GSJ: Volume 12, Issue 7, July 2024, Online: ISSN 2320-9186

www.globalscientificjournal.com

SEISMIC PERFORMANCE OF SIMPLY SUPPORTED BRIDGES WITH RESTRAINER SYSTEMS UNDER NEAR-FAULT VELOCITY IMPULSIVE EARTHQUAKE

Gavriliuk Maksim[1] , Kelvin Nyoni Mkwezalamba [2]

Author Details

Author Gavriliuk Maksim *is currently pursuing masters degree program in Civil engineering（Bridge and Tunnel Engineering）at Southwest Jiaotong University, Chengdu, Sichuan, China. E-mail:* maximys-95.ru@mail.ru

Co-Author Kelvin Nyoni Mkwezalamba *is currently pursuing masters degree program in Civil engineering （Road and Railway Engineering） at Southwest Jiaotong University, Chengdu, Sichuan, China.Email:* kelnyoni@hotmail.com

KeyWords

Simply supported bridge, Near-fault ground motion, Cable restrainer, Initial gap

ABSTRACT

Simply-supported bridges with isolation bearings are vulnerable to near-fault pulsed ground motion. Such bridges could suffer serious seismic damages, such as unseating, because of the insufficient seat width or excessive displacements of the girder, as evidence collapse of the main girders of the Gaoyuan Bridge in the 2008 Wenchuan earthquake. Unreasonable design often leads to damage even or collapse of the bridges. Now more and more bridges that apply isolated devices are designed, however, the codes haven't given clear rules about how to design these devices, which creates puzzles for designers. A seismic displacement control method based on unseating prevention device (UPD) is proposed to solve the problem of beam-falling risk in bridges with laminated rubber bearings (LRB). Take a six-span highway simply-supported girder bridge as an example, nonlinear time-history method is used to analyze the influence laws of an initial gap on the relative pier-beam displacement under near-fault pulsed earthquake with different seismic acceleration. The study shows that under design earthquake conditions (0.4g-0.5g), the relative displacement between piers and girders remains within safe limits, but under unexpected (0.6-0.85g) earthquake scenarios, beam unseating can occur. The implementation of cable restrainers significantly reduces peak relative displacements, thereby reducing the risk of beam unseating damage. It is recommended to set the initial gap within the range of 60-80% of the seat length to prevent beam unseating without causing excessive increases in internal pier forces. Additionally, the internal force of the pier bottom section decreases with an increase in the restrainer gap, emphasizing the need to check the bearing capacity of the pier bottom section to prevent damage, especially when the initial gap is 20%. Overall, the findings suggest that proper restrainer initial gap can effectively mitigate bridge damage and ensure structural safety during seismic events.

1. Introduction

Several bridge earthquake damage investigation reports have shown that the phenomenon of large displacement or even falling beams in the upper structure of the bridge is very prominent, and the beam unseating devices, as an important component to limit the relative displacement of the bridge and prevent the disaster of falling beams, was not caused enough attention in the design and construction. During the 2008 Wenchuan earthquake, three bridges experienced beam failures. The fifth span of the Baihua Bridge on the G213 highway collapsed, with insufficient support between two spans leading to significant longitudinal displacement and ultimately causing the collapse of the entire span[1]. The tenth span of the Miaoziping Minjiang Bridge on the Duwen highway, with a pier height of about 70 meters, also experienced beam failure due to inadequate support length and significant longitudinal displacement of the main beam during the strong earthquake. Additionally, the South Ba Bridge on the S105 highway, which was under construction at the time, collapsed entirely as the bridge deck had not been paved and the joints in the hollow slab were not poured. Most of the main beams fell into the river.

The Beam unseating mainly occurs on bridges that have been subject to neat-fault ground motion. Near-fault ground motions have unique characteristics that differ from far-fault ground motions. These ground motions are characterized by a large velocity pulse, which exposes structures to high input energy at the beginning of the earthquake. Directivity effect due to the propagation of the rupture towards the recording site can significantly influence these pulses. Research has shown that certain combinations of site location, configuration of the seismic source, and direction of fault rupture can result in a significant enhancement to the long period motions at a bridge site, which can be very damaging to certain classes of bridges.

