Hindawi
Advances in Civil Engineering
Volume 2022, Article ID 7554440, 9 pages
https://doi.org/10.1155/2022/7554440

Research Article

Near-Fault Ground Motion Impacts on High-Speed Rail Large-Span Continuous Girder Bridge considering Pile-Soil Interaction

Yefei Zhou,[1] **Gang Wang**,[2] **Shuyi Yang**,[2] **and Niu Liu**[2]

[1]*The 4th Construction Co., Ltd. of China 15th Corporation, Zhengzhou 450051, China*
[2]*College of Transportation Engineering, Nanjing Tech University, Nanjing 210009, China*

Correspondence should be addressed to Gang Wang; swjtu_wg@163.com

Received 3 December 2021; Accepted 12 February 2022; Published 21 March 2022

Academic Editor: Lingkun Chen

This paper examines and discusses the dynamic response of a high-speed train-bridge-soil-pile foundation system to near-fault earthquakes. A 72 + 120 + 72 m continuous girder bridge of a high-speed railroad was selected as the model for calculation. Based on the p-y model for simulating pile-soil interaction, the moment-curvature analysis program XTRACT is used to calculate the moment and curvature of bridge piers and pile foundation sections, and the finite element (FE) software is used to establish two nonlinear global bridge models under seismic effects in the high-intensity zone, one considering pile-soil interaction and one without considering pile-soil interaction. The Ap/Vp parameter, the ratio of peak acceleration to peak velocity of transverse ground shaking, is used to reflect the impulse characteristics of earthquakes and the effect of the Ap/Vp parameter on the dynamic response of bridges to earthquakes was studied. The elastic-plastic response of the bridge system was calculated under lateral and vertical near-fault (NF) impulse/NF nonimpulse/far-field (FF) ground motions (GMs). The study shows that the structural displacement increases, and the internal force decreases after considering the pile-soil interaction. The results show that the bridge piers enter the elastoplastic phase under rare earthquakes. The NF ground shaking couples with the bridge into the elastoplastic phase with a more significant impulse period than the FF ground shaking intensifies the dynamic response of the bridge structure.

1. Introduction

A high-speed railroad has the advantages of high speed, high density, all-weather, large capacity, comfort, safety, and reliability compared with other means of transport. It has become the trend of railroad development in the world. It is considering that the construction of railroads will inevitably pass through some densely populated urban areas and soft soil areas in the plains or other geological conditions. Therefore, ensuring the overall safety of the bridge structure and the safety of the trains on the bridge has become an urgent problem for the bridge designers to solve, which is because high-speed railroad bridges are subjected to forced vibration due to the powerful impact of the upper high-speed trains and structural fatigue under the long-term, high-density effect of this power, which reduces the stability and strength. This vibration of the bridge structure, in turn, affects the safety and smoothness of the running vehicles on the bridge. Therefore, the study must consider the dynamic response of the vehicle-bridge coupling.

Pile foundations are widely used for their high bearing capacity, good stability, low settlement, and ability to adapt to various geological conditions and loading situations. Due to multiple factors such as superstructure, overlying infinite foundation, and far-field ground motion, the pile-soil-structure dynamic interaction is one of the most complex topics in structural dynamics and soil dynamics and has received wide attention.

Erhan and Dicleli [1] developed a soil-bridge nonlinear model considering SSI and calculated the seismic response of bridges under different earthquake intensities and found the influence of SSI on the seismic response of bridges under

design. Khoshnoudian et al. [2] established SSI by building a simplified vertebral soil model and studying impulsive earthquakes' effect on dynamic structural stability. For SSI can cause lateral displacement of the structure, Khoshnoudian and Ahmadi [3] investigated the impact of the impulsive earthquake on the displacement ratio of the structure and pointed out that a smaller structural length to slenderness ratio as Timoshenko type piers may offset part of the lateral displacement response. Wang et al. [4] and Chotesuwan et al. [5] investigated the effect of SSI on the seismic response of bridges based on experiments. Moghaddasi et al. [6] investigated the effect of bending properties of pile foundations on the seismic response of structures by using a robust Monte Carlo method to develop an equivalent linear model of soil-pile foundation-bridge. Xie et al. [7] studied the SSI effect on the seismic response of a typical bridge in California. Durucan and Dicleli M [8] and Liu and Zhang [9] investigated the impact of Ap/Vp parameters on the seismic response of seismically isolated structures.

The study by Wang et al. [10] analyzed the effect of soil-structure interaction SSI (SSI) on the seismic response of bridges due to vertical earthquakes, including liquefaction potential. The study results indicate that the SSI effect tends to reduce the amount of response to certain ground motions and increase the demand for other ground motions relative to the fixed base case. This phenomenon can be explained by the frequency components of ground motions, the drift of the vertical self-oscillation period, and the generalization of the vertical spectral acceleration for higher modes. In addition, the liquefaction mechanism of nonliquefied soils is isolated concerning the SSI effect, revealing the impact of liquefaction on the bridge response. Li et al. [11] developed a three-dimensional nonlinear vibration isolation finite element model of a prototype California High-Speed Rail (CHSR) bridge under NF earthquakes by considering soil-structure and track-structure interactions and calculating the seismic response of the bridge. The study did not compare the seismic response of the bridge before and after considering SSI. Galvín et al. [12] proposed a method for calculating the dynamic response of railroad bridges considering soil-structure interactions. The technique uses the substructure method to decompose the problem into two coupled interactions: the soil-foundation and the soil-foundation-bridge systems. The foundation and surrounding soil are discretized using the finite element method and filled with perfectly matched layers to avoid boundary reflections. The benefit of the technique is that as the complexity of the problem increases, the technique allows access to specialized analysis tools to deal with both the soil-foundation and superstructure domains. Bhure et al. [13] studied the dynamic response of a subway bridge under moving loads. Track unevenness and train inertia effects were not considered. Moving load analysis was performed for the fixed foundation and the full pile models. It was shown that the resonance phenomenon of the full pile model was lower than that of the fixed foundation model in both loading cases.

