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Seismic response analysis of base isolated highway bridge: Effectiveness of using laminated rubber bearings

M. N. Haque, A. R. Bhuiyan & M. J. Alam
Chittagong University of Engineering and Technology, Chittagong 4349, Bangladesh

ABSTRACT: This study is devoted towards evaluating the seismic responses of a base-isolated highway bridge with different isolators. To this end, a nonlinear dynamic analysis of a multi-span continuous seismically isolated highway bridge is carried out with three types of laminated rubber bearings: natural, high damping, and lead rubber bearings. The mechanical behavior of the bearings as observed in experiments is characterized by nonlinear elasto-plastic, strain-rate dependence and strain-hardening features at high strain levels as documented in published papers of the authors. However, the equivalent linear and the bilinear models are used in the analysis for idealizing the mechanical behavior without considering the strain-rate dependence of the bearings. The mechanical behavior of the bridge pier is approximated using the Takeda trilinear model and the remaining parts of the bridge are idealized using simple elastic model. Two design earthquake ground motions as recommended by codes and specifications, applied in the longitudinal direction, are used in the analysis. The seismic responses of the bridge are evaluated by solving the equations of motion of the bridge system using a standard direct integration method. The parametric studies are conducted for different system configurations and isolation systems. The seismic response of base-isolated bridge is seen to be considerably altered due to the dissimilarity in the isolator properties. Finally, a comparative assessment of the bridge responses shows the sensitivity of isolation bearings' mechanical properties in evaluating seismic responses of the bridge.

1 INTRODUCTION

Bridges are considered to be lifeline structures, since they provide an emergency link in a surface transportation network during natural disasters, such as earthquakes and hence bridges are required higher seismic performance than standard buildings, especially in Japan. There are many cases of bridge damage in past earthquakes all over the world even though a considerable progress has been made in seismic design for bridges in the last few decades. For standard medium and short span bridges with short piers, their fundamental period of vibration remains in the range of the predominant periods of earthquake-induced ground motions. For these bridges, merely increasing member strength is not a cost-effective approach. Instead, restricting the transmission of earthquake forces and energy into the bridge structure is a more promising approach (Wang et al., 1998). This second approach has been widely adopted in many bridges by means of the seismic base isolation devices (Kelly, 1997).

Three types of base isolation rubber bearings are available to be used for this purpose: natural rubber bearings (RBs), lead rubber bearings (LRBs), and high damping rubber bearings (HDRBs). The laminated rubber bearing consists of two mounting steel plates located at the top and bottom of the bearing, several alternating rubber layers, and steel shims. The steel shims provide vertical stiffness of the isolation bearing without altering the horizontal flexibility of the rubber layers. Among these, HDRBs and LRBs are widely used as base isolation devices in earthquake prone area especially in Japan, because they have enhanced damping property. For HDRB the rubber composition itself is changed to provide the damping property, while for LRB one or more central lead plug is inserted through its height.

Several studies reported in the past on the effectiveness of these isolation bearings for the seismic performance of bridges. Unjoh and Ohsumi (1998) have conducted numerical study on the earthquake response characteristics and the design method of the multi-span continuous girder bridge with seismic isolation design concept. Ghobarah and Ali (1988); Turkington et al. (1989a); Turkington et al.,(1989b) and Jangid (2004) have evaluated the suitability of using LRBs in reducing the seismic responses of bridges. However, it has been pointed out by several researchers that in nonlinear dynamic analysis the response of isolated bridges is significantly affected by modeling of isolation bearings. For example, Su et al. (2002) and Pagnini et al.

(1998), Tongaokar and Jangid (2000) have evaluated the effect of modeling of the isolation bearings on seismic responses of bridges. In most of the previous studies, they used only RBs and LRBs as the base isolation bearings in evaluating seismic responses of the bridge. However, no such a study of seismic responses of the bridge using HDRBs as isolation devices is reported in literatures.

