Seismic Fragility Study of Rigid-frame Bridges with Varying Pier Heights

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Abstract. The heights and height differences of pier structures in different terrains vary, and their damage characteristics under seismic conditions also differ. In order to further explore the influence of pier height on the seismic resistance of rigid frame bridges, this study takes a group of equally high rigid frame bridges with different pier heights and a group of unequally high rigid frame bridges with different pier height differences as the research objects. The piers are taken as the main vulnerable components, and their seismic fragility is calculated and compared through Incremental Dynamic Analysis (IDA) method. The results show that the higher the piers of equally high rigid frame bridges, the smaller the probability of damage under seismic action; when the pier height is increased from 70 meters to 80 meters, the seismic performance of the piers is significantly improved compared to other pier heights.

Keywords: Rigid-frame Bridges; Varying Pier Heights; Incremental Dynamic Analysis (IDA); Seismic Fragility

1 Introduction

In the mountainous areas of southwest China, continuous high-pier rigid-frame bridges are essential for post-disaster rescue operations. However, their fragility to seismic events poses a significant challenge. To address this issue, researchers have extensively studied the seismic performance and influencing factors of continuous high-pier rigid-frame bridges. While previous studies have assessed structural response under seismic motion, the impact of pier height on seismic fragility remains understudied. Wu et al. [1] established models of continuous rigid-frame bridges with three different structural forms, analyzing seismic response patterns and fragility under varied structural configurations. Song et al. [2] developed finite element models for four bridges with diverse pier heights, investigating transverse and longitudinal displacements of piers ranging from 20m to 80m in height. Therefore, this paper focuses on evaluating the influence of pier height variations on the seismic performance of continuous high-pier rigid-frame bridges. Finite element models were developed using Midas, and

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fragility curves were obtained through nonlinear time history analysis. A comparative analysis of fragility curves for different pier heights was conducted to provide more accurate references for seismic design of bridges in China.

2 Fragility Analysis Methodology

Based on the methodology of establishing fragility curves in existing research, this paper adopts the capacity demand-to-capacity ratio model for fragility analysis, where the probability of damage exceedance can be expressed as:

$$P_f = P\left[S_D \geq S_C \mid IM\right] \tag{1}$$

In the equation: Pf represents the failure probability of the bridge structure; D represents the seismic demand of the structure; C represents the seismic capacity of the structure; IM represents the seismic intensity measure. In this study, peak ground acceleration (PGA) is selected as the seismic intensity measure. Assuming that both the seismic demand and the seismic capacity of the structure follow a normal distribution, their natural logarithms ln(D)and ln(C)also follow normal distributions. It can be yieled:

$$P_f = P\left[\ln\left(S_D / S_C\right) \geq \ln\left(1\right) \mid \mathrm{PGA}\right] \tag{2}$$

Setting the regression mean as λ and the regression standard as μ, transforming equation (1) into standard normal distribution form yields：

$$P_f = 1 - \Phi\left[\frac{\ln(1) - \lambda}{\mu}\right] = \Phi\left[\frac{\lambda}{\mu}\right] \tag{3}$$

The regression formula can be expressed as:

$$\lambda = c_1\left(\ln\left(\mathrm{PGA}\right)\right)^2 + b_1 \ln\left(\mathrm{PGA}\right) + a_1 \tag{4}$$

According to the study, the regression accuracy of quadratic polynomial is higher than that of linear regression. Therefore, this paper adopts equation（4）which is a quadratic polynomial for fitting. In this equation: represents the standard normal distribution function; a1, b1, c1 are regression coefficients.

3 Establishment of Bridge Models and Determination of Damage Indicators

3.1 Finite Element Model and Engineering Overview

This study focuses on a three-span prestressed concrete continuous rigid frame bridge in southwestern Chongqing, China. The bridge has rectangular double-leg thin-walled piers and spans (95+180+95) m with a width of (12.25×2) m. Main beam: C50 concrete; Piers: C40 concrete with 5m high reinforced zones. Varying beam height: 11.5m to 3.6m at ends, 3.3m at midspan. Symmetrical layout with 60m high piers, 8m apart double legs. Steel: HRB335 for longitudinal bars, HPB235 for hoop reinforcement. Connection: fixed connections between main beam and piers, basin-type rubber bearings at abutment ends. See Figure 1 for bridge layout.

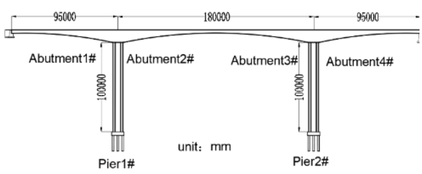

Fig. 1. Layout plan of the rigid-frame bridge.