Through the investigation and comparison of different research results at home and abroad, it can be found that the study of the vehicle-bridge coupling dynamics of high-speed railroad continuous girder bridges under the action of earthquakes is of great significance to the design of both high-speed railroad bridges and high-speed trains in the future, so this research topic has gradually received extensive attention from various researchers. However, the existing research still has many shortcomings, mainly in the following points.

Firstly, the continuous girder bridges have received wide attention for their structural stiffness, small deformation, good dynamic performance, and benefits to high-speed traffic. So far, the leading research at home and abroad has been limited to simply supported girder bridges, and the vibration response of continuous girder bridges lacks systematic analysis. Therefore, the seismic response of large-span continuous girder bridges for high-speed railroads needs to be studied in depth.

Secondly, the existing domestic studies on the elastic-plastic seismic response analysis of high-speed railroad continuous girder bridges are few and limited to the elastic-plastic analysis of supported girder bridges. Still, the dynamic characteristics of the two are different. Therefore, the elastic-plastic seismic response analysis of high-speed railroad continuous girder bridges is needed.

Again, most of the studies at this stage only establish the train-bridge model and ignore or simplify other system elements, such as not considering the influence of the soil on the structure. Therefore, a more detailed model to analyze the pile-soil-structure interaction should be established.

This paper selects the research object of a 72 + 120 + 72 m continuous girder bridge of high-speed railroad. The nonlinear model of the soil-pile foundation is established with the SHAKE91 program. P-y curve, t-z curve, and q-z curve and the hysteresis characteristics of bridge piers and pile foundation are simulated with the bilinear model to establish the dynamic responses railroad bridge-soil-pile foundation continuous girder bridge system in the wrong geological development area. The dynamic calculation of the train large-span bridge system under velocity impulse NF earthquake is carried out. The study analyzes the elastic-plastic seismic response of the bridge pile foundation system under NF earthquakes. It reveals the dynamic performance of railroad bridges in poorly developed geological areas under multidimensional seismic action. The research aims to promote the preliminary research results to the application by solving the core scientific problems behind the technical bottlenecks.

2. Power p-y (t-z and q-z) Curve Method

In recent years, the simulation of soil confining action around piles under intense earthquake action has been a complex problem and a hot research topic. Due to the complexity of pile-soil interaction, in this paper, based on the Winkler foundation assumption that the response of each soil layer is independent of the adjacent soil layers, an analytical model with dynamic p-y (t-z and q-z) curves is shown in Figure 2(e), which consists of three main parts: free-field soil, structural, and pile units. Among them, the

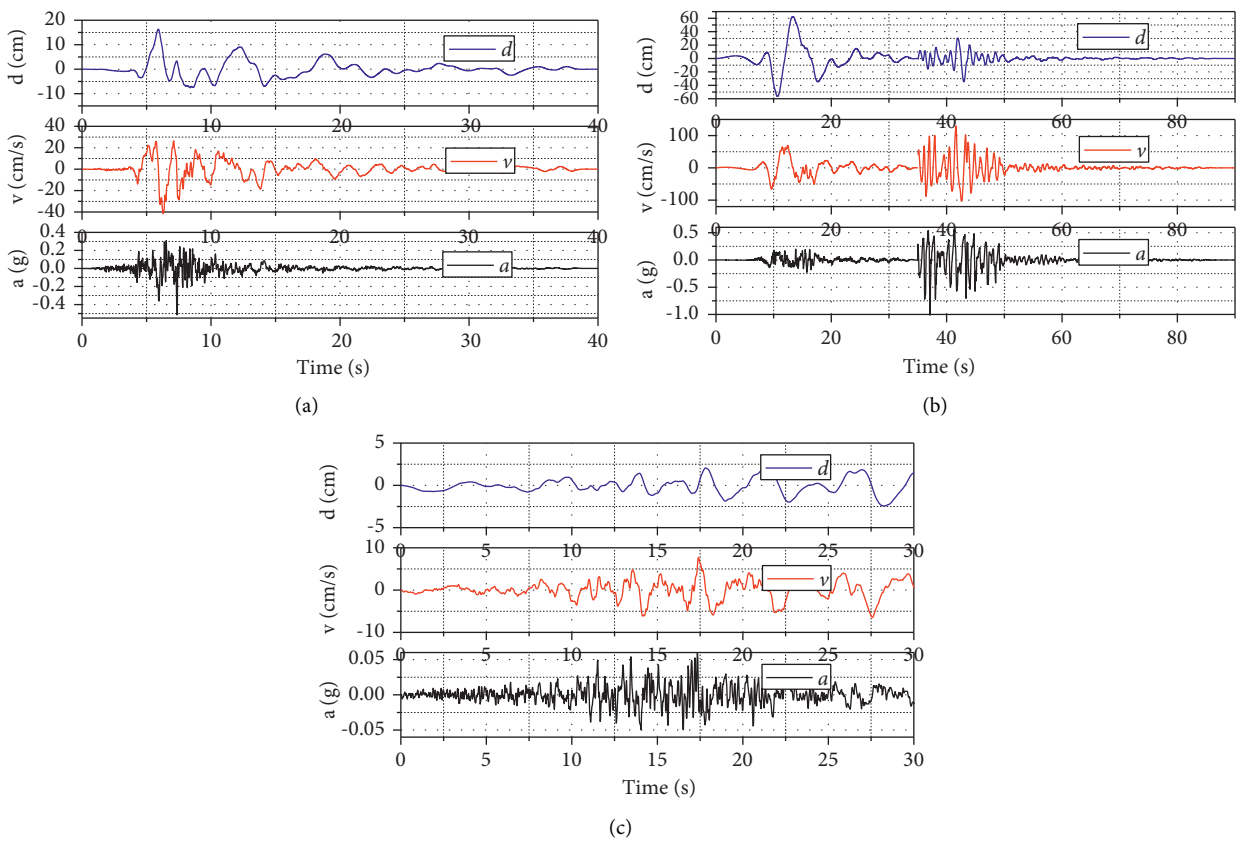

Figure 1: Time-history curves of ground motions: (a) Loma Prieta STG000; (b) Kocaeli_ Yarimca; (c) Hector Mine BRS090.