The current study is devoted towards evaluating the effectiveness of using isolation bearings on seismic responses by conducting nonlinear dynamic analysis of an isolated five-span continuous highway bridge. In this analysis, three types of isolation bearings, i.e. HDRB, LRB and RB are considered. Two analytical models of the isolation bearings were utilized in the analysis: the conventional bilinear model for HDRB and LRB models, and the equivalent linear model RBs as specified in Japanese Specifications for Highway Bridges (JRA, 2002). Nonlinear force-displacement relationship for the isolation bearings and the piers are employed in analytical modeling of the bridge. In the comparative assessment four response of the bridge are considered: the pier base shear, the pier top shear force, the deck acceleration, and the deck top displacement, etc. The analytical results have indicated that the seismic responses of the bridge are significantly reduced by using isolation bearings.

2 MODELING OF BRIDGE

2.1 *Physical model*

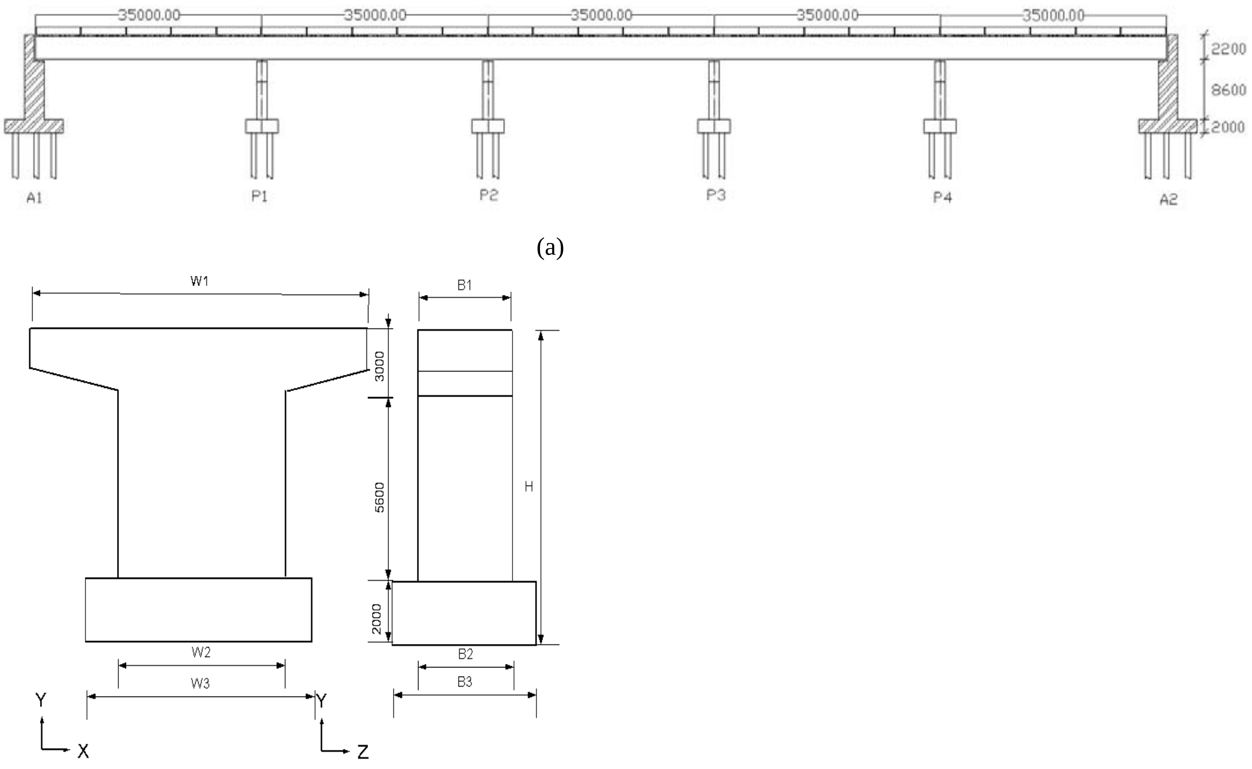
A typical five-span highway bridge with 35000 mm span is used in this paper as shown in Fig. 1(a). The superstructure consists of 280 mm continuous composite slab with 100 mm of asphalt supported on two continuous steel girders. The depth of the continuous steel girder is 2200 mm. The substructure of bridge consists of rigid abutments at the two ends and four intermediate reinforced concrete piers. The footings are supported on pile foundation. Fig. 1(b) shows typical cross section of the bridge. Three types of isolation bearings are considered: high damping rubber bearing (HDRB), lead rubber bearing (LRB) and natural rubber bearing (RB). The dimensions and material properties of the bridge deck, piers with footings are given in Table 1 and those of the isolation bearings are presented in Table 2.