In the last three decades, many devices have been implemented to retrofit bridges. Those devices employed different methodologies in controlling the structural response during a seismic event [2].These unseating prevention devices were developed primarily to mitigate the drawbacks of excessive support lengths by limiting seismic displacements. For example, various types of unseating prevention devices were proposed for highway bridges including stiffness dependent restrainers or energy dissipation devices [3]. Vlassis (2004) assessed the longitudinal seismic behavior of straight bridges with in-span hinges retrofitted by cable restrainers. He then subjected the design to actual seismic excitation by performing experimental tests. The results indicated that the cable restrainer was able to diminish the bridge hinge relative displacement [4]. Besides that, Gao (2018) developed a design procedure and theoretical formulation for steel cable restrainer and assessed the influence of equipping the highway bridge with the steel restrainer. The results showed that the performance of the developed restrainer is highly effected by the bridge bent height, the effect of the restrainer will be negligible if the pier height more than 15 m [5]. In addition, Guo, Zhao and Li (2012) conducted an experimental study to evaluate the performance of SMA restrainers to alleviate the unseating of highway viaducts [6]. While Shrestha (2018) performed experimental and numerical studies to evaluate the effects of SMA restrainer on bridge performance subjected to a special variety of ground motions. The results from these studies verified that the SMA restrainers can decrease the relative opening displacement [7].

Feng (2000) and Kim (2000), on the other hand, assessed the effects of implementing viscoelastic dampers in bridges to avoid the superstructures' unseating and pounding of decks throughout a seismic event. They concluded that utilizing these dampers would lead to the hinge openings without enlarging the bridge bent ductility demand [8], [9].

"Guidelines for Seismic Design of Highway Bridge" in China (JTG/T B02-01-2008) [10] only provides simple avoidance principles and general guidance for unseating prevention device design. Taking the beam bridge with the cable restrainer device as the background, this paper researches the behavior of the typical cable restrainer with the lower structure, values of an initial gap at different seismic dynamic intensities are analyzed and compared. Through this research, it provides technical support for the application of cable displacement restrainer devices in bridges.

2. Minimum seat length

Currently, the simplest method to prevent beam unseating is to reserve enough support length through seismic design, which belongs to the first-level seismic measure. According to the "Seismic Design Code for Highway Bridges" (JTG/T 2231-01-2020) [11], the minimum support length has been revised, taking into account factors such as bridge pier height and beam length based on the comprehensive consideration of the American ASSHTO specification, giving the calculation formula for the overlap length of the upper structure of a girder bridge, expanding the applicability range.

In the upper structure of simply supported girders and continuous girders, there should be a certain distance between the end of the girder and the pier, abutment cap, or edge of the cap beam, as shown in Figure 1. The minimum value calculation formula is as follows (and should not be less than 60cm):

$$\boldsymbol{a} \geq 50 + 0.1\boldsymbol{L} + 0.8\boldsymbol{H} + 0.5\boldsymbol{L_k}$$

Where: $\boldsymbol{L}$ - The total length of the superstructure (m)；

$\boldsymbol{H}$ - The average height (m) of the piers supporting a superstructure, and the stiffness of the abutment is 0；

$\boldsymbol{L_k}$ —The maximum single-hole span diameter (m) of a superstructure.

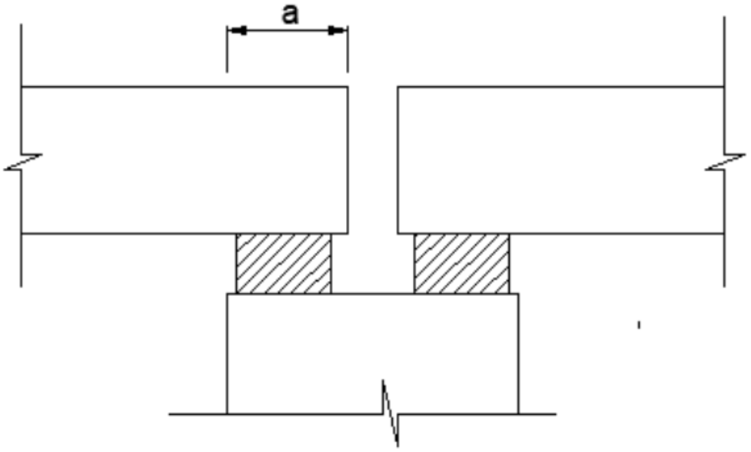


Fig. 1 Schematic diagram of the minimum seat length

In this paper, the design seat length is set at 70 cm.

3. Unseating prevention device

In order to limit the excessive relative displacement caused by near-fault ground motion with velocity pulse, an unseating prevention device (cable restrainer) is applied to the structure. Cable displacement restrainers were installed at both sides of the box girders and were anchored to the bridge's piers (capping beam). There were 4 restrainers in total on one side of the bridge's superstructure which were composed of four prefabricated small box girders. A schematic drawing of the commercial CDR system was presented in Figure 2, whose yield force was 1540 kN with an axial stiffness of 1.7×10^4 kN/m (the total axial stiffness of the cables at one side of the bridge substructures was 6.8×10^4 kN/m). The arrangement of the device is also shown in Figures 3.