Table 1: Impulse-type NF ground vibration information table.

Earthquake name	Stations	Magnitude	Time	Amount	PGA(g)	Ap/Vp	V/H	Fault distance (km)	V_{s30} (m/s)
Irpinia Italy	Sturno (STN)	6.9	1980	STU270 STU-UP	0.321 0.235	4.47	0.73	10.84	382
Loma Prieta	Saratoga-Aloha Ave	6.93	1989	STG000 STG-UP	0.514 0.396	12.37	0.77	8.5	380
Cape Mendocino	Petrolia	7.01	1992	PET090 PET-UP	0.662 0.165	7.48	0.25	8.18	422
Landers	Lucerne	7.28	1992	LCN260 LCN-UP	0.725 0.823	5.44	1.14	2.19	369
Northridge	Sylmar-Olive View Med FF	6.69	1994	SYL360 SYL-UP	0.843 0.536	6.52	0.64	5.3	440
Kocaeli Turkey	Izmit	7.51	1999	IZT090 IZT-UP	0.230 0.145	6.01	0.63	7.21	811

pile is simulated with a beam unit. The nonlinear soil is simulated with three indifferent dynamic units: the active p-y unit acts as the horizontal resistance of the Earth, the dynamic t-z unit simulates the vertical frictional force of the soil, and the dynamic q-z unit simulates the vertical support of the ground, and the free field is part of the pile-soil interaction, and the springs used are not one, but multiple springs in series.

The load transfer (T-Z) method models the pile as a series of cells supported by discrete nonlinear springs representing the frictional resistance at the soil surface (T-Z springs) and nonlinear springs at the pile ends, meaning the end-bearing springs (Q-Z springs). The soil spring is a nonlinear representation of the soil reaction force T (or Q at the pile end) versus the displacement Z, as shown in Figure 2(e). With known T-Z and Q-Z curves, the axial load-settlement response can be obtained using the computer program.

Appropriate T-Z and Q-Z curves are necessary to obtain reliable settlement and axial monopile load transfer calculations. Such load transfer curves were initially obtained empirically. Coyle and Sulaiman [14] received T-Z curves based on models and experience with full-size sand pile loading tests. Vijayvergiya [15] and API [16], based on this work and other empirical results, made general recommendations for estimating T-Z and Q-Z curves for sandy

