Latin American Journal of Solids and Structures
www.lajss.org

Seismic Performance of Cable-sliding Modular Expansion Joints Subject to Near-fault Ground Motion

Abstract

According to the research fruits of the diverse damages of bridge in the past, bearings' invalidation is the main reason of the damage of isolated bridges and causes oversized relative displacements between pier and girder. Eventually, it may lead to severe collision of superstructure. It is extremely dangerous when near-fault motion occurs, because it has obvious velocity pulse effect and increases the risk of colliding between girders.

Aiming at this problem, this paper puts forward a device named cable-sliding modular expansion joints (CMEJs) that can control the relative displacement and avoid collision. The working principle and mechanical model are described, and then based on a triple continuous seismic isolation bridge which has different heights of piers, a 3D model with or without CMEJs is established. The responses of continuous beam bridges using the CMEJs are comprehensively inspected under the consideration of the velocity pulse effect, and then a real simulation of limit performance of CMEJs is made, focused on CMEJs' restraining effect.

The calculation shows that velocity pulse effect would magnify the seismic response of isolation bridges. In addition, the device can well control the displacement and prevent collisions. And the isolation technology combined with CMEJs can be more effective to play their respective roles. The advantage in controlling displacement is obvious.

Keywords

near-fault ground motion, the effect in limiting relative displacement; cable-sliding modular expansion joints (CMEJs), seismic isolation bridge, velocity pulse effect

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http://dx.doi.org/10.1590/1679-78251486

Received 29.07.2014
In Revised form 11.11.2014
Accepted 26.11.2015
Available online 17.12.2014

1 INTRODUCTION

Near-fault earthquake movement has caught the attention of both seismologists and engineers and has become a hot spot worldwide. In recent twenty years, many major earthquakes have occurred around the world, and they have led to the heavy losses of life and property, such as the United States' Northridge earthquake in 1994(M6.7), Japan's Kobe earthquake in 1995(M7.2), China's Taiwan Chi-Chi earthquake in 1999(M7.6), Turkey's Izmit earthquake in 1999(M7.4), China's Wenchuan earthquake in 2008(M8.0) and Yushu earthquake in 2010(M7.1). One of the most distinctive characters of these earthquakes is that earthquake focuses are very close to cities. From the earthquake disaster investigation, we found that buildings and bridges near the fault were seriously damaged by near-fault effect.

Bridge expansion joints are necessary units for the accommodation of movements resulting from thermal effects, traffic vibrations, and natural hazards, to name a few (Emily and Timothy et al, 2014). A variety of expansion joints are used for small movements $<$100 mm. For movements $>$100 mm, there are only a few types of joints: mainly finger joints and modular bridge joint systems (MBJS). MBJS with its good three-dimensional deformation capacity, large displacement, and easy replacement has been more and more widely used. The main spans of bridges have continually increased during recent decades. Extreme movements lead to large expansion joints, such as the Run Yang Bridge, China, the Golden Ears Bridge, Canada and the John James Audubon Bridge, America, especially the Run Yang Bridge, which is equipped with some of the world's largest expansion joints that can take 2160mm movement.

For long multi-span continuous bridges, collisions between girders and falling are common among earthquake damages and these may always result in the failure of expansion joints and bearings, so it is necessary to take account of the effect of expansion joints. However, as one of the important components of bridge, the aseismic behavior of expansion joints have long been neglected by researchers (Saiidi, 1996; Kawashima, 2000; Ruangrassamee, 2001; Zanardo, 2001; DesRoches, 2002) and the past papers have given importance to the enhancement of durability, cold resistance and noise-resistance of expansion joints. For example, Ancich et al studied the dynamic anomalies of the modular bridge expansion joints (Ancich, et al, 2006). Crocetti et al studied the fatigue performance of the modular bridge expansion joints (Crocetti et al 2003).Dexter et al have done a systematic study of the modular bridge expansion joints (Dexter et al,1997,2001,2002).Roeder et al studied fatigue cracking in modular expansion joints.(Roeder et al,1993).

The damage of expansion joints not only poses a threat to the state of serviceability after the earthquake, but also affects the overall aseismic behavior of bridge. In recent years, some researchers have paid a closer attention to the contributions of the expansion joints under seismic events. For example, Quan and Kawashima studied the effect of steel finger-type expansion joints on the overall seismic response of a bridge (Quan and Kawashima, 2010). McCarthy, Wright et al assessed the effectiveness of a burgeoning subgroup of modular bridge expansion joints composing of shape memory alloy improved single support bar variations (McCarthy, Wright et al,2010). Further, McCarthy, Wright et al also developed an analytical model representative of a common expansion joint and then supported it through full-scale experimental testing of the joints (McCarthy, Wright et al, 2014). Ramanathan have suggested that bridge expansion joints should be incorporated in

reliability models of bridge performance under seismic events, particularly when considering functionality and repair based damage levels (Ramanathan, 2012).

In the past decades, seismic isolation is being widely popularized in the engineering. Although installing seismic isolation bearings can decrease the damage of bridges when earthquake occurs, it results in an increase of girder response displacement and the risk of pounding between adjacent girders. Therefore, it is important to consider the effect of expansion joints on the overall bridge response. In addition, there are some disadvantages on the standards at home and abroad, when it comes to the effect of the near-fault earthquake to the structure. Therefore, it is necessary to study the seismic performance of the bridge under near-fault earthquakes. Although scholars have been gradually carried out some studies of using the common bearings under near-fault earthquake, there were still fewer for seismic isolation bridges.

According to the research fruits of the diverse damages of bridge in the past, bearings' invalidation is the main reason for the damage of isolated bridges and causes oversized relative displacements between pier and girder. Eventually, it may lead to severe crash of superstructure. This is dangerous when near-fault motion occurs, because it has obvious velocity pulse effect and increases the risk of colliding between girders.