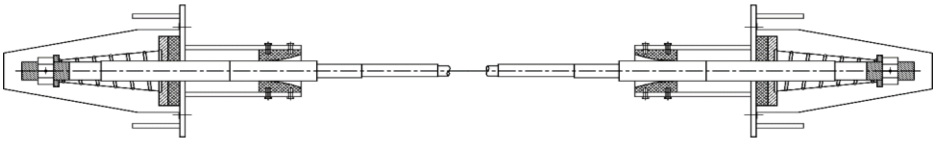
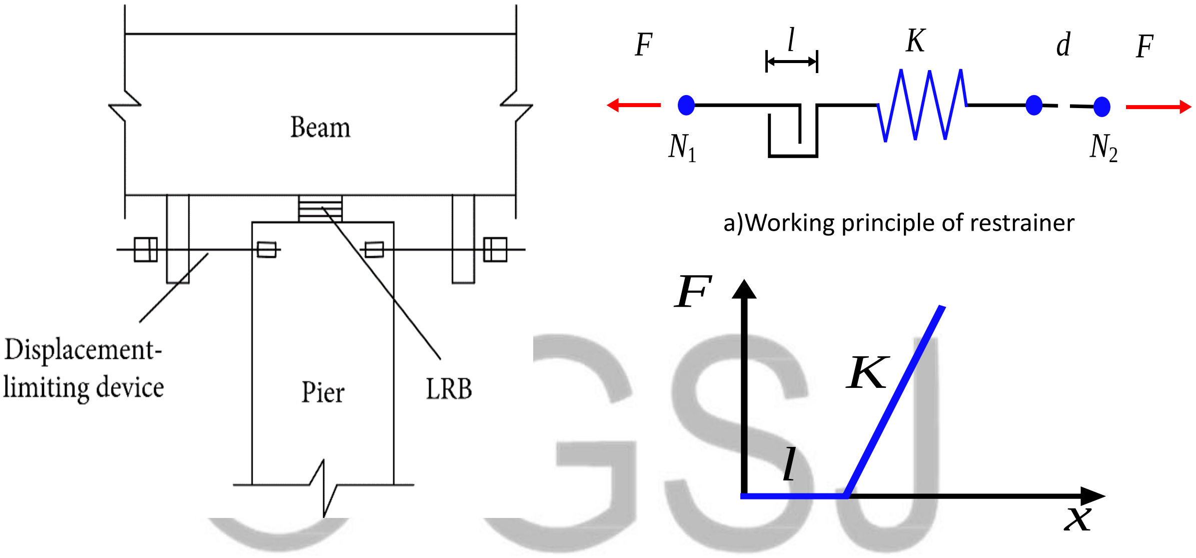


Fig. 2 Schematic drawing of cable displacement restrainer

The anti-falling beam device with no energy-consuming effect basically adopts a linear model, and the seismic force of the anti-falling beam device is calculated by formula (3-1):

$$F=\begin{cases}K(d-l) & d-l>0\\ 0 & d-l\leq 0\end{cases} \tag{3-1}$$

Where, *F* is the seismic force of the anti-falling beam device; *d* is the relative displacement between the piers and beams; *l* is the initial gap of the restrainer; *K* is the stiffness of the restrainer. The working principle and constitutive relationship of the restrainer are shown in Figure 3.



a)Working principle of restrainer

b) Arrangement of restrainers

c) Linear relationship of restrainer

Fig. 3 Arrangement, working principle, and linear model of restrainer

4. Numerical example

The bridges adopted in this study represent a typical highway bridge located in a high seismic region. The bridge encompasses simply supported concrete box beams. The bridge has a total of 6 spans with 5 column piers and two end abutments. The length of the span is 20 m. and the total length of the bridge is 120 m. The bridge's superstructures consist of four 1.3 m high prestressed precast single-cell concrete box girders. The concrete material is C35. The total width of the bridge is 12.6 m. Bridge piers denoted as #0 - #5 in Figure 3, are designed with circular C35 concrete columns. The columns have a solid circular cross-section with a diameter of 1.4 m and a height of 10m as shown in Figure 4. Each column at the intermediate piers is supported by a 10 m by 15 m by 4 m deep pile cap on top of 2 cast-in-place drilled shafts. Each drilled shaft is 1.5 m. in diameter and 30 m in length. The expansion joint between the two spans measures 60 mm in length.

Minimum seat length: according to the "Highway and Bridge Seismic Design Specifications" (JTGT 2231-01-2020) [11]. The calculation formula given calculates that the minimum support length is 70 cm.