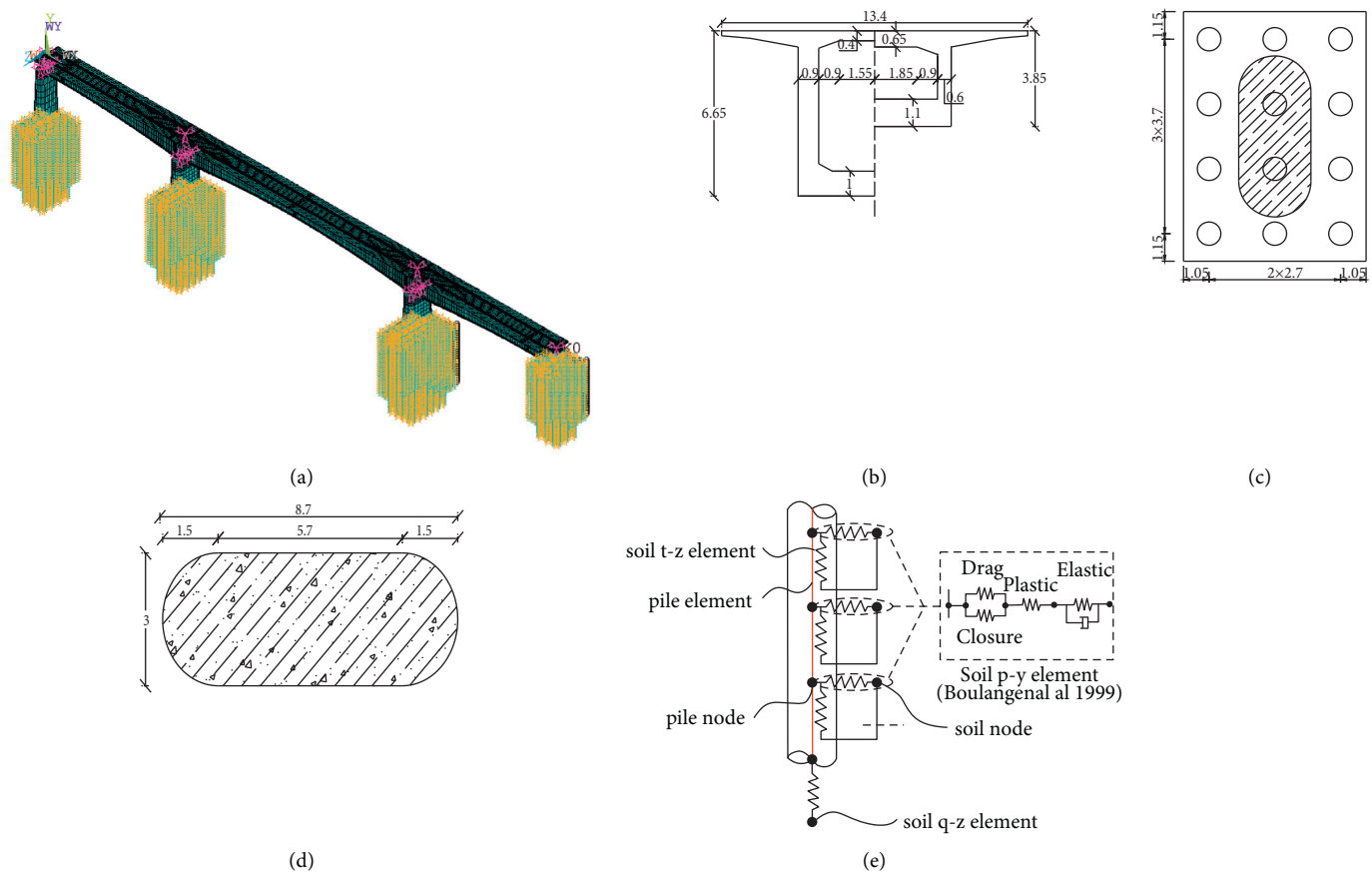

Figure 2: Typical bridge sections. (a) Bridge structure, (b) girder section, (c) bearing section, (d) pier section, and (e) pile-soil interaction model.

soils. The load transfer curves can also be satisfactorily constructed using theoretical methods related to the shear stiffness of the soil around the pile [17, 18].

The dynamic p-y (t-z and q-z) curve approach is a nonlinear foundation response method that takes into consideration soil nonlinearity, soil stratification, soil type, load type, soil interface slip and detachment, and far-field soil radiation damping, among other factors. It overcomes the shortcomings of the single parameter method (such as the 6-spring method) for calculating the deflection, angle of rotation, and maximum bending moment of the pile by horizontal load-bearing pile, which cannot be well-matched with the actual measured data and boundary conditions at the same time, and resolves the issue that the linear soil pressure and displacement solution method is not applicable to the actual soil nonlinear reaction when large deformation occurs.

3. Ground Vibration Selection

In this paper, based on PEER strong seismic records, concerning the recommendations of FEMA-P695 Quantification of Performance and Response Parameters for Building Systems (ATC-63 Project) [19], and according to the USGS code, according to the difference of the average shear wave velocity (Vs30) within 30 m below the ground surface, the average shear wave velocity of 360 m/s was used as the boundary.

The type of site ground shaking with shear wave velocity more significant than 360 m/s was selected. The ground vibrations were chosen from six groups of the near-fault (NF) impulse ground motions (GMs), six NF nonimpulse GMs, and six far-field (FF) GMs, each group including one horizontal ground vibration and one vertical ground vibration. Figure 1 depicts the time-history curves of selected ground movements, such as the Loma Prieta earthquake that struck STG000, the Kocaeli earthquake that struck Yarimca, and the Hector Mine earthquake that struck BRS090. Data on the characteristics of each ground vibration may be found in Tables 1 through 3.

4. Vibration Analysis of Railroad Bridges under near (Span) Fault Seismic Action

4.1. Project Overview. This paper uses a section of $48\,m + 80\,m + 48\,\mathrm{m}$ stubble-free cast-in-place prestressed concrete continuous girder bridge (double line) on the high-speed rail as the research background. Among them, the bridge structure schematic diagram is shown in Figure 2.

The girder adopts the form of a single-box single-cell section with variable cross section, and the bottom curve of