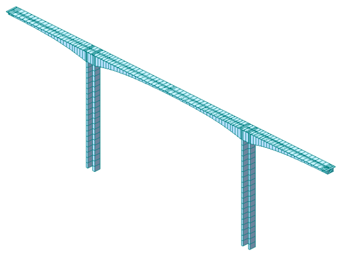

Fig. 2. Schematic diagram of the finite element model of the rigid-frame bridge.

Using Midas Civil software to establish the bridge's finite element model: main beam - variable section beam elements, piers-beam elements. Boundary conditions: fixed at pier base, rigid connections between pier tops and main beams, basin-type rubber bearings at abutments simulated with master-slave constraints. Sustained loads converted to element loads on main beam. Materials: main beam and pier concrete - Mander model, rebar - bilinear model.

To study seismic fragility, pier heights adjusted (70m, 80m, 90m, 100m), The distance between the two limbs of the entire slender section is 1/15 of the pier height, while keeping the cross-section unchanged., section reinforcement varied. Various models created, including solid rectangular pier models at different heights. See Figure 2 for illustrations.

3.2 Seismic Motion Selection and Input

Seismic characteristics significantly impact structural response, especially for high-pier continuous rigid-frame bridges. Previous studies have focused on seismic motion selection, following FEMA's "Seismic Quantification Factors for Buildings"[3]. Fifteen seismic records were chosen from the PEER Ground Motion Database for input in Incremental Dynamic Analysis (IDA) [4] to adequately consider seismic uncertainties. Detailed seismic record selections are listed in the table 1 below.

Table 1. Detailed information on selected seismic motion records.

Number	StationName	Year	Magnitude	PGA (g)
1	San Fernando	1971	6.6	0.225

2	Friuli Italy-01	1976	6.5	0.357
3	Imperial Valley-06	1979	6.5	0.236
4	Landers	1992	7.3	0.245
5	Superstition Hills-02	1987	6.5	0.357
6	Superstition Hills-02	1987	6.5	0.286
7	Loma Prieta	1989	6.9	0.511
8	Loma Prieta	1989	6.9	0.559
9	Kocaeli Turkey	1999	7.5	0.210
10	Kobe Japan	1995	6.9	0.483
11	Erzican Turkey	1992	6.7	0.496
12	Northridge-01	1994	6.7	0.443
13	Kobe Japan	1995	6.9	0.225
14	Kocaeli Turkey	1999	7.5	0.312
15	Northridge-01	1994	6.7	0.404

Based on Liu's research [5], vertical seismic effects have minimal impact on the seismic response of rigid-frame bridges, leading this study to input only the two horizontal components of the selected seismic motions.

4 Damage Index

The seismic fragility curves for bridge structures require a rational damage assessment system. Referring to established definitions, this study described seismic damage phenomena for girder bridges at various damage levels. Calculation results under PGA=1.5g showed maximum displacements of 293mm for the main girder and 172mm for the girder end bearing, categorizing them into five damage levels. Curvature ductility analysis, widely used for concrete fragility analysis, was applied, with curvature [6] ductility ratios from μ=1.0 to μ=7.0 corresponding to different damage states. Using X-Tract software, critical curvature values of solid bridge piers at different heights under various damage states were calculated. (Table 2)

Table 2. Bridge Pier Damage Index Assessment Table.

Pier Height	Damage State	Curvature Range	Curvature Ductility Ratio
100m	Slight Damage	$1.485\times10^{-3} < \varphi \leq 2.97\times10^{-3}$	1
	Moderate Damage	$2.97\times10^{-3} < \varphi \leq 5.94\times10^{-3}$	2
	Severe Damage	$5.94\times10^{-3} < \varphi \leq 1.0395\times10^{-2}$	4
	Completely Damage	$\varphi > 1.0395\times10^{-2}$	7
90m	Slight Damage	$1.467\times10^{-3} < \varphi \leq 2.934\times10^{-3}$	1
	Moderate Damage	$2.934\times10^{-3} < \varphi \leq 5.868\times10^{-3}$	2