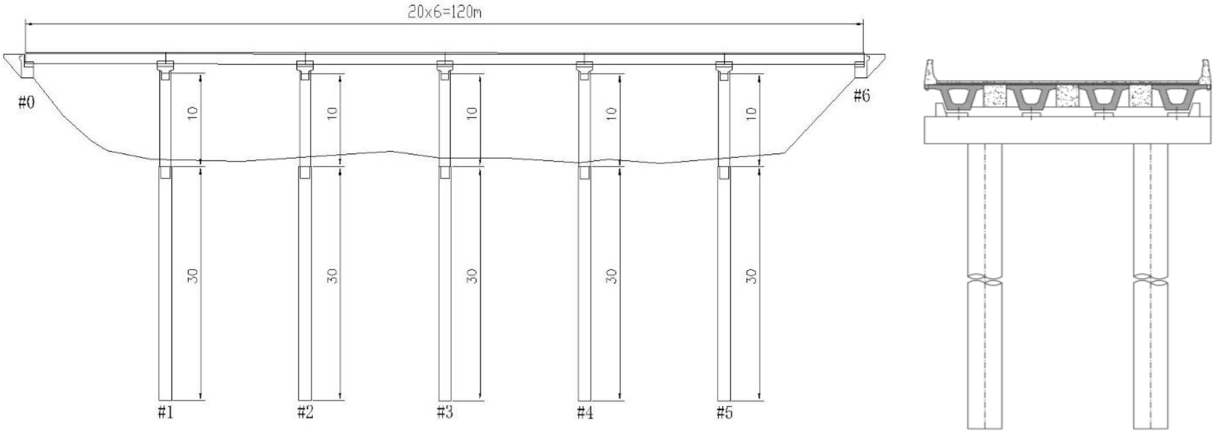


Fig. 4 Elevation and transverse section of the bridges

The 3D finite element model of the bridge is prepared using the software SAP2000 (Figure 5). In this paper, the program is used to develop the three-dimensional numerical model of the bridge and perform non-linear time history analyses. Both pier and girder are modeled by frame beam element, while the laminated rubber bearings are modeled by using Wen plastic elements with nonlinear property. The restrainer is modeled by using Hook element.

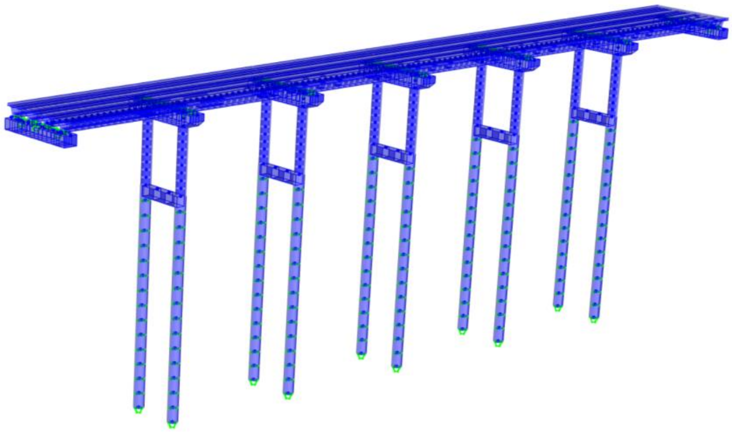


Fig. 5 Three-dimensional numerical model of the bridge.

5. Ground motion input

Near-fault seismic activity has the characteristics of long pulse period and large peak value, which is highly destructive to bridge structures, especially small and medium-span beam bridges with large quantities and wide areas. In this study, near-fault ground motions with velocity pulse records are selected as input ground motion from 1999 Chi-Chi, 1995 Kobe, and 1994 Northridge, 1992 Landers earthquakes. These records are taken from station numbers TCU 067, Port Island, Jensant plant and Lucerne, respectively. The ground motion records are obtained from the PEER Strong Motion Database [12]. The database has information on the site conditions and the soil type for the instrument locations. The original seismic data are shown in Table 1. In Figure 6, the acceleration response spectrum curves of the elastic single-degree-of-freedom system with a 5% damping ratio line for 4 seismic actions are plotted. In order to analyze the restraining effect of the device and the seismic response of the bridge structure under different shaking intensities, the peak acceleration (PGA) is adjusted to 0.4~0.85g, and the input is along the longitudinal direction of the bridge.