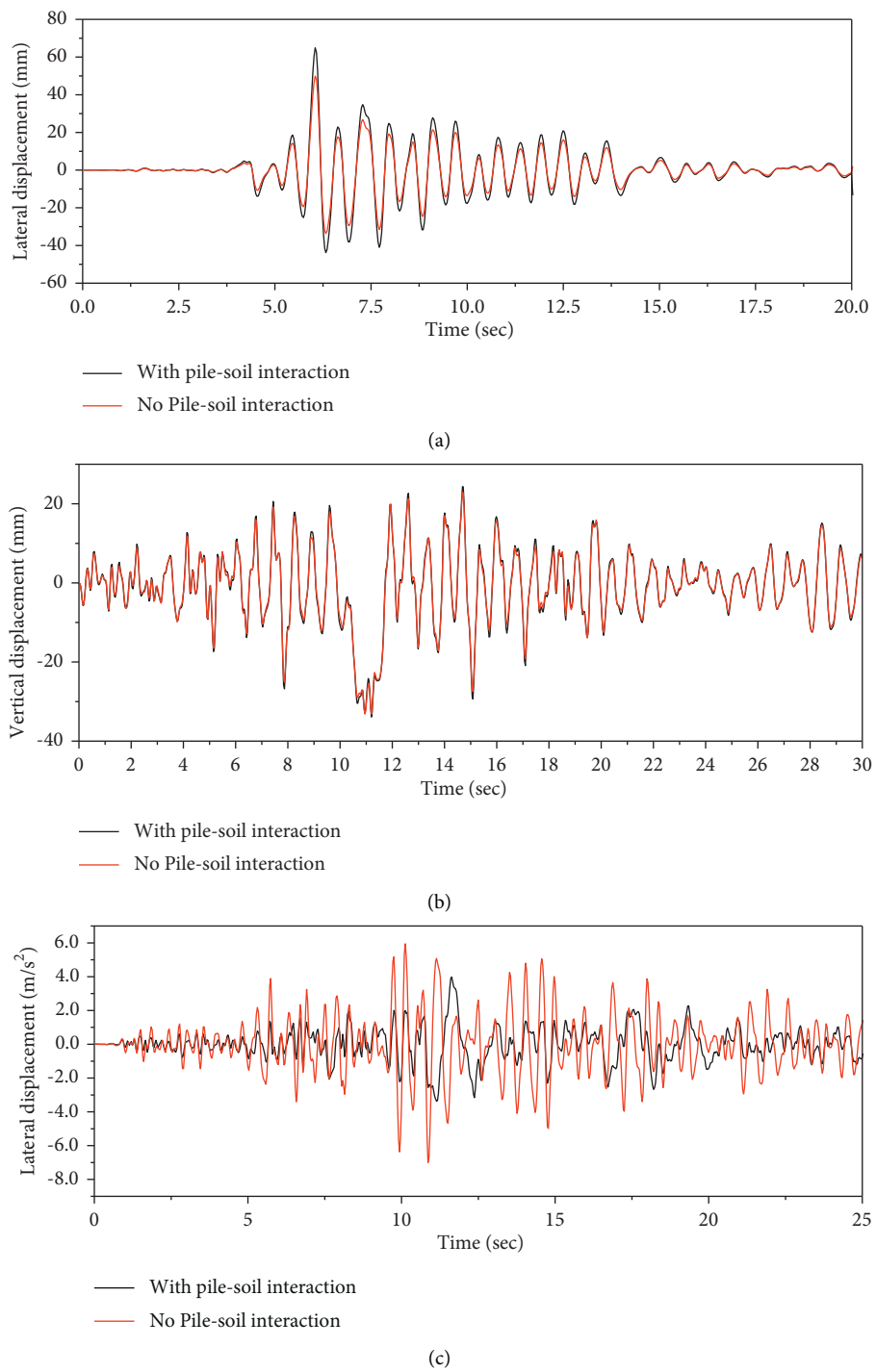

Figure 3: Time-history curves of the comparison of two models considering pile-soil interaction and without interaction: (a) Loma Prieta 1989 lateral displacement of beams in span under earthquake action; (b) Hector Mine 1999 Vertical mid-span displacement of beams under seismic action; (c) Kocaeli Turkey 1999 transverse acceleration in the span of a beam under seismic action.

the beam varies in a quadratic curve; the height of the cross section girder varies from 3.85 m to 6.65 m in the middle of the span; the thickness of the web differs from 0.6 m to 0.9 m; the thickness of the top plate varies from 0.4 m to 0.65 m; the thickness curve of the bottom plate varies from 0.4 m to 0.9 m; the typical cross section of the bridge is shown in Figure 2(b). The concrete material used in the girder is C40. The bridge pier is around an end-shaped hollow pier with variable cross sections. The pier abutment is made of C35 concrete, and the pile foundation is made of concrete (C25) infill pile with 1 m diameter and 26 m pile length, and the foundation bearing is rigid and does not contact the soil. Standard reinforcement adopts HPB235 and HRB335 steel bars.

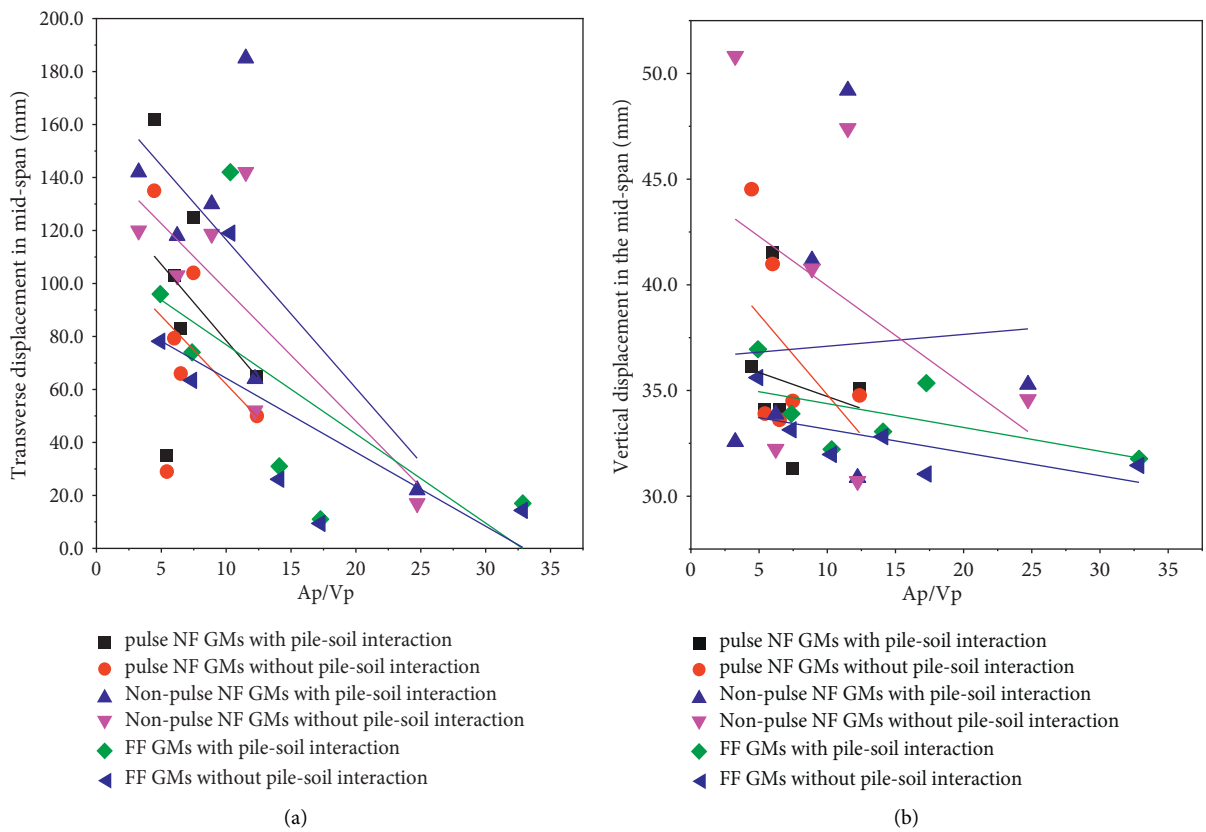

Figure 4: A_P/V_P values and seismic dynamic response. (a) Transverse displacement in the beam span. (b) Vertical displacement in the beam span.