	Severe Damage	$5.868\times10^{-3} < \varphi \le 1.0269\times10^{-2}$	4
	Completely Damage	$\varphi > 1.0269\times10^{-2}$	7
80m	Slight Damage	$1.454\times10^{-3} < \varphi \le 2.908\times10^{-3}$	1
	Moderate Damage	$2.908\times10^{-3} < \varphi \le 5.816\times10^{-3}$	2
	Severe Damage	$5.816\times10^{-3} < \varphi \le 1.0178\times10^{-2}$	4
	Completely Damage	$\varphi > 1.0178\times10^{-2}$	7
70m	Slight Damage	$1.441\times10^{-3} < \varphi \le 2.882\times10^{-3}$	1
	Moderate Damage	$2.882\times10^{-3} < \varphi \le 5.764\times10^{-3}$	2
	Severe Damage	$5.764\times10^{-3} < \varphi \le 1.0087\times10^{-2}$	4
	Completely Damage	$\varphi > 1.0087\times10^{-2}$	7
60m	Slight Damage	$1.431\times10^{-3} < \varphi \le 2.862\times10^{-3}$	1
	Moderate Damage	$2.862\times10^{-3} < \varphi \le 5.724\times10^{-3}$	2
	Severe Damage	$5.724\times10^{-3} < \varphi \le 1.0017\times10^{-2}$	4
	Completely Damage	$\varphi > 1.0017\times10^{-2}$	7

5 Seismic Fragility Analysis

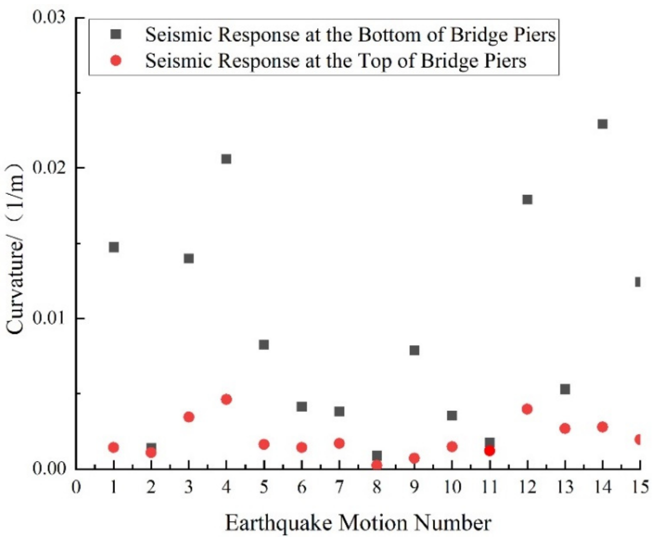

Fig. 3. Comparison of the response of the bottom and top structures of Pier 2# when PGA=1.5

In this study, seismic responses of pier top and bottom sections were computed. Results showed higher response at pier bottom than top, especially at 100m height (Fig. 3). Pier damage assessment relied on bottom section peak seismic response. Analyzing symmetric bridge piers with equal heights, 1st and 2nd segments were studied.

Time-history results at pier bottoms were extracted. Using PGA as x-axis and exceedance probability as y-axis based on Eq. (5), linear regression yielded fitting functions. Combining critical curvature values (Table 2), fragility curves for 1st and 2nd segments under seismic loads at different pier heights were obtained (Figs. 4, 5).

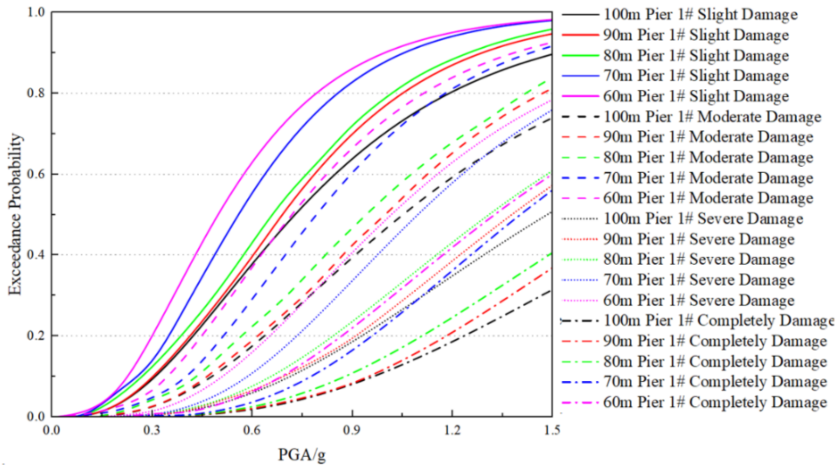

Fig. 4. Comparison of seismic fragility curves for Pier 1# of rigid-frame bridges with different pier heights