Table 1 Properties of selected near-fault and far-fault ground motion records

№	Earthquake	Mw	Station	PGA(g)	Rjb(km)	PGV (cm/s)	PGV/PGA
1	Kobe Japan	6,9	Port Island	0,36	3,32	90,59	260,28
2	Chi-Chi	7,6	TCU 067	0,48	1,10	94.30	181,10
3	Northridge	6,69	Jensant plant	0,41	0,00	111.00	270,73
4	Landers	7,28	Lucerne	0,73	2,19	133	183,45

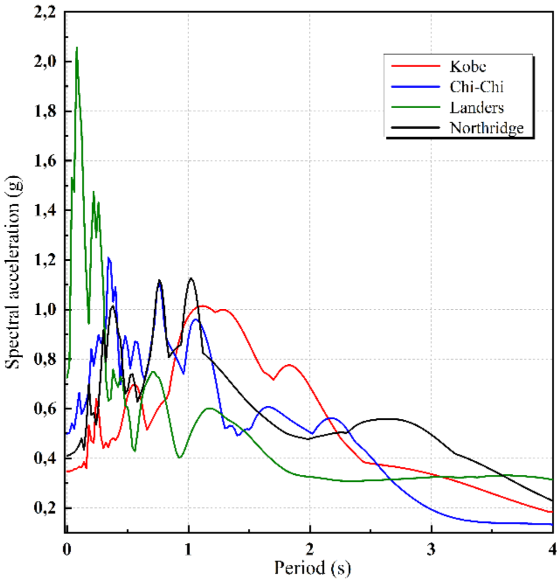


Fig. 6 Acceleration response spectrum

6. The impact of the initial gap

Under normal circumstances, a small and medium-span bridge will set a certain initial gap between the restrainer and the main beam, so that the beam body has a certain ability to freely shift under external load. Under the action of an earthquake, the main beam will produce a large displacement response after the slip of the plate rubber bearings, and the beam body can easily unseat. Therefore, the seismic response of the bridge must be closely related to the value of the initial gap, and the reasonable initial gap value of the restrainer is also the key to the best seismic performance of the stop.

In order to discuss the reasonable value of the initial gap of the cable restrainer, this paper takes the design seat length **a** as the design parameter, and takes different scale coefficients θ as the initial gap value of the restrainer, and discusses the law of the influence of the initial gap on the seismic response of the highway simple support beam bridge. According to existing research on the initial gap range, the proportion coefficient θ is increased by 20% from 20% to 80% in increments, totaling 4 operating conditions.

The initial gap design values for each operating condition are shown in Table 2.

Table 2 Different initial gap design table

Scale coefficients θ	20%	40%	60%	80%
Design seat length a	70			
Initial gap (cm)	14	28	42	56

6.1 Effect on relative pier-beam displacements

Figure 7 describes the maximum relative displacement value between piers and girders under different initial gaps, it can be seen that as the seismic acceleration increases, the relative displacement also increases. Therefore, under the action of the design earthquake (0.40g and 0.50g), the relative displacement between piers and girders did not exceed seat width. Under the action of the unexpected earthquake (0.60g, 0.7g,0.85g), relative displacement exceeded the seat width and led to the beam unseating. When the gap increases, the restrainer's ability to limit the beam displacement weakens. Upon implementing the UPD, a substantial reduction in peak relative displacement is observed. The peak relative displacements decrease significantly, the different restrainer gap limit rates can be seen in Table 3. It can be concluded that once the cable restrainer is engaged, the relative pier-beam displacement can be effectively decreased and the risk of beam unseating damage to the bridge structure can be reduced.