2.2 *Analytical model*

The analytical model of the bridge is shown in Figure 2. The entire bridge is approximated by a 2-D model bridge. The bridge deck is idealized as a rigid body ignoring flexibility of the bridge deck. The piers were restricted to participate in energy absorption in the entire bridge system to some extent in addition to the isolation bearings. So the secondary plastic behavior was expected to be lumped at bottom of the piers where plastic hinges are occurred. The plastic hinges of the piers are modeled by nonlinear link elements. The nonlinear link elements are modeled using the tri-linear Takeda model (Takeda et al., 1970). The steel girder, the pier cap, the pier body, the footing, and the two ends of the plastic hinge are modeled using the simple elastic frame elements. The foundation is modeled by linear translational and rotational springs (soil-springs elements) to simulate the foundation-structure interaction. In order to describe the mechanical behavior of isolation bearing, two types of analytical models of the bearings are used in the study: the bilinear model and the equivalent linear model specified in JRA (2002) and Bhuiyan, 2009. The bilinear model was used to characterize the mechanical behavior of LRB and HDRB whereas the linear model was used to characterize the RB. These two models are briefly discussed in the following sub-sections.

2.2.1 *Bilinear model*

It is recognized that the isolation bearing has generally nonlinear inelastic hysteretic property. Some specifications have specified guidelines for using the bilinear model in order to represent the nonlinear inelastic hysteretic property of the HDRB and the LRB (AASHTO 2000; JRA 2002). In this case, three parameters are required to represent the hysteresis loop of HDRBs and LRBs: initial stiffness $k_{1,}$ post yield stiffness k_2 and the yield strength of the bearings q_d as shown in Figure 3. In the subsequent numerical study, these parameters are assigned for HDRB and LRB in accordance with the manual of bearings for highway bridges (JRA 2004) and Bhuiyan, 2009. Parameters of the of the bilinear model are given in Table 3 & 4.



(a)

(b)

Figure 1. Physical model of a five-span continuous seismically isolated highway bridge (a) longitudinal sectional elevation of the bridge, and (b) transverse sectional elevation of the bridge; all dimensions are in [mm](Bhuiyan, 2009)

Table 1: Geometric and material properties of the bridge

Properties	Specifications	
	Piers with RBs	Piers with LRBs and HDRBs
Cross-section of the pier cap (mm^2), (B1x W1)	1500x9000	1800x9000
Cross-section of the pier body (mm^2), (B1xW2)	1500x6000	1500x5000
Cross-section of the footing (mm^2), (B3xW3)	5000x8000	5000x8000
Number of piles in each pier	4	
Young's modulus of elasticity of concrete(N/mm^2)	25000	
Young's modulus of elasticity of steel (N/mm^2)	200000	

Table 2: Properties of the isolation bearings

Dimension	Specifications		
	RBs	LRBs	HDRBs
Length (mm)	650.0	650.0	650.0
Width (mm)	650.0	650.0	650.0
Thickness of rubber layers (mm)	81.3	81.3	81.3

2.2.2 *Equivalent linear model*

From experimental observations of RBs, it has been found that the force-displacement hysteresis loop of RBs can be approximated by the equivalent linear model (JRA 2002). Accordingly, the equivalent linear model is employed for RBs in the numerical analysis. The equivalent stiffness of the RB can be evaluated based on the nominal shear modulus Ge of the rubber material and the damping constant of the bearing is set to be 5.0%.