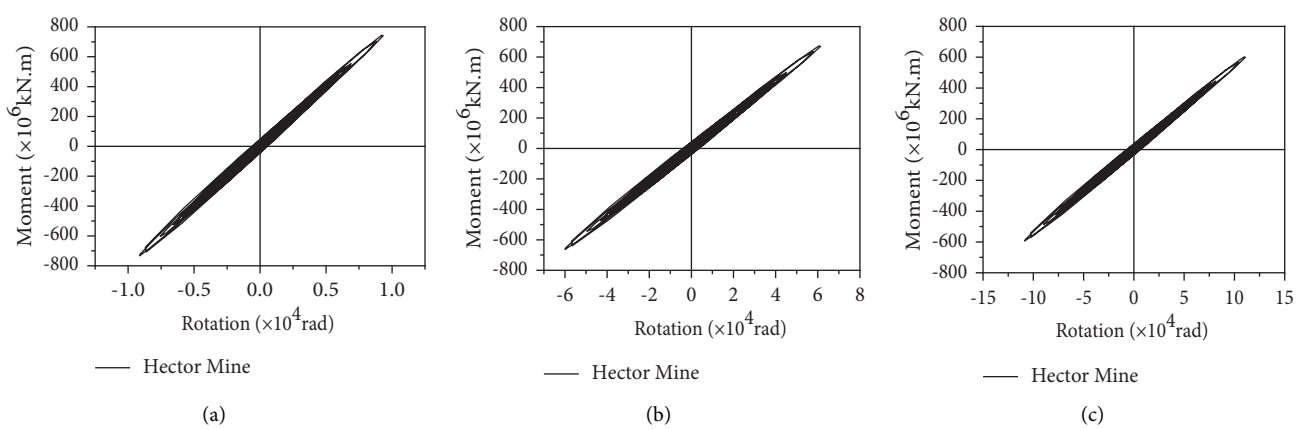

Figure 5: Moment-curvature relationship of pier bottom element under seismic action of Hector Mine earthquake. (a) First element. (b) Second element. (c) Third element.

4.2. Moment-Curvature Analysis of Bridge Pier Section. In this paper, XTRACT software is applied to perform the section bending-curvature analysis, and the bridge pier section is discretized into various fiber unit models. Then the section moment-curvature calculation is performed. The specific implementation process is as follows: after defining the ground vibration input, the plastic hinge is formed through the centralized plastic model for nonlinear time-history analysis. Using the FE program to calculate the average axial pressure at the bottom of the pier when the train crosses the bridge, according to the actual cut-off and size, the arrangement position of various types of reinforcement, based on the Mander restrained concrete stress-strain relationship, the section fiber unit is established. Calculate the yield curvature and yield bending moment, ultimate curvature, and ultimate bending moment of the pier section under the action of axial force. Table 4 shows the values of the characteristic points of the equivalent bifurcation moment-curvature relationship of the cross section.

In order to realize the nonlinear analysis of piers and piles, firstly, the parameters of mass density, axial strain, moment-curvature, and torsional and shear modulus of

Table 2: Nonimpulse type NF ground vibration information table.

Earthquake name	Stations	Magnitude	Time	Amount	PGA(g)	Ap/Vp	V/H	Fault distance (km)	V_{s30} (m/s)
Loma Prieta	BRAN	6.93	1989	BRN000 BRN-UP	0.456 0.506	8.88	1.10	10.72	476
Loma Prieta	Corralitos	6.93	1989	CLS090 CLS-UP	0.483 0.458	10.16	0.94	3.85	462
Cape Mendocino	Cape Mendocino	7.01	1992	CPM090 CPM-UP	1.039 0.739	24.51	0.71	6.96	567
Northridge-01	LA-Sepulveda VA Hospital	6.69	1994	SVP360 SVP-UP	0.932 0.318	12.23	0.34	8.44	380
Chi-Chi_ Taiwan	TCU067	7.62	1999	TCU067-N TCU067-V	0.319 0.235	6.22	0.74	0.62	433
Kocaeli_ Turkey	Yarimca	7.51	1999	YPT060 YPT-UP	0.394 0.242	3.25	0.61	4.83	297

Table 3: Far-fault general earthquake information sheet.

Earthquake name	Stations	Magnitude	Time	Amount	PGA(g)	Ap/Vp	V/H	Fault distance (km)	V_{s30} (m/s)
Friuli Italy-01	Tolmezzo	6.5	1976	TMZ270 TMZ-UP	0.315 0.277	10.33	0.88	15.82	505
Cape Mendocino	Shelter Cove Airport	7.01	1992	SHL000 SHL-UP	0.229 0.0543	33.10	0.24	28.78	518
Northridge -01	Featherly Park-Main	6.69	1994	FEA000 FEA-UP	0.101 0.0243	13.23	0.24	82.32	367
Kobe_Japan	Chimayo	6.9	1995	CHY000 CHY-UP	0.0921 0.0752	17.30	0.82	49.91	609
Kocaeli Turkey	Iznik	7.51	1999	IZN090 IZN-UP	0.124 0.0754	4.91	0.61	30.73	467
Hector Mine	Barsto	7.13	1999	BRS090 BRS-UP	0.0589 0.0445	7.60	0.76	61.2	370

Table 4: Equivalent bifurcation moment-curvature relationship of bridge pier section.

