Research on Seismic Response Characteristics of Rigid Frame Bridges

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ABSTRACT:
A survey is given for the development of rigid frame bridges with super high piers in China and the different structural characteristics are summarized between super-high-pier bridges and ordinary bridges. Based on the finite element model of a rigid frame bridge, modal analysis is performed, and then the earthquake response of bridge is calculated respectively by spectrum method and time history method. The differences of seismic response characteristics between high piers and low piers are analyzed. Structural style's influences on seismic response of piers with different heights are compared. And the strategies on vibration mitigation for low pier are investigated. The results indicate that the characteristics of piers' earthquake response differ complicatedly, and that the low piers and high piers suffer severer response respectively under longitudinal and transverse earthquake. It's also found that changing structural style and setting bearing-damper restrainers reasonably can effectively mitigate not only the vibration of piers but also the deformation of superstructures and the shear force of bearings.
KEY WORDS: bridge engineering, rigid frame bridge, finite element model, earthquake response, super high piers, vibration mitigation for low pier

1. Introduction

With rapid progress of Western Development in China, brilliant achievements have been procured in bridge engineering. Because of the complex landform in Western China, the bridges with long span and high piers play very important roles for their eximious capabilities of span and economical costs. In China recently, a series of super-high pier rigid frame bridges with the height of over 100 meters have been constructed as shown in table1 [1].

Table 1：The constructed rigid fame bridges with super high piers in China (H: Highway; R: Railway)

Name of bridge	H or R	Location	Height of piers (m)	Name of bridge	H or R	Location	Height of piers (m)
Red River	H	Yunan	123	Taizao River	H	Shanxi	123.5
Huatupo	R	Guizhou	110	Longtan River	H	Hubei	178
Lizigou	R	Guizhou	107	Weijiazhou	H	Hubei	114.2
Qingshuigou	R	Guizhou	100	Mashui River	H	Hubei	143.2
Badu Nanpan	R	Guizhou	100	Dukou River	R	Hubei	128
Luo River	H	Shanxi	143.5	Mashui River	R	Hubei	108

Fig.1 shows Red River Bridge built in 2003, from which it can be seen that the piers differ greatly in heights with discrepant height of beyond 100 meters! The different characteristics between super high-pier bridges and ordinary bridges can be described as:(1) The high-pier bridges exhibit large flexibility and small damping with very heavy superstructures. (2) The lateral stiffness of piers with different height differs greatly, which leads to their distinct dynamic characteristics. (3) Geometric nonlinearity with large displacement in super high piers occurs under earthquakes, which induces buckling damage with a increscent probability [2,3]. (4) The engineering site is charactered with complex geology and terrain; so the input ground motion of piers are different [4-6].

Fig.1 Red River Bridge in Yunnan province China

The current Codes for seismic design of highway engineering or railway engineering in China have not provided seismic designing specifications for this kind of bridge. So, it's necessary to study the seismic response characteristics of piers with different heights, and the research is surely significant in seismic design, appraisal and strengthening for this kind of bridges.

2. Bridge example and finite element model

2.1 Bridge example

A typical of existing Shanxi province highway rigid frame bridge is shown in Fig.2. Fortification intensity is 7 degree. Young's modulus is 34.5Gpa for superstructures and 32Gpa for piers; mass density =2.5Mg/m^3. The geometric configurations, and the thin-walled box piers and section of beam are given. A rubber bearing was set between p1 and superstructures.

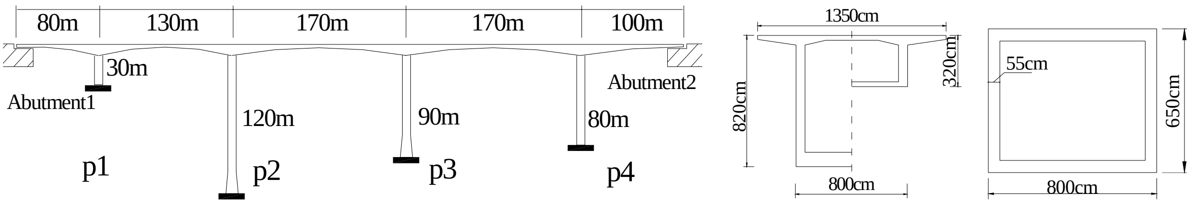


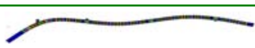
Fig.2 Elevation of example bridge

2.2Finite element model

Based on actual structural styles, the finite element models are constructed, which consists of 680 elements. The piers and beams are modeled with spatial beam element and using springs simulates the roles of bearings with the precondition of no pounding between superstructures and abutments.

3.Modal analysis

Table2: Modal analysis results

No.	Freq.(HZ)	Mode	Characteristic	No.	Freq.(HZ)	Mode	Characteristic
1	0.2074		Transverse	4	0.3417		Transverse
2	0.2323		Longitudinal	5	0.5149		Transverse
3	0.2933		Transverse	6	0.6504		Longitudinal

The modal analysis results are shown in table2. The results indicate that 4 of the former 6 modes show transverse free vibration including the first mode. And the natural frequency is much lower in super-high-pier bridges than ordinary bridges.