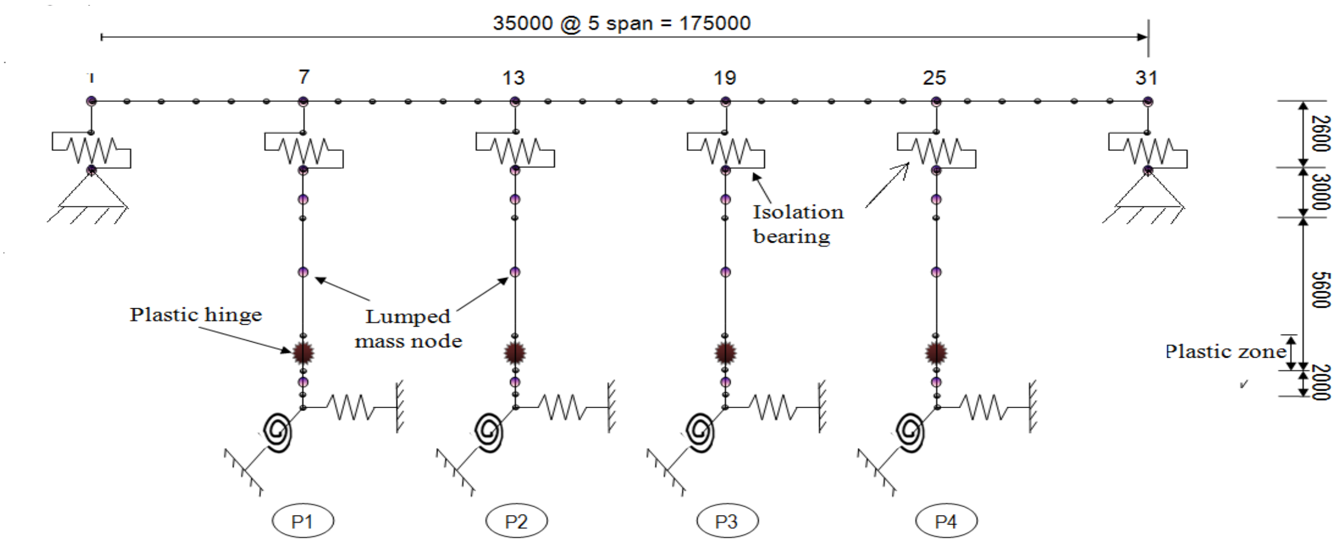


Figure 2. Analytical model of the bridge

Table 3: Parameters of the Bilinear model forHDRB

Effective Stiffness, (kN/mm)	16.347
Initial Stiffness, K_1(kN/mm)	69.665
Post yield ratio	0.1655
Yield Strength(kN)	962.7

Table 4: Parameters of the Bilinear model for LRB

Effective Stiffness (kN/mm)	15.932
Initial Stiffness, K_1(kN/mm)	124.993
Post yield ratio,	0.0945
Yield Strength(kN)	825

