU052	0.66	0.4469	0.1757	0.2238	0.3932
3	TCU054	5.28	0.1336	0.0442	0.0836	0.3308
4	TCU065	0.57	0.7897	0.1278	0.1108	0.1618
5	TCU068	0.32	0.5117	0.1228	0.2704	0.2400
6	TCU071	5.8	0.4961	0.0533	0.0111	0.1074
7	TCU072	7.08	0.4771	0.0424	0.0513	0.0889
8	TCU075	0.89	0.2332	0.1117	0.0985	0.4790
9	TCU076	2.74	0.0283	0.0528	0.0339	1.8657
10	TCU078	8.2	0.4156	0.0301	0.0205	0.0724

#### 3.2 Orbital Response Analysis

The ground vibration record is input into the finite element model for nonlinear time course analysis to calculate the rail response, and the results are shown in Fig. 2.

The maximum value of rail displacement is 13.25 cm, the average maximum displacement value of rail is 11.32 cm, the maximum value of rail stress is 240.41 Mpa, the average maximum value of rail stress is 172.02 Mpa. Compared with the literature

[12], the consideration of pile-soil action increases the rail displacement by 25.4% and the rail stress by 18.33%. The rail stresses under near-fault earthquakes are always extreme on the left side at the location of the right movable bearing near the first span of the main girder and on the right side at the movable location of the abutment.



(a) Rail displacement (b) Rail Stress

Fig. 2. Rail Response

### 3.3 Bridge Damage Indicator Determination

Huang [13] defines the bridge damage states: no damage, slight damage, moderate damage, severe damage and complete damage, and the boundaries between the different damage states are described. Due to the paucity of pile foundation limit damage state boundaries, the fact that curvature can more accurately respond to the structural damage state in higher order vibration modes [14]. In this paper, the curvature ductility coefficient is chosen as the damage index for bridge piers and pile foundations. Curvature ductility coefficient is the ratio of ultimate curvature to yield curvature of bridge pier or pile foundation section [15].

$$\mu_s = \frac{\phi_\mu}{\phi_y} \tag{1}$$

Where:  $\mu_s$  is the curvature ductility coefficient of the abutment or pile foundation;  $\phi_\mu$  is the limit curvature of the section;  $\phi_y$  is the yield curvature of the section.

Indicators of injury status are listed in Table 2.

Table 2. Damage indicators for the damaged state of bridges

destructive state	Impairment indicators	repairability
minor damage	$\mu_{d1} < \mu_s < \mu_{d2}$	No need to repair
medium damage	$\mu_{d2} < \mu_s < \mu_{d3}$	easy repair

serious damage	$\mu_{d3} < \mu_s < \mu_{d4}$	hard repair
Complete damage	$\mu_{d4} < \mu_s$	beyond repair

Where:  $\mu_s$  is the coefficient of curvature ductility of a pile or abutment section under the action of ground shaking;  $\mu_{d1}$  is the coefficient of curvature ductility at first yielding of the section;  $\mu_{d2}$  is the coefficient of curvature ductility at equivalent yielding of the section;  $\mu_{d3}$  is the coefficient of curvature ductility at a maximum compressive strain of 0.004 in the concrete of the section;  $\mu_{d4}$  is the curvature ductility coefficient when the section is completely destroyed.

### 3.4 Establishment of Fragility Curves

The seismic wave modulation is input into the finite element model to calculate the curvature ductility coefficients of the bridge piers and pile foundations under seismic action  $\mu_s$ . The results of nonlinear time course analysis were analyzed by linear regression analysis and mathematical regression equation was used to express the relationship between damage results and PGA under earthquake as shown in Equation (3).

There is a functional relationship between structural demand  $S_D$  and ground vibration strength  $IM$ , and the expression of the relationship is shown in equation (2)

$$S_D = a \times IM^b \tag{2}$$

$$\begin{cases} b = \frac{\sum_{i=1}^n \ln S_{ci} \ln IM_i - n \overline{\ln S_c} \overline{\ln IM}}{\sum_{i=1}^n S_{ci}^2 - n \overline{S_c}^2} \\ a = \overline{IM} - b \overline{\ln S_c} \end{cases} \tag{3}$$

Where:  $S_D$  is the value of the ability to destroy the state;  $S_c$  is the demand value for the destruction state.