The article is carried on in view of the following questions:

1).Study the characteristics of near-filed ground motion and select earthquake waves;
2).Develop the research of cable-sliding modular expansion joints (CMEJs) and describe the working principle and mechanical model;
3).Based on a triple continuous beam bridge, a 3D model with or without CMEJs was established. By selecting 12 earthquake waves with or without pulse effect, 6 respectively and using nonlinear time history analysis, comparing the seismic response with or without CMEJs under these two sets of waves.

2 SELECTION OF NEAR-FAULT GROUND MOTION

In general, near-fault pulse-type ground motions have a high acceleration、velocity、amplitude of displacement time history, rich low-frequency component, long cycle and short duration. According to Somerville and Yang, there is a judgment for velocity pulse ground motions, when the ratio of PGV/PGA to around or larger than 0.2 (Somerville et al, 1997 and Yang et al, 2005). The records of earthquake events in the past are as the seismic input in this paper and all ground motion records from the Pacific Earthquake Engineering Research center (PEER) database, as shown in Table 1. Among them, No.1-No.6 are the near field pulse ground motions and No.7-No.12 are non-pulse ground motions. For better analyze the effect in limiting relative displacement of cable-sliding modular expansion joints (CMEJs), 12 waves' PGA is adjusted to 0.6g and 5% damping ratio. Figure 1 is the acceleration response spectra corresponding to the selected ground motions.

This paper focused on the effect in limiting relative displacement of cable-sliding modular expansion joints (CMEJs) and effect on seismic isolation system under near-fault pulse-type ground motions. Their PGV/PGA ratios are generally large and much larger than the general ground motion records.

Types	NO.	Name	M	Station	PGA /(cm/s^2)	PGV /(cm/s)	PGD /(cm)	Dist. /(km)	PGV/PGA /(s)
With pulse effect	1	1999-Chichi	7.6	TCU068-NS	462	263	430	3.01	0.569
	2	1999-Chichi	7.6	TCU068-EW	566	177	324	3.01	0.313
	3	1999-Chichi	7.6	TCU120-NS	193	36.93	33.6	7.41	0.191
	4	1999-Chichi	7.6	TCU120-EW	225	63.17	50.61	7.41	0.281
	5	1994-Northridge	6.7	JEN-022	424	106	43.1	5.43	0.250
	6	1994-Northridge	6.7	SCS-052	612	117	54.3	5.35	0.191
Without pulse effect	7	1971-San Fernando	6.6	ORR021	324	15.6	2.4	1.80	0.048
	8	1989-Loma Prieta	6.9	CAP000	529	35	9.1	15.20	0.066
	9	1999-Chichi	7.6	TCU065-EW	814	126.22	126.2	0.59	0.155
	10	1994-Northridge	6.7	PKC-360	433	51.2	8.0	7.3	0.118
	11	1994-Northridge	6.7	ELI-090	155	7.3	2.7	36.50	0.047
	12	1994-Northridge	6.7	TUJ-262	163	8.0	0.8	19.70	0.049

Table 1: Characteristic parameters of selected ground motions.

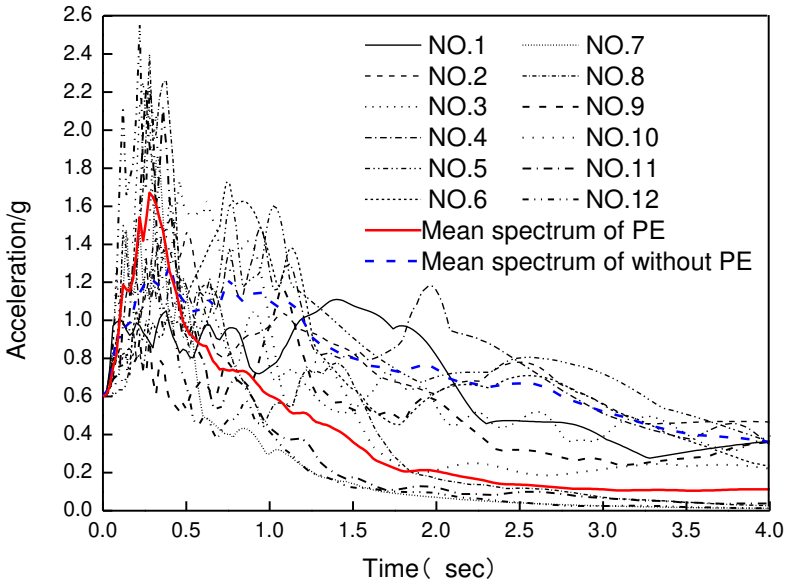


Figure 1: Acceleration response spectra corresponding to the selected ground motions.

3 BASICS, STRUCTURE AND RESTORING FORCE MODEL OF CMEJS

3.1 Basics of CMEJs

With the improvement in the overall performance of the cable materials, the cable can effectively enlarge mechanical properties, and it has been widely used in such fields as prestressed concrete structure、cable-stayed bridge、bridges' displacement-limited and isolation, etc. In addition, cable has become the most active and potential material in modern structures.

Abdel-Ghaffar et al analyzed Aptos Creek Bridge which used cable restrictor under 1989 America Loma Prieta earthquake, and drew the following conclusion: the device has little response to earthquake at the bridge site, but it can lessen the force and displacement of structure response under strong earthquake (Abdel-Ghaffar et al, 1997). To assess the force-displacement relationship of cable restrictor device, Reginald et al carried out a full-scale model test of multi-span simply supported girder bridge which used the device in Tennessee and found that the main failure modes were not cables damage, but the connecting components destructed firstly and cables' capacity has not been fully exploited; Then he conducted the modified connecting components test, in order to ensure that it has higher strength and damages less than the cable restrictor (Reginald et al,2003).