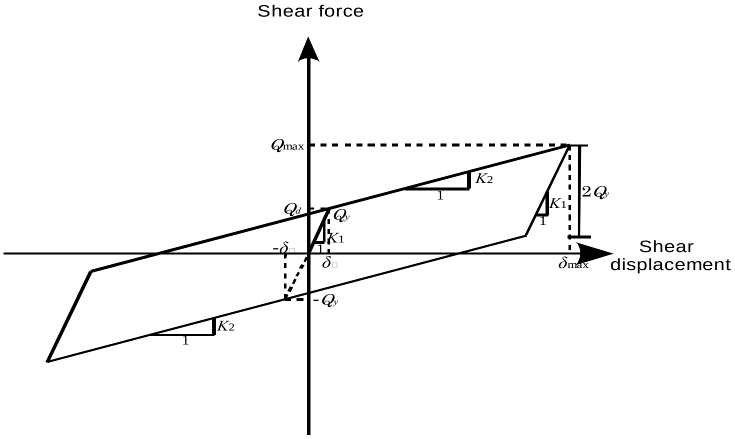
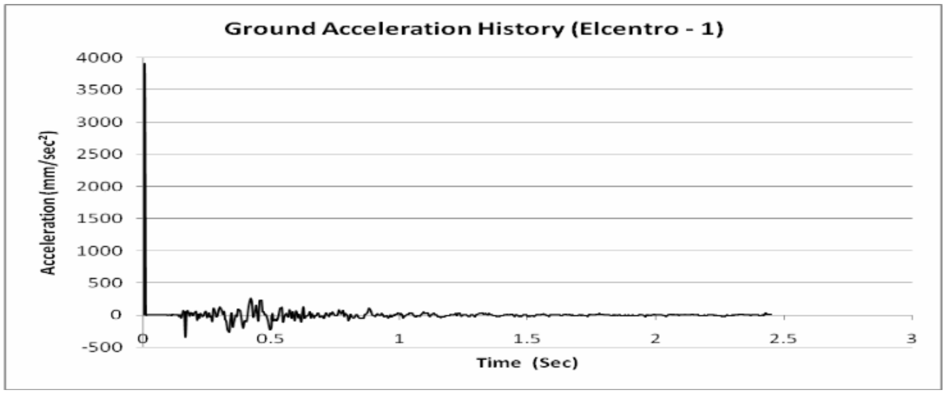


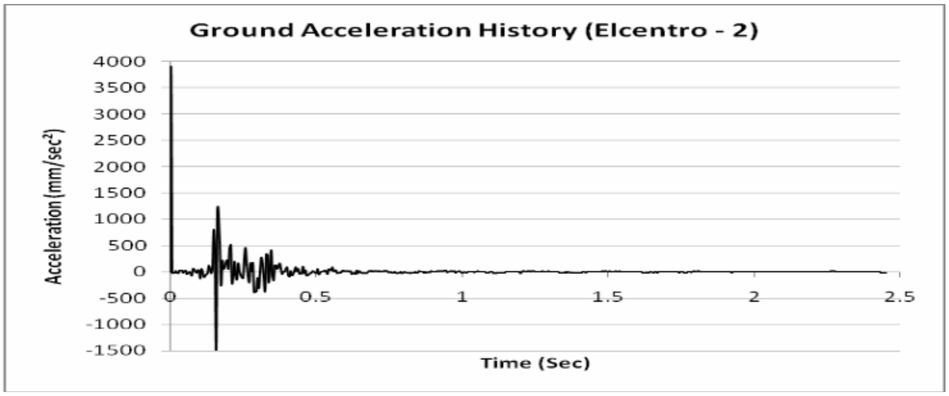
Figure 3: Bilinear force-displacement relationship of the bearings (JRA, 2002)

3 EARTH QUAK E GROUND MOTIONS

Two historical earthquake records are used in the subsequent analysis. These two ground motions refer the 1940 El-Centro earthquake occurred in California, with different PGA values. In order to consider the variation of the amplitude, phase characteristics of the ground motions, different ground motion histories are applied in the longitudinal direction of the modeled bridge to evaluate the seismic responses. Figure 4 shows typical ground acceleration time histories for two types of earthquakes.



(a)



(b)

Figure 4. Ground acceleration histories used in the seismic analysis (a) El Centro -1, (b) El Centro -2