4.Seismic response analysis

4.1 Input ground motion

Based on the seismic safety evaluation report of engineering sites [7], acceleration response spectrum and artificial time history ground motion with the peak of 100gal are given. The direction of input ground motion can be described as: case1:x+z,z=2x/3， case2: y+z,z=2y/3[8], in which x, y and z respectively represent longitudinal, transverse and vertical coordinate.

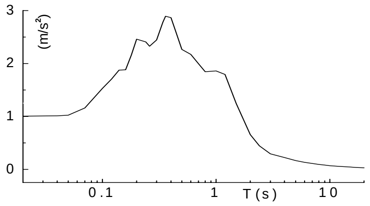


Fig.3: Spectrum

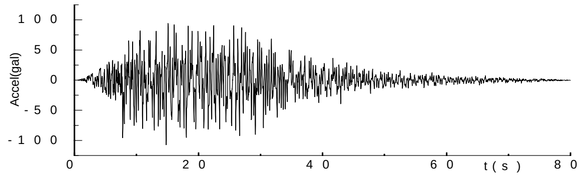


Fig.4: Artificial ground motion

4.2 Response spectra analysis

Table 3: Results of spectra analysis (unit: 10^3kN,m)

	Pier	Location	**P**	$\mathbf{V_x}$	$\mathbf{V_y}$	$\mathbf{M_x}$	$\mathbf{M_y}$		**P**	$\mathbf{V_x}$	$\mathbf{V_y}$	$\mathbf{M_x}$	$\mathbf{M_y}$
Case1	p1	Top	4.0	1.1	0	0	0	**Case2**	3.7	0.1	3.9	0	0
		Bottom	4.2	3.2	0	0	83.3		4.0	0.1	4.6	159.7	1.5
	p2	Top	5.9	2.6	0	0	100.2		6.2	0.9	2.4	15.1	38.7
		Bottom	7.8	3.8	0	0	188.1		7.5	1.4	3.3	197.1	32.9
	p3	Top	6.6	3.8	0	0	143.7		5.5	1.6	2.5	22.2	32.7
		Bottom	7.9	4.5	0	0	207.7		7.4	2.3	4.3	165.1	77.3
	p4	Top	6.5	4.3	0	0	149.2		6.1	1.31	1.47	17.70	68.2
		Bottom	7.6	5.1	0	0	209.9		7.2	2.06	2.35	115.81	47.1

The results indicate that the directions of input earthquake have obvious influences on rigid frame bridges. It can be described as: (1) The response under transverse earthquake is much more complex than that under longitudinal earthquake. The transverse response of structures under longitudinal earthquake $\mathbf{M_x}$ and $\mathbf{V_y}$ are quite trivial; However the longitudinal response of structures under transverse earthquake $\mathbf{M_y}$ and $\mathbf{V_x}$ could not be neglected. (2) Under longitudinal earthquake, the lower piers (P4) rigidly connected with the superstructures undergo severe response. (3) Under transverse earthquake, the higher piers undergo severe response.

4.3Time history analysis and strategies on vibration mitigation

As has been demonstrated, low and high piers undergo severe response respectively under longitudinal and transverse earthquake. Accordingly it is necessary to study vibration mitigation for piers. In this study three projects (Viz. rigid connection, setting bearing, and setting bearing-damper restrainers between p1 and superstructures) are adopted to be compared with each other. Bearings are modeled by linear springs with the stiffness of 10^4kN/m [9]; Dampers are set in two directions shown in Fig5. Damping coefficient *c* ranges from10^3 to 10^4 kN·sec/m at the interval of 10^3 kN ·sec/m. The vibration reduction ratio f can be defined as $f=(r_o- r_a)/ r_o\times100\%$.

Where, r_o and r_a respectively denote the response without dampers and with dampers.

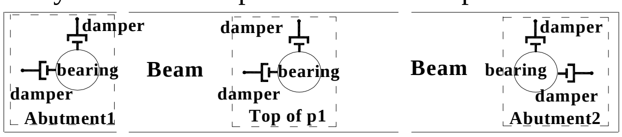
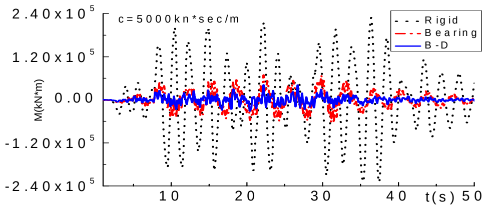


Fig5: Collocation of bearing and dampers



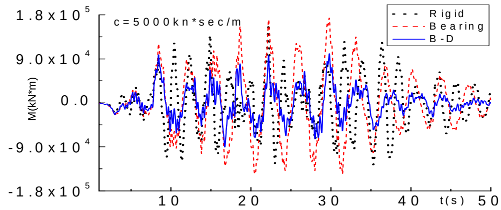
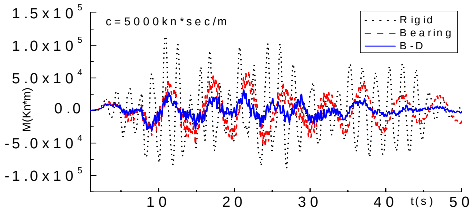