According to the beyond probability formula for structures:

$$P_f = P[S_D \geq S_c | IM] = \varphi \left( \frac{\ln a + b \ln IM - \ln S_c}{\sqrt{\beta_{D|IM}^2 + \beta_C^2}} \right) \tag{4}$$

Where:  $\varphi(x)$  is the standard normal distribution;  $\beta_{D|IM}$  is the log standard deviation of seismic demand;  $\beta_C$  is the log standard deviation of the seismic capacity of the structure;

When PGA is used as the seismic intensity,  $\sqrt{\beta_{D|IM}^2 + \beta_C^2}$  takes the value of 5.

The abutment and pile foundation susceptibility curves are shown in Figures 3, 4.

As shown in Fig. 3, the probability of damage of bridge piers increases with the increase of pier height in each damage state, and in the range of PGA of 0-1g, the change trend of slight damage and moderate damage is similar. The occurrence of elastic-plastic damage threshold of the bridge pier is 0.3g.

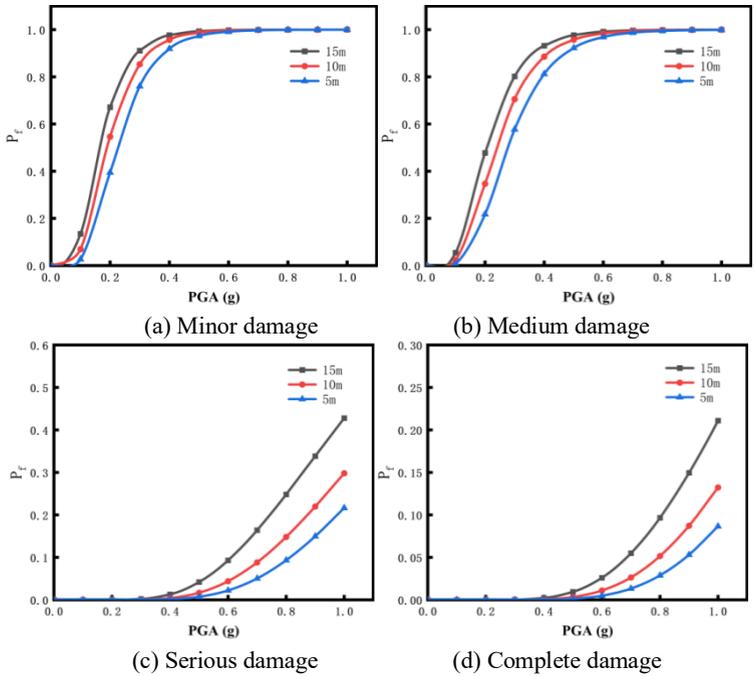


Fig. 3. Bridge pier susceptibility curve

As shown in Fig. 4, the damage probability of the pile foundation is lower than that of the abutment under the same PGA, and the abutment undergoes damage before the pile foundation. The occurrence of elastic-plastic damage threshold of pile foundation is 0.4g.

The comparison reveals that the susceptibility curves of bridge piers and pile foundations have the same trend under seismic excitation. The damage probability of pile foundation is less than that of bridge abutment under the same conditions.

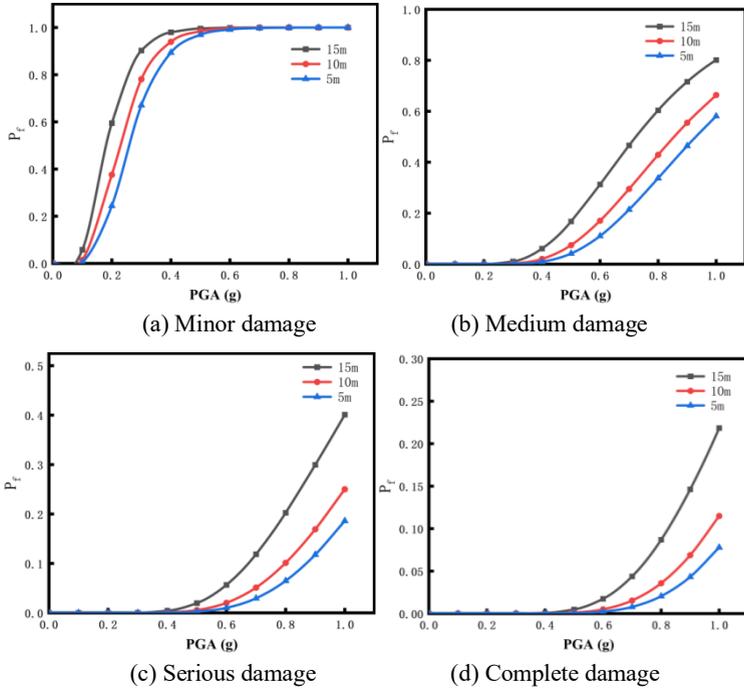


Fig. 4. Piling susceptibility curve

## 4 Conclusions

The main conclusions of this paper are shown below:

(1) Bridge structures in earthquakes show increased damage with increasing abutment height, but abutments and pile foundations are differently sensitive to bridge height. Taking medium damage as an example, the maximum interval of change in the damage probability of abutment is 0.1g-0.2g, and the maximum interval of change in the damage probability of pile foundation is 0.2g-0.3g interval, and the damage probability of abutment changes faster than the damage probability of pile foundation. In engineering practice, attention should be paid to the observation of crack damage of bridge abutments to prevent cracks from expanding and intensifying during earthquakes.

(2) Under the action of near-fault earthquake, the stresses of rails are always large at the left side of the main girder of the first span near the location of the right movable bearing and at the location of the right movable position of the bridge deck, and large-diameter piles or group piles should be used to improve the overall bending stiffness and bearing capacity of the abutment.

(3) In the seismic design of bridges, pile foundations and track systems should not be neglected. They should be studied in more detail.

## References

1. JIN Ruyi, SHEN Yanli. Composite parametric analysis of seismic vulnerability of bridge high piers under pile-soil interaction[J]. *Journal of Disaster Prevention and Mitigation Engineering*,2023, 43(05): 1016- 1023+ 1056.
2. Zhu Baiyang. A vulnerability analysis method for simply supported girder bridges with optimized selection of ground vibration parameters[D]. Institute of Engineering Mechanics, China Earthquake Administration, 2024.
3. Gao Feifan, Wang Jingyu, Chen Boyu, et al. Analysis of pile-soil effect on seismic susceptibility of waveform steel web continuous girder bridges[J]. *Journal of Hebei University of Engineering (Natural Science Edition)*,2025,42(01):82-89.
4. Tinghui Li. Analysis of seismic susceptibility and seismic toughness of simply supported girder bridges under environmental erosion conditions[D]. Institute of Engineering Mechanics, China Earthquake Administration, 2023.
5. KANG Lin, CUI Jiawei, YAN Wujian, et al. Near-fault seismic vulnerability analysis of Lanzhou-Xinjiang high-speed railway bridge based on probabilistic seismic demand model[J]. *Journal of Earthquake Engineering*, 2024,46(03):644-654.
6. Kuang Wenfei. Seismic vulnerability analysis of portal pier-bridge-track-contact network system[D]. Central South University,2023.
7. QU Juntong, QIN Tianyang, SUPPLEMENTARY MENG Qiang, et al. Structural susceptibility analysis of multi-span simply supported girder bridges under multi-factor conditions[J/OL]. *Hunan Transportation Science and Technology*,1-8[2025-03-06].
8. DONG Jun, ZENG Yongping, LEN Dan. Analysis of reasonable seismic isolation system for simply supported beams of high-speed railroads in nine-degree seismic zone[J]. *Journal of Harbin Institute of Technology*, 2023,55(11):115-124+134.
9. Qu Cun. Research on the theory and method of seamless line design of ballastless track for high-speed railroad with large bridges [D]. Beijing: Beijing Jiaotong University, 2013: 41-42.
10. ZHU Hailong, ZHANG Yongliang, ZHOU Youquan, et al. Analysis of seismic isolation effect of simply supported girder bridge of high-speed railroad based on friction pendulum bearing[J]. *Engineering Seismic and Reinforcement Retrofitting*,2024,46(01):69-76.
11. SHOME N. Probabilistic seismic demand analysis of nonlinear structures[M]. Stanford, CA, USA: Stanford University,1999.
12. LI Junge,ZHOU Chao. Response analysis of beam-rail system of high-speed railroad under impulse earthquake[J]. *Railway Standard Design*,2021,65(09):116-120+126.
13. Hwang H, Liu JB, Chiu YH. Seismic fragility analysis of highway bridges[R].Memphis: Mid-America Earthquake Center,2001.
14. Zhang Shaoxiong. Research on seismic vulnerability analysis of high pier bridges [D]. Southwest Jiaotong University,2014.
15. Liang Zhiyao. Study on the calculation method of displacement ductility capacity of high piers of bridges[J]. *Engineering Seismic Resistance and Reinforcement Retrofitting*, 2005,(05):57-62.

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