Seismic specifications for highway bridges including Caltrans, AASHTO, specifications of Japan and China all mentioned that using cable-sliding devices to restrict relative displacement between girders, especially, the AASHTO also mentioned that the devices should be set more flexible and convenient to check and replacement (Caltrans,2006; AASHTO,2007;JRA,1996;CCP,2008).

Practice has proved that the application of cable in limiting displacement is very extensive in civil engineering and cable has a good effect. These experiences are worth emulating.

3.2 Structure and restoring force model of CMEJs

Continuous beam bridge will cause oversized relative displacements between pier and girder under earthquake, which may lead to severe collision of superstructure, even girder falling. Aiming at this problem, this paper puts forward a device named cable-sliding modular expansion joints (CMEJs) that can control the relative displacement and avoid collision.

In a modular expansion joint, there is a support box every few meters along the transverse direction of the bridge, as shown in Figure 2. Based on the conventional design, CMEJs use the cable through the both ends of the support boxes and support bars and connect them. When earthquake occurs, the relative displacement between beams is limited through controlling movement of bars in the boxes by cables. Because both ends of the support boxes are fixed in the two ends of the beams, the cable can limit the relative displacement of beams. CMEJs does not exist right now and it is the latest design. For more details, we will introduce it in additional studies. Moreover, the premise is that connected units do not damage before cables. Figure 3 is the working mechanism of CMEJs.

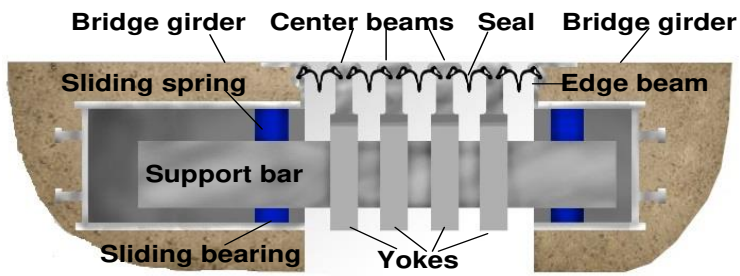
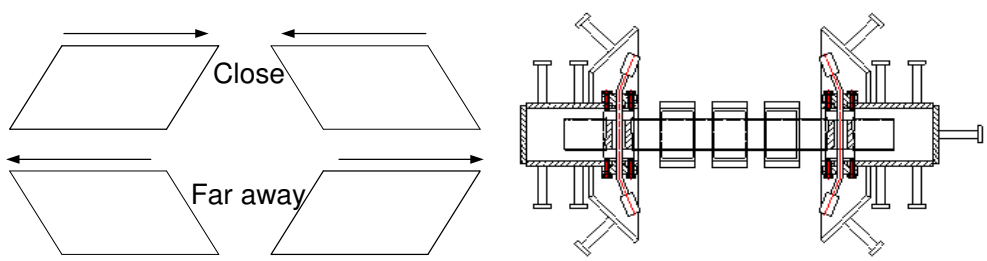
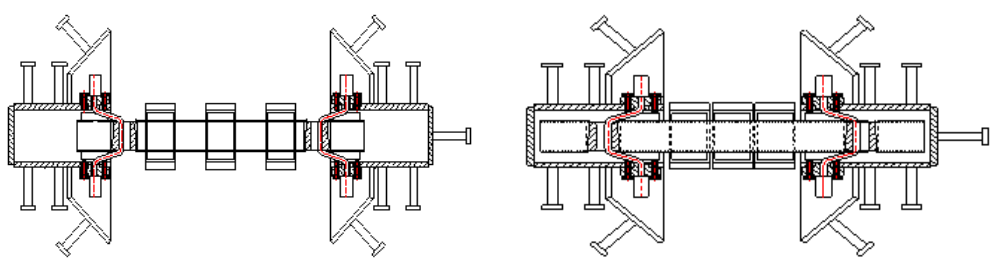


Figure 2: Cross-section view of a CMEJs system.



(a) Two extreme movements of adjacent girders. (b) Normal state of a CMEJs system



(c) When the adjacent girders far away (d) When the adjacent girders get close

Figure 3: Working mechanism of CMEJs

When the adjacent girders get close and an impending collision，the cable can control the girders to prevent collision and play a role in limiting the relative displacement, as shown in Figure 3(d); And vice versa, as is shown in Figure 3(c). In addition, as the cable is running through support boxes and bars, CMEJs will not be easily damaged. According to the requirements of different bridge structural design, adjusting cable free movement can realize the limiting effect. When an earthquake occurs, if the relative displacement between the girders is within the free movement, the cables do not work; if larger than the free movement, they can work effectively.

This paper does not consider expansion joint itself constitutive model. According to Emily et al, the expansion joint has little function of limiting the relative displacement (Emily et al 2014), but it is limited and far less than the cables' stiffness. What's more, the cases of expansion joints damages before cables are not in the scope of our considering.

4 ANALYSIS MODEL

4.1 General information of model

Figure 4 is a triple continuous beam bridge (4×30m+36+56+36+4×30m) and its superstructures adopt the prestressed concrete box girders with variable cross section constructed by simple supported-continuous system, deck width 23.3m. Its substructures are double-column bridge piers and 9 piles under each pile cap, pile diameter 1.5m. In this paper, we do not consider the effect of abutment. Table 2 is the cross-sectional properties of piers. Figure 8 and Table 3 are the details of the bearings.

According to the design, a three-dimensional dynamic finite element model is established and girders、piers are simulated as space beam and column element. Pile cap simulate as a particle and secondary dead load is imposed on the beam in linearly distributed weight, as is shown in Figure 5. By summarizing the previous earthquake damage of bridges, we found that collision and beam falling mostly occurred in longitudinal direction. So in this paper only longitudinal inputs are considered. Nonlinear time-history method is used to analyze the seismic response and using the transient direct integration method.