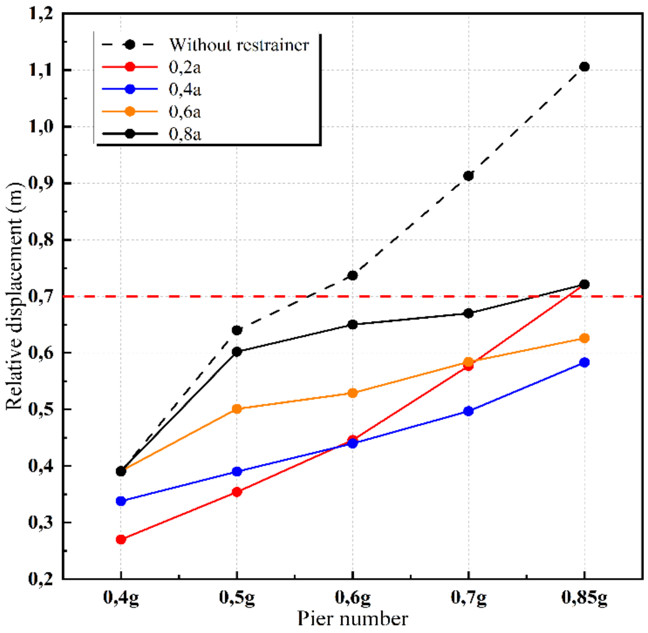
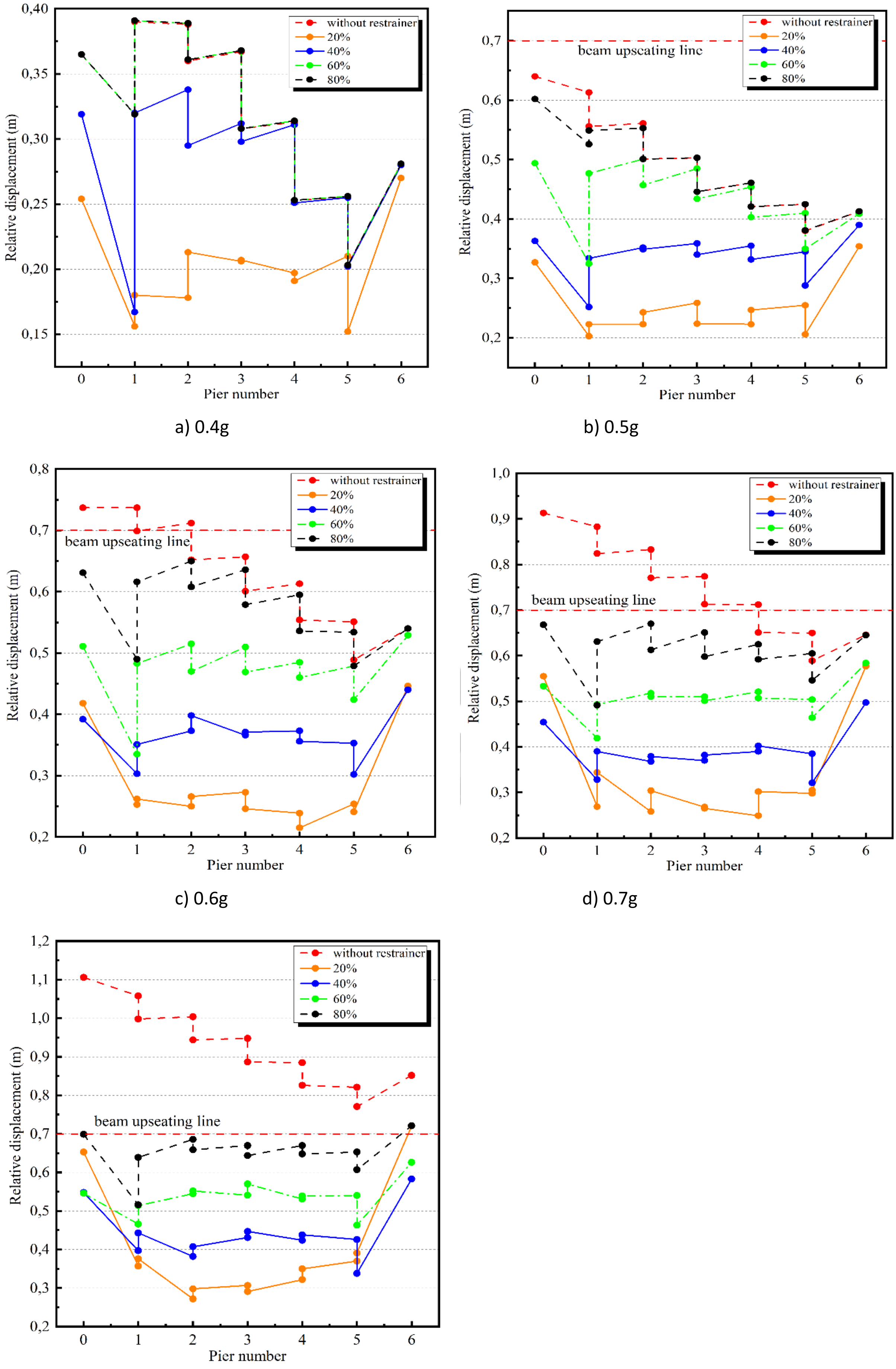


Fig. 7 Elevation and transverse section of the bridges

Table 3 Different restrainer gap limit rates (%)

Design seat length a	0,4g	0,5g	0,6g	0,7g	0,85g
20%	31	45	39	37	35
40%	13	39	40	46	47
60%	0	22	28	36	43
80%	0	6	12	27	35



a) 0.4g

b) 0.5g

c) 0.6g

d) 0.7g

e) 0.85g

Fig. 8 Comparison chart of the relative displacement of each pier under different restrainer gap

Figure 8 illustrates the distribution of relative pier-beam displacements in the longitudinal direction at different initial clearance values and different intensities. From the figure, it can be seen that the distribution of relative displacements along the bridge is nonlinear, with the largest deformations observed in the left part of the bridge, which is due to the beam collision effect where the collision force on supports 1 and 2 is much greater.