	Equivalent yield		Equivalent limit	
	Curvature (rad/m)	Bending moment (kN • m)	Curvature (rad/m)	Bending moment (kN • m)
Longitudinal	0.002310	5051	0.04705	6142
Lateral	0.002310	5051	0.04705	6142

piers and piles are defined, and the above parameters can realize the nonlinearity of piers; when the moment response of piers and piles cross section exceeds the yield moment of cross section, the turning spring will be activated. The nonlinear properties, such as the abovementioned moment-curvature relationship, are assigned to the bridge pier and pile units, and the bending moment and turning angle of each element of the bridge pier are calculated.

4.3. Dynamic Response of the Bridge. The combination of horizontal and vertical earthquake high-level seismic action is taken following the bridge design instructions and the site classification on which the bridge is built. The peak acceleration of ground vibration is considered to be 0.4 g following GB5011-2006 "Code for Seismic Design of Railway Engineering" [20]. All earthquakes are specified in the calculation to the fortification earthquake level. The train passes at 350 kilometers per hour across the bridge structure. The peak elastic-plastic seismic response of two models of high-speed railroad reinforced concrete continuous girder bridges with and without pile-soil is computed in this article after lengthy computations.

Under rare earthquakes, the dynamic response of the bridge should be calculated by the nonlinear time-response analysis method, and the train travels over the bridge structure at 350 km/h. The peak elastic-plastic seismic response of two models of high-speed railroad reinforced concrete continuous girder bridge considering pile-soil and not considering pile-soil is calculated, which is shown in Table 5, with the NF impulse/NF nonimpulse/FF typical earthquake Loma Prieta 1989 earthquake, Hector Mine 1999, and Kocaeli Turkey 1999 as examples, and the corresponding time-history curves for the comparison of the two models considering pile-soil and not considering pile are shown in Figure 3.

Table 5: Summary of peak seismic response of continuous girder bridge of high-speed railroad under the action of rare impulse-type NF earthquake.

Earthquake type	Earthquake	Model type	Transverse displacement in the span/m	Vertical displacement in the span/m	Transverse acceleration in the span/(m/s^2)	Vertical moment in the span (10^3N • m)
Impulse NF GMs	Irpinia Italy-01 1980 Sturno (STN)	With pile-soil interaction	0.162	0.036	3.324	1.678
		No pile-soil interaction	0.135	0.044	6.621	2.098
	Loma Prieta 1989 Saratoga-Aloha Ave	With pile-soil interaction	0.065	0.035	3.532	0.921
	Landers 1992 Lucerne	No pile-soil interaction	0.050	0.034	6.751	1.940
	With pile-soil interaction	0.125	0.031	3.552	1.452	
		No pile-soil interaction	0.104	0.035	12.62	2.074
	Northridge-01 1994 Sylmar-Olive	With pile-soil interaction	0.035	0.034	2.713	3.142
		No pile-soil interaction	0.029	0.031	4.073	4.189
	Northridge-01 1994 Sylmar-Olive	With pile-soil interaction	0.083	0.034	3.414	1.703
		No pile-soil interaction	0.066	0.033	9.226	2.129
	Kocaeli Turkey 1999 Izmit	With pile-soil interaction	0.103	0.042	3.403	4.091
		No pile-soil interaction	0.079	0.041	7.707	5.842

As shown in Table 5 and the time-history curves in Figure 3, the mid-span horizontal and vertical displacements and vertical bending moment response of the bridge under NF ground shaking are more significant than those under FF ground were shaking, which is due to the high amplitude effect of NF ground shaking. Thus the increased energy demand of the bridge under the impact of NF ground shaking should be considered.

4.4. Effect of Ap/Vp on Seismic Response. AP/VP is the ratio of peak lateral acceleration to peak lateral velocity (see equation (1)), whose value has a strong connection with the seismic dynamic response of the structure.

$$\frac{A_p}{V_p} = \frac{2\pi}{T_g}, \tag{1}$$

where Ap and Vp are the peak lateral acceleration and the velocity, respectively; T_g is the remarkable period of ground shaking.

It is shown in Figure 4 that the AP/VP values and dynamic seismic reaction are linked. The dynamic response values of the two bridge structural models that include pile-soil and do not consider pile-soil are decreasing under the action of NF impulse-type ground shaking, NF no-impulse ground shaking, and FF ground shaking, as can be seen from the scattering trend.

According to the calculated value of the moment-curvature skeleton curve response of the pier, as shown in Figure 5, the top moment of the first unit of the pier bottom is 7.65×10^5 kN m at 350 km/h, which is larger than the yield moment and beyond the yield moment into the elastic-plastic phase. The moment of the third element of the pier bottom is 6.38×10^4 kN m, which is smaller than the yield moment; the element is in an elastic state. The study shows that the pier needs more excellent ductility and reinforcement under impulse-type NF earthquakes.

From the moment-angle relationship of the pier bottom unit in the above figure, it can be seen that the pier bottom is in the elastic-plastic stage under the action of NF impulsive ground shaking, NF nonimpulsive ground shaking, and far-fault ground shaking, and the bridge structure has different responses under different ground shaking excitation. In the case of pulsed NF ground shaking, the moment response of the pier bottom unit under the action of pulsed NF earthquake is larger than the other two types of earthquakes because of its long-held high amplitude pulsed action characteristics.

5. Conclusion

An earthquake-induced model of the dynamic interaction between trains and bridges is presented in this work. The high-speed train-bridge model is chosen. The finite element software is used to study the continuous girder bridge's self-vibration characteristics, which are then used to conduct the dynamic analysis of the bridge. This model was used to determine the elastic-plastic response of the bridge piers to transverse and vertical seismic stresses. That is evident from the findings.