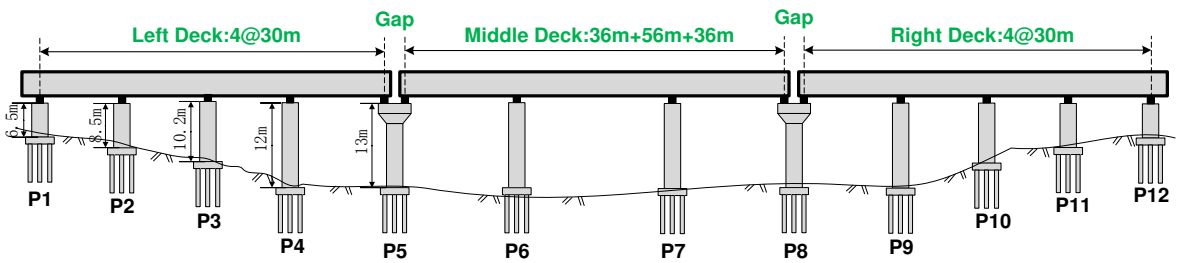


Figure 4: Target bridge.

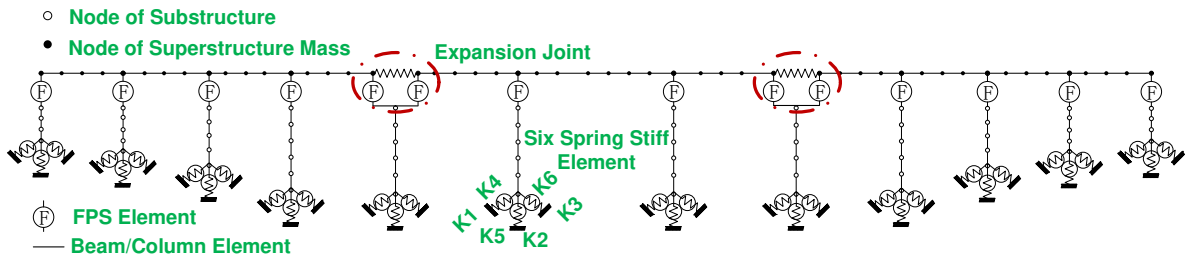


Figure 5: Finite element model of isolated bridge with FPS bearings and CMEJs.

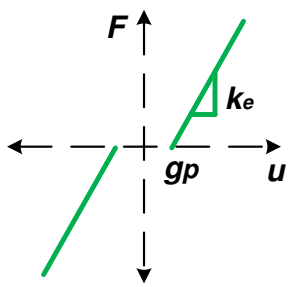


Figure 6: Force vs. displacement relation of CMEJs

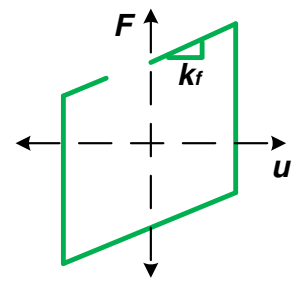


Figure 7: Typical bilinear FPS hysteresis/

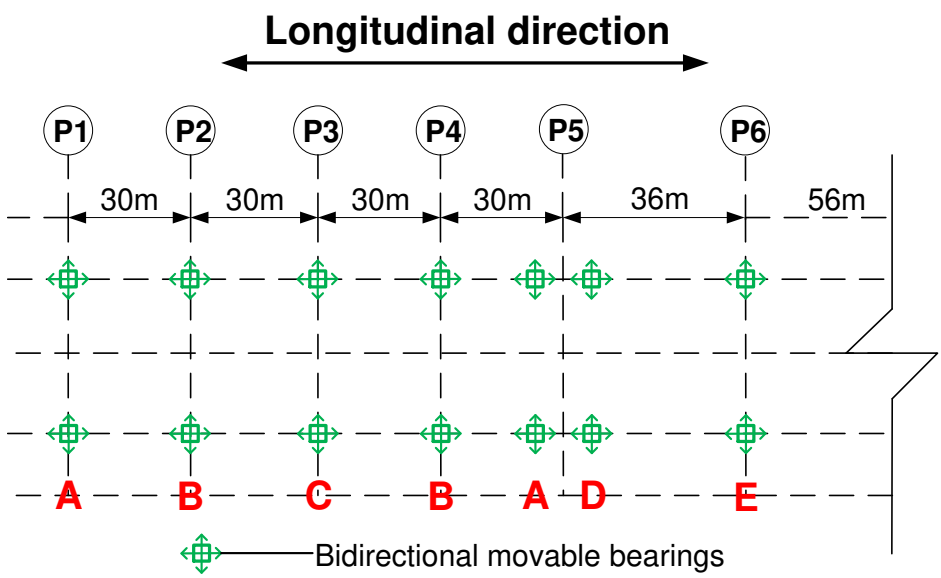


Figure 8: Distribution diagram of the bearings.

Structure component	Area, $A(m^2)$	Torsion Constant, $J(m^4)$	$I_{33}(m^4)$	$I_{22}(m^4)$
P1~P5	3.6	1.804035	0.972	1.2
P6~P7	4.8	3.175031	2.304	1.6
P8~P12	3.6	1.804035	0.972	1.2

Table 2: Cross sectional properties of piers.

FPS Types	Effective Stiffness (kN/m)	Yield Strength (kN)	Stiffness (kN/m)	Post Yield Stiffness Ratio	Yielding Exponent
A	1750	175	87500	0.02	9
B	1920	480	240000	0.01	9
C	1660	415	207500	0.01	9
D	1650	165	82500	0.02	9
E	3017	905	452500	0.008	9

Table 3: FPS base isolation system parameters.

4.2 Expansion joint model

The seismic response of the target model was investigated by SAP2000 V15.1 in this paper. The damping ratio of the concrete structure is 5%. The damping mechanism is introduced in the analysis through the Rayleigh damping matrix. Figure 6 is the force vs. displacement relation of CMEJs. In addition, according to Karayannis and Favvata, Collisions are simulated using special purpose contact elements that become active when the corresponding nodes come into contact. The contact element responds as a spring with almost infinite stiffness (Karayannis, Favvata, 2005 and Karayannis, Favvata , 2009).