It can also be observed that with an initial clearance of 20%, the value of relative deformation is minimal, but with an increase in deformation intensity, the deformations on the abutments increase significantly.

6.2 Effect on pier displacement

The relationship between the maximum displacement response of the pier top and and the initial gap of the restrainer is shown in Figure 9. As can be seen from Figure 4., when the gap between the stopper is 20%, the seismic force transmitted by the beam body to the lower structure through the stopper is very large, causing the lateral displacement of the pier body to become larger. And when the gap between the stops is greater than 20%, as the gap increases, the displacement of the top of each pier gradually begins to decrease; when the initial gap is large, the displacement of the top of the pier has the minimum values and for design earthquake (0.4g, 0.5g) does not change at all, because the restrainer didn't start working.

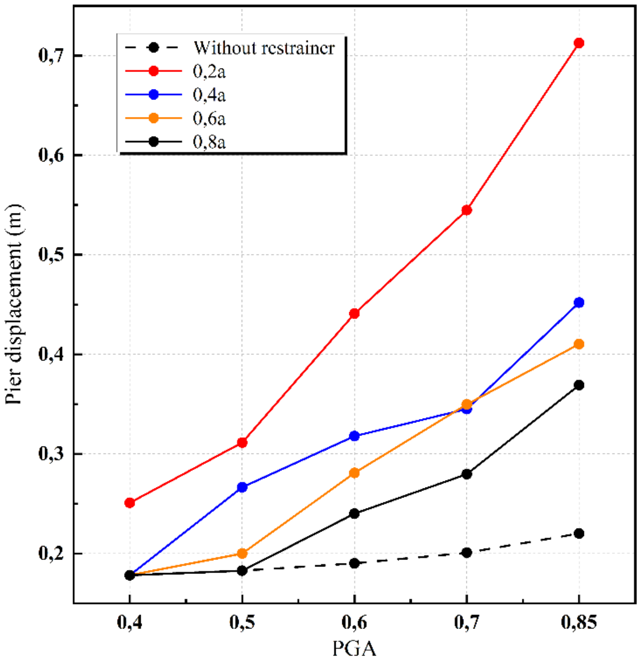
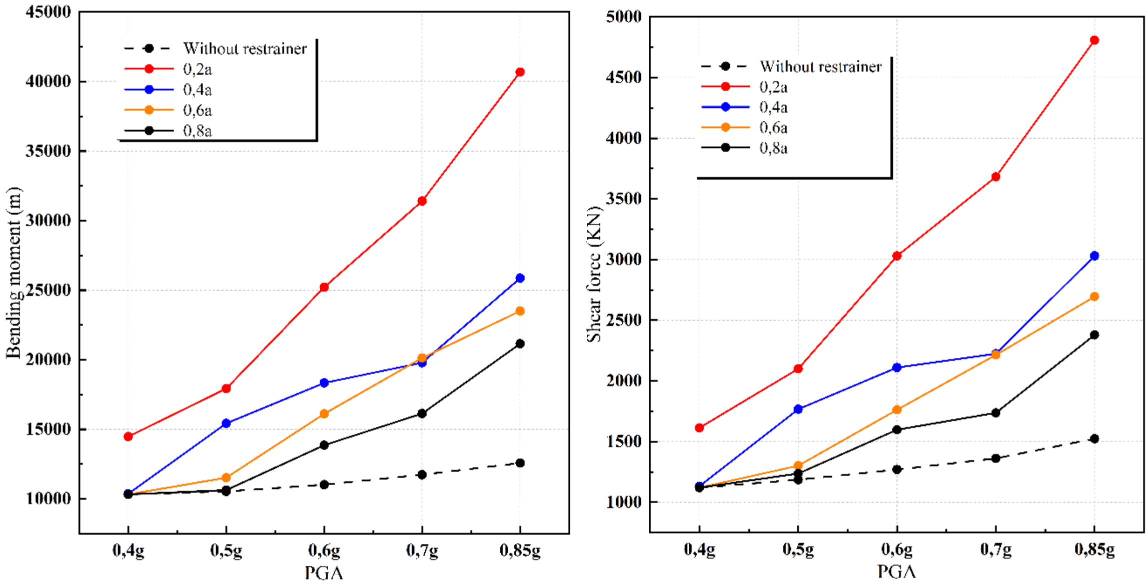


Fig. 9 Comparison chart of the maximum pier displacement under different restrainer gap

6.3 Effect on internal forces

A simply supported beam bridges not only suffers from the damage of main beams but also saffers from the shear failure, bending failure, and bending-shear failure of pier bottom. In order to avoid this kind of damage, it is fairly necessary to check whether the bearing capacity of pier bottom section meets the requirements.