(1) Based on the finite element software, two nonlinear analytical models of a large-span continuous girder bridge for high-speed railroad without considering pile-soil interaction (i.e., pier bottom consolidation) and considering pile-soil interaction are established, and the bridge response corresponding to ground shaking is obtained by inputting eighteen groups of ground shaking effects. The structural displacement increases, and the internal force decreases after considering the pile-soil interaction. Hence, the internal structural force decreases, but the extended period will lead to a more significant structural displacement.

(2) With the increase of Ap/Vp, the dynamic response values of the two bridge structure models, considering pile-soil and not considering pile-soil, under the action of NF impulsive ground shaking, NF nonimpulsive ground shaking, and FF ground shaking, all show a decreasing trend in the eight taken in this paper. For the 18 ground vibrations studied in this paper, the most pronounced structural response is found for Ap/Vp between 0 and 10.

(3) Due to the brief duration of high amplitude pulsed action during pulsed NF ground shaking, substantial displacements of the bridge structure and the bottom unit of the piling are caused. This indicates that structural requirements are increased during pulsed NF seismic activity.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

References

[1] S. Erhan and M. Dicleli, "Effect of dynamic soil-bridge interaction modeling assumptions on the calculated seismic response of integral bridges," *Soil Dynamics and Earthquake Engineering*, vol. 66, pp. 42–55, 2014.

[2] F. Khoshnoudian, E. Ahmadi, M. Kiani, and M. Hadikhan Tehrani, "Collapse capacity of soil-structure systems under pulse-like earthquakes," *Earthquake Engineering & Structural Dynamics*, vol. 44, no. 3, pp. 481–490, 2015.

[3] F. Khoshnoudian and E. Ahmadi, "Effects of inertial soil-structure interaction on inelastic displacement ratios of SDOF oscillators subjected to pulse-like ground motions," *Bulletin of Earthquake Engineering*, vol. 13, no. 6, pp. 1809–1833, 2015.

[4] S.-C. Wang, K.-Y. Liu, C.-H. Chen, and K.-C. Chang, "Experimental investigation on seismic behavior of scoured bridge pier with pile foundation," *Earthquake Engineering & Structural Dynamics*, vol. 44, no. 6, pp. 849–864, 2015.

[5] A. Chotesuwan, H. Mutsuyoshi, and T. Maki, "Seismic behavior of bridges with pier and foundation strengthening: PsD tests and analytical study," *Earthquake Engineering & Structural Dynamics*, vol. 41, no. 2, pp. 279–294, 2012.

[6] M. Moghaddasi, M. Cubrinovski, J. G. Chase, S. Pampanin, and A. Carr, "Probabilistic evaluation of soil-foundation-structure interaction effects on seismic structural response," *Earthquake Engineering & Structural Dynamics*, vol. 40, no. 2, pp. 135–154, 2011.

[7] Y. Xie, Y. Huo, and J. Zhang, "Development and validation of p-y modeling approach for seismic response predictions of highway bridges," *Earthquake Engineering & Structural Dynamics*, vol. 46, no. 4, pp. 585–604, 2017.

[8] C. Durucan and M. Dicleli, "AP/VPspecific inelastic displacement ratio for seismic response estimation of structures," *Earthquake Engineering & Structural Dynamics*, vol. 44, no. 7, pp. 1075–1097, 2015.

[9] T. Liu and Q. Zhang, "AP/VP specific equivalent viscous damping model for base-isolated buildings characterized by SDOF systems," *Engineering Structures*, vol. 111, pp. 36–47, 2016.

[10] X. Wang, Z. Li, and A. Shafieezadeh, "Seismic response prediction and variable importance analysis of extended pile-shaft-supported bridges against lateral spreading: exploring optimized machine learning models," *Engineering Structures*, vol. 236, Article ID 112142, 2021.

[11] Y. Li and J. P. Conte, "Effects of seismic isolation on the seismic response of a California high-speed rail prototype bridge with soil-structure and track-structure interactions," *Earthquake Engineering & Structural Dynamics*, vol. 45, no. 15, pp. 2415–2434, 2016.

[12] P. Galvín, A. Romero, E. Moliner, D. P. Connolly, and M. D. Martínez-Rodrigo, "Fast simulation of railway bridge dynamics accounting for soil–structure interaction," *Bulletin of Earthquake Engineering*, pp. 1–19, 2021.

[13] H. Bhure, G. Sidh, and A. Gharad, "Dynamic analysis of metro rail bridge subjected to moving loads considering soil-structure interaction," *International Journal of Advanced Structural Engineering*, vol. 10, no. 3, pp. 285–294, 2018.

[14] H. M. Coyle and I. H. Sulaiman, "Skin friction for steel piles in sand," *Journal of the Soil Mechanics and Foundations Division*, vol. 93, no. 6, pp. 261–278, 1967.

[15] V. N. Vijivergiya, "Load-movement characteristics of piles," in *Proceedings of the 4th Symp. of Waterway, Port, Coastal and Occean Div*, vol. 2, pp. 269–284, New York ,NY ,USA, March 1977.

[16] API, *Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms—Working Stress Design*, American Petroleum Institute, Washington, DC, USA, 20th edition, 1993.

[17] J. T. Chin and H. G. Poulus, "A "T-Z" approach for cyclic axial loading analysis of single piles," *Computers and Geotechnics*, vol. 12, no. 4, pp. 289–320, 1991.

[18] H. G. Poulos, "Settlement of single piles in nonhomogeneous soil," *Journal of the Geotechnical Engineering Division*, vol. 105, no. 5, pp. 627–641, 1979.

[19] FEMA, *Quantification of Building Seismic Performance Factors, Rep. FEMA P695*, Federal Emergency Management Agency, Washington, DC, USA, 2009.

[20] C. P. Press, *Code for Seismic Design of Railway Engineering (GB 50111-2006)*, Chineses Standard, Beijing, China, 2009.