The stiffness k and the restoring force f of the cables are expressed as:

$$k = \begin{cases} \tilde{k} & \Delta_d > \Delta_g \\ 0 & \Delta_d \leq \Delta_g \end{cases} \tag{1}$$

$$f = \begin{cases} k(\Delta_d - \Delta_g) & \Delta_d - \Delta_g > 0 \\ 0 & \Delta_d - \Delta_g \leq 0 \end{cases} \tag{2}$$

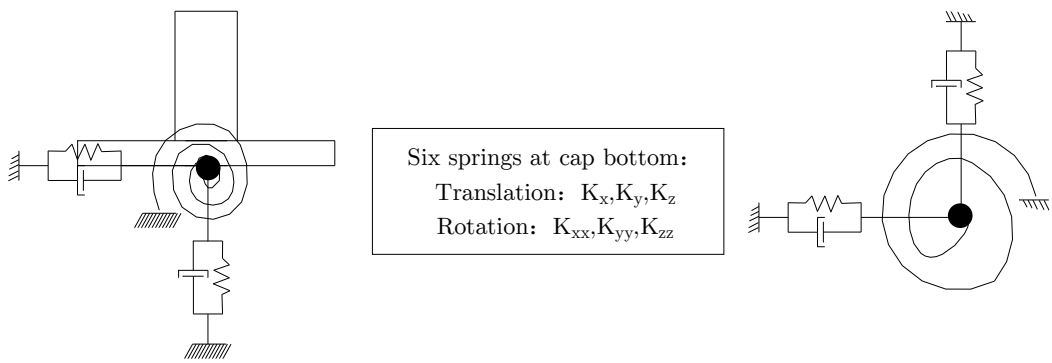
where Δ_g is the initial clearance between two decks, Δ_d is the relative displacement between the adjacent decks, and $\tilde{k}$ is the stiffness of the cables. The stiffness $\tilde{k}$ is determined from

$$\tilde{k} = \frac{nEA}{L} \tag{3}$$

where E is the modulus of elasticity of the cable, A is the sectional area of the cable, n is the number of the cable, and L is the length of the cable. The stiffness of the cable is equal to 4.0×10^2MN/m.

4.3 Simulation of the Pile Foundation

The commonly used processing method for pile foundation is adding a 6×6 stiffness matrix to simulate the pile-soil interaction under pile cap. Spring stiffness depends on soil conditions and the layout of piles, which can be calculated by the principle of equivalent static. This proposed method is simple but efficient, and widely used in low cap pile foundation (Tang et al.2008). Figure 9 is the six springs' model of pile foundation. Table 4 is the spring stiffness value of each pile foundation. It should be noted that 1 axis represents longitude direction,2 axis represents transverse direction,3 axis represents vertical direction.



(a) Elevation drawing (b) Planar drawing

Figure 9: Six springs' model of pile foundation.

No.	Translational stiffness (kN/m)			Rotational stiffness (kN·m/Rad)		
	1	2	3	Around 1	Around 2	Around 3
1	1.53E+06	1.53E+06	1.56E+07	1.83E+08	-4.88E+06	1.83E+08
2	1.98E+06	1.93E+06	2.08E+07	4.28E+08	-6.35E+06	2.44E+08
3	1.98E+06	1.93E+06	2.08E+07	4.29E+08	-6.36E+06	2.44E+08
4	1.07E+06	1.07E+06	1.59E+07	1.84E+08	-3.77E+06	1.84E+08
5	1.32E+06	1.32E+06	1.56E+07	1.82E+08	-4.34E+06	1.82E+08
6	1.35E+06	1.35E+06	1.56E+07	1.82E+08	-4.46E+06	1.82E+08
7	1.30E+06	1.30E+06	1.56E+07	1.82E+08	-4.38E+06	1.82E+08
8	1.40E+06	1.40E+06	1.56E+07	1.83E+08	-4.58E+06	1.83E+08
9	1.46E+06	1.46E+06	1.59E+07	1.86E+08	-4.70E+06	1.86E+08
10	1.47E+06	1.47E+06	1.56E+07	1.83E+08	-4.71E+06	1.83E+08
11	1.37E+06	1.37E+06	1.56E+07	1.82E+08	-4.47E+06	1.82E+08
12	1.47E+06	1.47E+06	1.56E+07	1.83E+08	-4.71E+06	1.83E+08

Table 4: Spring stiffness value of each pile foundation

4.4 Case analysis

In order to analyze the seismic response of isolated bridges with CMEJs under near-fault earthquake, the following four cases are established, respectively:

Case I: The bridge model without CMEJs and pulse effect.
Case II: The bridge model without CMEJs and with pulse effect
Case III: The bridge model with CMEJs and without pulse effect
Case IV: The bridge model with CMEJs and pulse effect

Isolated bridge adopts friction pendulum bearings, which are widely used in engineering practice. Figure 7 is typical bilinear FPS hysteresis. In general, the expansion joint's clearance is determined by static calculation. The number is 10cm in this paper which means when the compression deformation is greater than 10cm, it can be considered that adjacent girders has been collided. In order to satisfy the requirements of the bridge temperature change and normal operation, the gap was assumed 0.08m in this analysis. If the relative displacement between girders is larger than 8cm, cable can play its roles; if the displacement is larger than 10cm, the cables can be seen as failing to achieve the expected goals.

5 SEISMIC RESPONSE WITH OR WITHOUT CMEJS UNDER NEAR-FAULT GROUND MOTIONS

To study the effect of the CMEJs under near-fault ground motions, the above analytical model for CMEJs was implemented to the target bridge as shown in Figure 4. Because the structure is symmetrical, we only consider the half bridge as discussed in this paper. To better reveal the effect of CMEJs in limiting the relative displacement of the adjacent girders under six pulse-type ground motions, we introduced the seismic response in detail under No.1 and No.5 as seen in Figure 10 and 11.