It can be seen from figure 10 that the law between the internal force of the bottom of each pier and the gap between the restrainer is consistent with the law of displacement of the top of the pier. Overall, with the increase of the gap between the restrainer, the internal force of each pier gradually decreases; when the gap is greater than 40%, the internal force of the cross-section gradually stabilizes, and the amplitude of change is very small. When the initial gap is 20%, the restrainer transverses a huge seismic force to piers, resulting in a significant increase in the internal force of the pier body, which considered as the most disadvantageous situation.



a) Bending moment b) Shear force

Fig. 10 The law of internal change at the bottom of the pier with different gaps

7. Conclusions

In conclusion, the analysis presented in this academic paper highlights the significant impact of initial gaps on the behavior of simply supported beam bridges under near-fault pulsed ground motion. The study demonstrates that the relative displacement between piers and girders increases with seismic acceleration, leading to beam unseating and potential damage to the bridge structure. However, the implementation of the UPD shows a substantial reduction in peak relative displacement, effectively reducing the risk of beam unseating.

Three key points can be highlighted from the analysis:

1. Under the action of unexpected earthquakes, relative displacement exceeded the seat width, leading to beam unseating; however, the cable restrainer effectively decreased relative pier-beam displacement and reduced the risk of damage.
2. The recommended value of the initial gap is set within the range of 60-80% of the seat length. At such a gap value, the reduction of relative deformations will be sufficient to prevent the beam unseating, and will also not lead to excessive increases in internal pier forces.
3. The internal force of the pier bottom section decreases with an increase in the gap between the restrainer, stabilizing when the gap is greater than 40%. The internal force significantly increases when the initial gap is 20%, highlighting the importance of checking the bearing capacity of the pier bottom section to prevent damage.

Overall, the findings emphasize the importance of considering initial gaps and the effectiveness of cable restrainers in mitigating the effects of seismic loading on simply supported beam bridges. Future research could further investigate the optimal design of restrainers to enhance the seismic performance of bridge structures.

References

[1] Jiang Jinsong, Zhuang Weilin, Liu Zhenyu. Investigation and analysis of earthquake damage of Baihua Bridge in Wenchuan Earthquake [J]. Bridge construction, 2008(06): 41-44+52.

[2] Shrestha B, Hao H, Bi K. Devices for protecting bridge superstructure from pounding and unseating damages: an overview. Struct Infrastruct Eng 2016;13(3):313–30.

[3] Xiang N, et al. Passive seismic unseating prevention strategies implemented in highway bridges: A state-of-the-art review. Eng Struct 2019;194:77–93.

[4] Vlassis AG, Maragakis E, Saiidi M. Experimental evaluation of longitudinal seismic performance of bridge restrainers at in-span hinges. J Test Eval 2004;32:96–105.

[5] Liu C, Gao R. Design method for steel restrainer bars on railway bridges subjected to spatially varying earthquakes. Eng Struct 2018;159:198–212.

[6] Guo A, Zhao Q, Li H. Experimental study of a highway bridge with shape memory alloy restrainers focusing on the mitigation of unseating and pounding. Earthquake Eng Eng Vibrat 2012;11(2):195–204.

[7] Shrestha B, et al. Experimental study on relative displacement responses of bridge frames subjected to spatially varying ground motion and its mitigation using superelastic SMA restrainers. Soil Dyn Earthquake Eng 2018;109:76–88.

[8] Feng MQ, et al. Viscoelastic dampers at expansion joints for seismic protection of bridges. J Bridge Eng 2000;5:67–74.

[9] Kim JM, Feng MQ, Shinozuka M. Energy dissipating restrainers for highway bridges. Soil Dyn Earthquake Eng 2000;19:65–9.

[10] Ministry of Transport of the People’s Republic of China (MTPRC), Guidelines for Seismic Design of Highway Bridges, JTG/T B02-01-2008, MTPRC, Beijing, China, 2008.

[11] JTG/T 2231-01—2020."Specifications for Seismic Design of Highway Bridges"[S].Beijing: People's Communications Press, 2020.

[12] PEER Ground Motion Database. 2018. http://ngawest2.berkeley.edu/.