Fig6: Longitudinal moment of p1（case1） **Fig7: Longitudinal moment of p2（case1）**



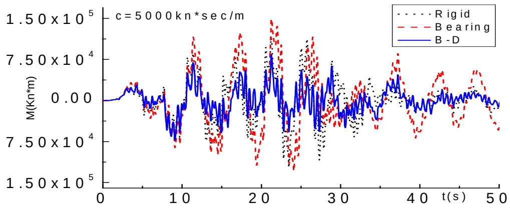
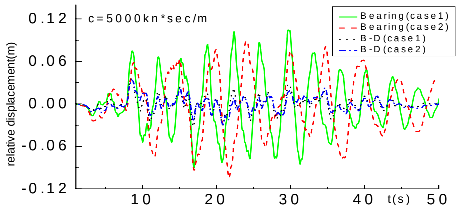


Fig8: Transverse moment of p1（case2） **Fig9: Transverse moment of p2（case2）**



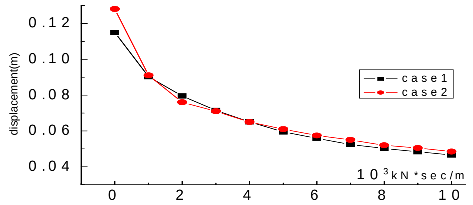
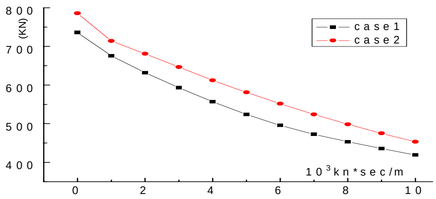


Fig10: Relative displacement between p1 and beam **Fig11: Displacement of beam in different damping**



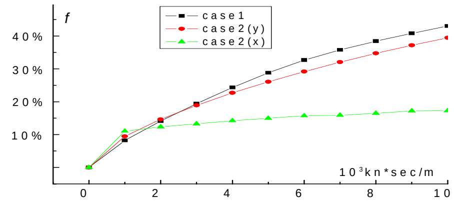
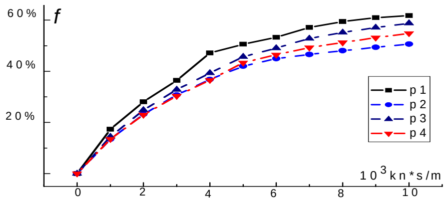


Fig12: Shear force of bearing **Fig13: Shear force reduction ratio of bearing**



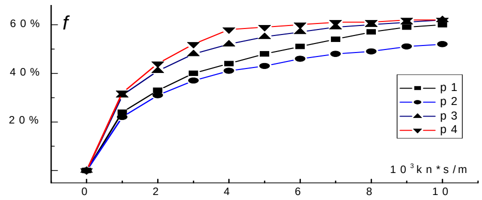


Fig14: Moment reduction ratio of piers（case1） **Fig15: Moment reduction ratio of piers（case2）**

The results indicate：(1) Compared with fixed connection, the response of low piers was 2/3~3/4 reduced with setting bearings (fig6、8)；however the response of high piers was 1/4~1/3 magnified (fig7、9).(2) Setting two-dimensional dampers could effectively mitigate not only the forces of high piers and deformation of beam but also the relative deformation between low pier and superstructures(fig10、11).(3) The shear force of bearing was much decreased and the shear force reduction ratio was heightened with increscent damping coefficient (Fig.12、13). (4)With the increscent damping coefficient, vibration reduction ratio of moments of piers enhanced gradually .However, vibration reduction ratio increased inconspicuously when it reached a value (about 5×10^3 KN*sec/m in this study)(Fig14、15). Although large damping coefficient can heighten vibration reduction ratio, too large damping coefficient is inadvisable considering the factors of vibration reduction ratio and costs [10]. Only a proper coefficient can archive satisfying effect.

5.Conclusions

(1) Super-high-pier rigid frame bridges are charactered with transverse free vibration including the first mode with low natural frequency obviously.
(2) The directions of input ground motion have distinct influences on response of super-high-pier rigid frame bridges. Under transverse earthquake, the structures show more complex response. Low piers and high piers undergo severer response respectively under longitudinal and transverse earthquake.
(3) Changing the connection styles between low pier and superstructures as well as setting bearing-damper restrainers with proper damping coefficient can effectively mitigate the response of piers and the deformation of superstructures. Generally speaking, bearing-damper restrainer is an effective measure for vibration mitigation.

Acknowledgements:
This research is granted by National Natural Science Fund (NO.50708100) and the Institute of Engineering Mechanics Fund (NO.2007B02).

Nomenclature

x= longitudinal coordinate	**P=**axial force	**V_x=** longitudinal shear force
y=transverse coordinate	**M_x=** moment about x coordinate	**V_y=** transverse shear force
z=vertical coordinate	**M_y=** moment about y coordinate	

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