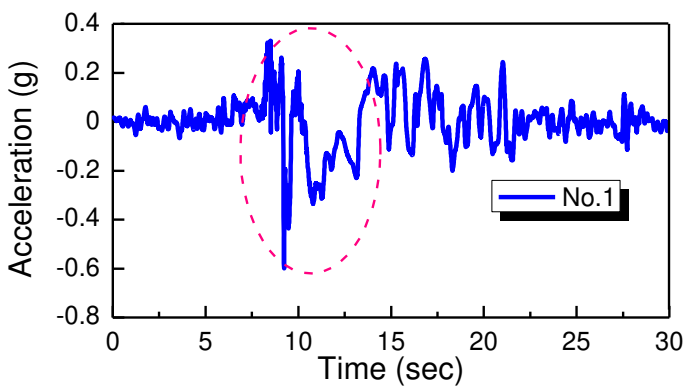


Figure 10:The No.1 ground motion record in the anslysis.

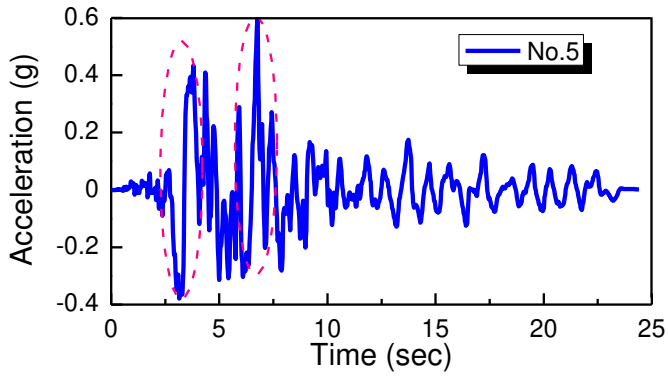


Figure 11: The No.5 ground motion record in the anslysis.

Figure 12 shows the relative displacement between left deck and middle deck under the No.1 ground motion. The responses of neglecting the effect of CMEJs in the analysis are also shown in Figure 12 for comparison. The relative displacement between left deck and middle deck by disregarding the effect of CMEJs are about +0.2m and -0.18m in tensile and compressive directions, respectively, which is larger than gap and pounding occurred. On the other hand, this value becomes +0.098m and 0.091m in the tensile and compressive directions, respectively, if the CMEJs is included in the analysis. Thus, the relative displacement decreased by 50% and 49% by including the CMEJs in the analysis in the tensile and compressive directions, respectively.

Figure 14 shows the pulling force of CMEJs under the No.1 ground motion. There are three times in the tensile direction and two times in the compressive direction, which is also clear in Figure 12. Because the free movement of cables is 8cm, the cables can work when the gap is larger than 8cm. As is obvious from Figure 10, there is pulse acceleration with high magnitude spikes from 8s to 15s. So we can see from Figure 12 and 14, the cables' pulling force are 7.4MN,2.1MN and 1.21MN at 11.83s,13.025s and 13.58s in the tensile direction and 4.5MN,1.68MN at 15.165s and 16.205s in the compressive directions. Similarly, the effect of CMEJs is obvious as shown in Figure 11 and 13 under the No.5 ground motion. But the difference is that No.5 has two pulse accelerations, so the Figure 13 and 15 both have a symmetrical property.

In conclusion,in the bridge with CMEJs, the peak relative displacement between the adjacent girders is significantly decreased, thus avoiding collision. The relative displacement of adjacent girders can be reduced within 0.1m by setting a reasonable length of free movement. The installation of a CMEJs can reduce the relative displacement and achieve a more economical design.

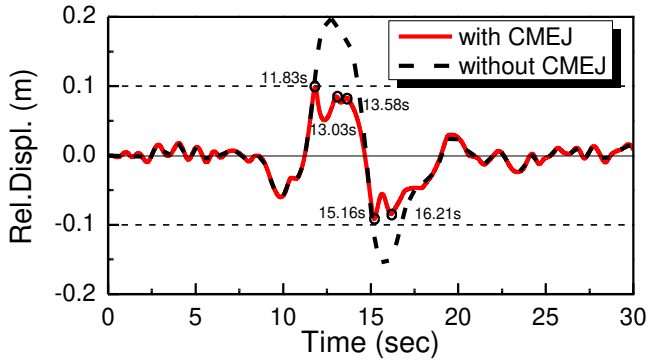


Figure 12: Relative displacement between Left deck and Middle deck under the No.1 near-fault ground motion.

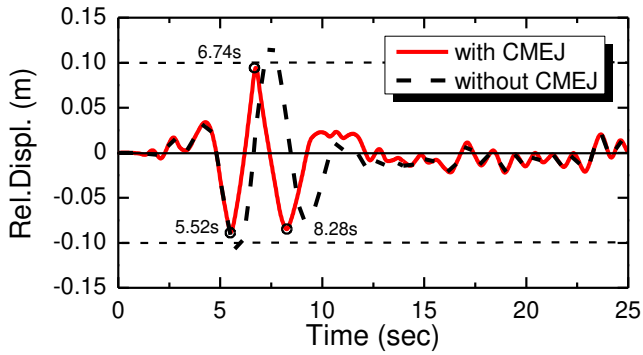


Figure 13: Relative displacement between Left deck and Middle deck under the No.5 near-fault ground motion.