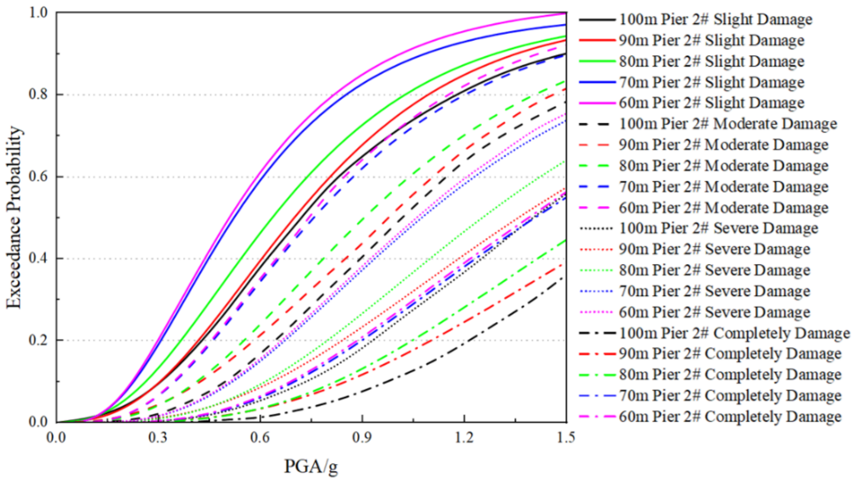

Fig. 5. Comparison of seismic fragility curves for Pier 2# of rigid-frame bridges with different pier heights

Compared to studying the impact of pier height on the seismic performance of rigid-frame bridges t-hrough the comparison of structural responses, fragility curves offer a more vivid and intuitive assess-ment of the influence of pier height on the seismic performance of rigid-frame bridges. Comparing seismic fragility curves for

1st and 2nd segments at different pier heights (Figs. 4, 5), it's found that smaller pier height rigid-frame bridges exhibit higher failure probabilities than taller ones. Increasing pier height leads to decreased yielding probability and improved seismic performance. At lower PGAs, both bridge types show similar failure probabilities due to good seismic resilience. Within 0.3g-1.2g PGA, the gap in failure probabilities between smaller and taller pier height bridges widens. For pier heights exceeding 70m, increased pier height enhances overall pier flexibility, reducing structural failure probabilities notably.

Using the pier height as the independent variable and the probability of pier failure as the dependent variable, a difference analysis was conducted on the data, and ANOVA analysis was performed on the fragility curve data for minor damage. The results of the homogeneity test of variance showed that the significance analysis based on the mean was 0.992, and the significance analysis based on the median was 1, both of which were greater than 0.05, indicating that the variance in this analysis is homogeneous and can be analyzed using one-way analysis of variance. The significance analysis of one-way analysis of variance was 0.02, which is less than 0.05, indicating that there is a significant difference in the probability of failure under seismic conditions for piers of different heights. In other words, the pier height has an impact on the seismic performance of rigid-frame bridges.

6 Conclusion

This study investigates seismic fragility of rigid-frame bridges with pier heights of 60m, 70m, 80m, and 100m Through elastic-plastic dynamic time-history analysis, seismic fragility curves for bridge piers were derived. Key findings include: (1) Increasing pier height in equal pier height bridges leads to higher fundamental vibration periods, indicating increased bridge flexibility. (2) Seismic performance improves with increasing pier height for equal pier height bridges, with 80m pier height showing significant enhancement. Optimal seismic performance and cost-effectiveness suggest a design preference for around 80m pier height over 50-70m and 90-100m options, subject to terrain and stability considerations.

Acknowledgments

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References

1. Wu Q, Zhang R and Xiang M. Comparison of Seismic Response and Vulnerability Analysis of High Pier Continuous Rigid Frame Bridges with Different Structural Forms (2022). Journal of Shijiazhuang, Tiedao University (Natural Science Edition). 35(4):1-7.

2. Song S, Wang S, Wu G. Study on seismic response of continuous rigid frame bridge with-double piers of different pier heights (2020). Earthquake Resistant Engineering and Retrofitting. 42(2):107-112.
3. Federal Emergency Management Agency(FEMA) (2009). Quantification of Building Seismic Performance Factors, Washington DC.
4. Fan X, Wang X M and Cheng S T, Seismic Vulnerability Analysis of Railway Super-High Pier Based on Incremental Dynamic Analysis (2024). Railway Standrad Design. 68(4):1-9.
5. Liu Q, Shijiazhuang Tiedao University (2023). Seismic Response Analysison (50+90+50) m Continuous Rigid Bridge of the Mati River.
6. Choi E, Desroches R, Nielson B. Seismic fragility of typical bridges in moderate seismic zones (2004). Engineering Structures.26(2): 187—199.