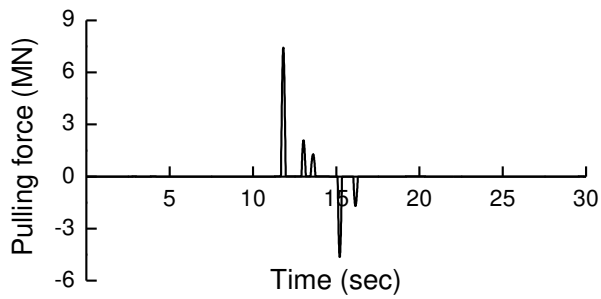


Figure 14: Pulling force of the CMEJs under the No.1 near-fault ground motion.

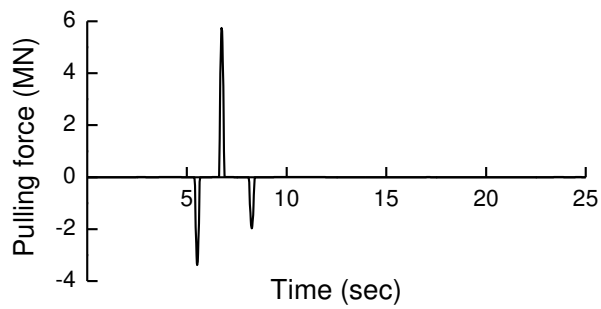


Figure 15: Pulling force of the CMEJs under the No.5 near-fault ground motion.

6 SEISMIC RESPONSE WITH PULSE EFFECT OR WITHOUT PULSE EFFECT IN CONSIDERING THE EFFECT OF CMEJS

Effect of near-fault earthquakes on bridges has high-energy pulse movement characteristics, which includes: long cycles, obvious peak velocity, acceleration and a duration waveform similar to pulse. Velocity pulse will increase the acceleration, velocity, displacement impact. For small damping, the effect of velocity pulse is larger and it allows bridges under high-energy impact, which may result in large displacements and deformations. To explain the seismic response with PE (pulse effect) or without PE (pulse effect) in considering CMEJs, the response of bridge under No.2 and No.8 ground motion were analyzed. As is obvious from Figure 16, the No.2 has significant pulse acceleration within 9-13s. Though they have the same PGA, but No.8 does not have such features.

Figure 17 shows the relative displacement between decks and piles and used left deck and P5 as an example. It is important to note that the relative displacements are significantly amplified if the PE is considered in analysis. The maximum relative displacement is -0.85m at 11.6s and +0.38m at 17.38s by taking account of the PE. However, this value is -0.11m at 9.06s and +0.07m at 7.2s by disregarding the PE. That means when near-fault earthquakes occur, the relative displacement between decks and piles becomes 7.2 times or 5.4 times the displacement without pulse effect for the seismic isolation bridges. From this figure， we can see that CMEJs cannot work very well in restraining the relative displacement between piers and girders. Once the relative displacement is larger than allowable displacement (overlap length), girder falling will occur. Whether the cables can hold the girders or not, further work is needed to validate this point. But in theory, the capacity of cables can satisfy the requirements.

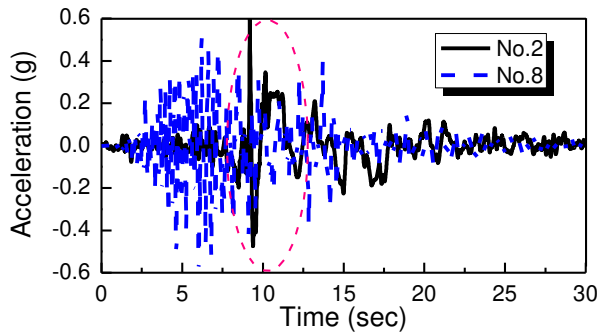


Figure 16: The No.2 and No.8 ground motion records in the anslysis.

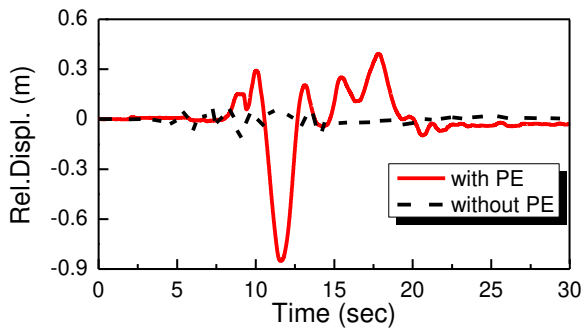


Figure 17: The relative displacement between left deck and P5.

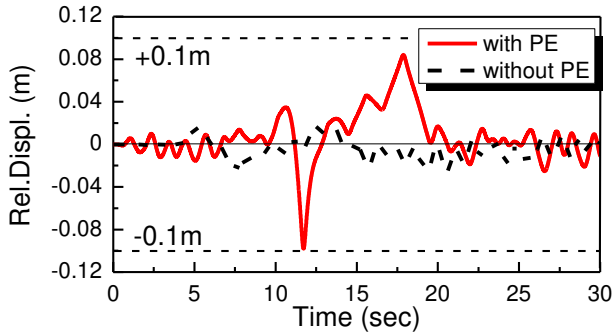


Figure 18: Relative displacement between left deck and middle deck.

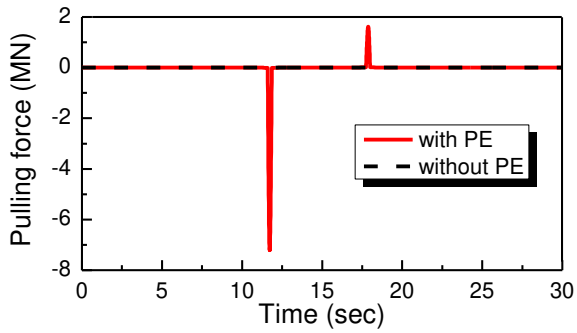


Figure 19: Pulling force of the CMEJ with PE or without PE.

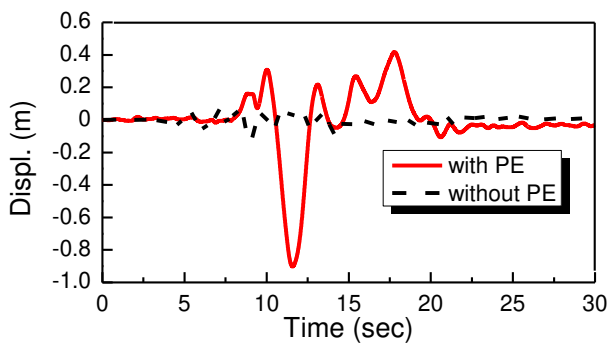


Figure 20: Displacement at the right end of the left deck.

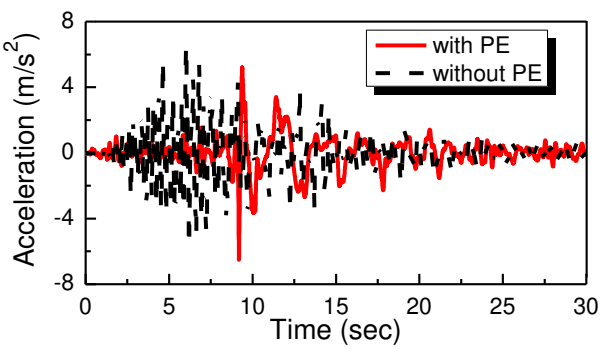


Figure 21: Acceleration at the right end of the left deck.

Figure 18 shows the relative displacement between adjacent girders with PE or without PE. Focusing on the responses during 10-20s, the displacements significantly amplified with PE. The relative displacements are 0.017m at 12.39s and 0.025m at 20.565s by disregarding the PE, while those values are 0.095m at 11.765s and 0.083m at 17.925s by taking account of PE. It is found that when near-fault earthquakes occur, the relative displacements are 5.58 times or 3.32 times the displacement without PE. However, the displacements are restricted to 0.1m when the CMEJs are installed and collision will not occur. On the other hand, the decks without CMEJs will be destroyed by pounding and aggravated the destruction of piers and girders under near-fault earthquake. Figure 19 shows the corresponding pulling forces at the expansion joints between left deck and middle deck.

Figure 20 is the displacement at the right end of the left deck. The maximum displacement is -0.897m at 11.645s and +0.413m at 17.86s by taking account of the PE. However, this value is 0.12m at 9.04s and +0.07m at 10.975s by disregarding the PE. And Figure 21 is corresponding acceleration at the right end of the left end. It is interesting to note that the shape of Figure 16 is very similar to Figure 21. As is obvious from Figure 21, there is significant pulse wave with PE.

7 COMPARISON OF FOUR CASES

The effectiveness of the CMEJs was investigated with PE or without PE. To illustrate the effect of CMEJs with PE or without PE, Table 5 shows the average results of shear force of P5, bending moment of P5, and shear force of P6, bending moment of P6, bearing displacement at P5 under 12 ground motions (6 with PE and 6 without PE). As is obvious from Table 5, all the five indexes have significantly increased by 1.90-3.95 times. Therefore, in the situations of pulse effect, neglecting its possible effects leads to non-conservative designs. However, there is no substantial change of the five indexes with CMEJs in comparison with without CMEJs. So the installation of CMEJs can be a protection device for the bridge near the earthquake fault zone and limit the relative displacement of the adjacent girders.

	Cases	Without PE	With PE	With PE/without PE
Shear force of P5(MN)	with CMEJs	1.66	3.16	1.90
	without CMEJs	1.66	3.16	1.90
	with CMEJs/without	1.00	1.00	-
Bending moment of P5(MN·m)	with CMEJs	10.66	23.38	2.19
	without CMEJs	10.66	23.34	2.19
	with CMEJs/without	1.00	1.00	-
Shear force of P6(MN)	with CMEJs	1.65	4.20	2.55
	without CMEJs	1.65	4.18	2.54
	with CMEJs/without	1.00	1.00	-
Bending moment of P6(MN·m)	with CMEJs	20.02	52.18	2.61
	without CMEJs	20.00	51.98	2.60
	with CMEJs/without	1.00	1.00	-
Bearing displacement at P5(m)	with CMEJs	0.14	0.56	3.93
	without CMEJs	0.14	0.57	3.95
	with CMEJs/without	1.00	0.99	-

Table 5: The bridge responses of different cases.

8 CONCLUSIONS

A new device named cable-sliding modular expansion joints (CMEJs) was developed to investigate the effect of controlling the relative displacement and avoid collision. The proposed model was implemented to an analysis of a triple continuous isolation bridge, which has different heights of piers with PE or without PE. Although experimental verification for the evaluation of properties of CMEJs is required, the following conclusions may be deduced from the analytical results presented herein.

1. For the bridge with CMEJs, the peak relative displacement between the adjacent girders is significantly decreased, thus avoiding collision. The relative displacement of adjacent girders can be reduced within safety range by setting a reasonable length of free movement. The installation of CMEJs can reduce the relative displacement achieving a more economical design.

2. CMEJs cannot work very well in restraining the relative displacement between piers and girders. Once the relative displacement is larger than allowable displacement (overlap length), girder falling will occur. Whether the cables can hold the girders or not, further work is needed to validate this point. But in theory, the capacity of cables can satisfy the requirements.

3. Pulse effect can significantly increased the seismic responses of bridges located near fault zone, especially for seismic isolation bridges. The disregarding of PE is dangerous for them and leads to non-conservative design.

4. The installation of CMEJs has no substantial change to the responses of the bridges with PE or without PE for seismic isolation bridges. But it can be a protection device for the bridge and limit the relative displacement of the adjacent girders.

Acknowledgments

This research is supported by the Ministry of Science and Technology of China under Grant No.SLDRCE14-B-14, and by the National Natural Science Foundation of China under Grants No.51278376 and No.90915011. Their supports are gratefully acknowledged.

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