4 SEISMIC RESPONSES OF BRIDGE

The seismic responses of both isolated and non-isolated bridge are investigated for two ground motion histories as shown in Figure 4. In this regard, a nonlinear dynamic analysis of the bridge mode (Figure 2) is carried out utilizing the nonlinear mechanical behavior of the isolation bearings and the piers. Before conducting the nonlinear dynamic analysis, an eigenvalue analysis of the bridge model has been done to evaluate the damping properties of the structures. The stiffness of the isolation bearings is adjusted in such way that the natural period of the isolated bridge model is twice the un-isolated one. This is done for ensuring isolation effect of the bridge acted upon by the given earthquake ground motions. The response quantities of interest for the bridge system are base shear of the pier, deck acceleration, the pier top force and the displacement of the deck. In Figures 5 to 8, the time variation of the base shear of the pier, deck acceleration, pier top force and relative displacement of the bearings are presented. Moreover, the peak responses of the bridge can be grasped at glance from Table 5. As can be seen from the figures and the table that the base shear, deck acceleration & pier top force responses are significantly reduced in the isolated model bridge as compared with the non-isolated one. However, the isolated bridge with natural rubber bearings have shown to be less effective in compared with other two types of isolation bearings (HDRBs and LRBs). This may be attributed to be less damping property inherited in the natural rubber bearings (RBs). Furthermore, the displacement responses of the deck are observed to be relatively higher in isolated bridge in compared with the non-isolated one. In order to mitigate this kind of over displacement of the bridge deck, a special kind of energy dissipating devices could be employed.

5 CONCLUDING REMARKS

In this paper the response of five-span continuous deck girder bridge seismically isolated by laminated rubber bearings acted upon by unidirectional earthquake ground motion is presented. Three different types of isolation bearings are used to investigate the effect of isolation over bridge system. These bearings are modeled using the design model as specified in manual for highway bridges (JRA 2004): the bilinear model is employed for modeling LRB and HDRB, and the equivalent linear model for RB. It should be noted that a set of parameters corresponding to design models are estimated using the design equations as specified in JRA (2004). In this paper, the bridge responses are discussed in terms of the base shear of the pier, deck acceleration, displacement of deck & pier top force, since these responses are predominant for seismic design of bridge systems. The effect of laminated rubber bearings is significantly observed in the responses indicating that isolation reduces the response of stiff bridge system significantly and can be used effectively to design a safe bridge system.

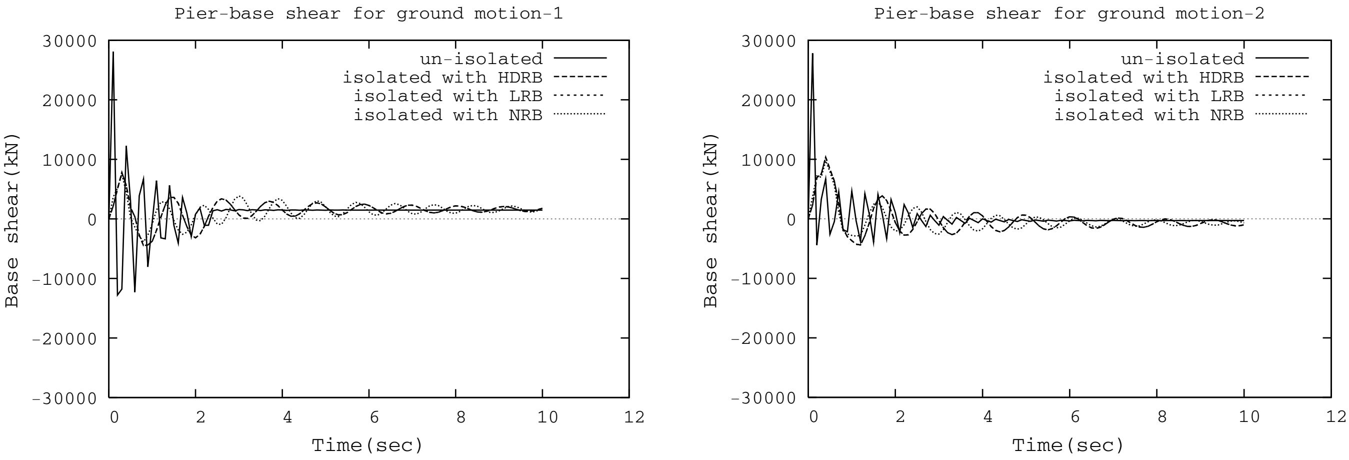


Figure 5. Time variation of pier base shear for two earthquake ground motions (a) El Centro-1 (b) El Centro-2

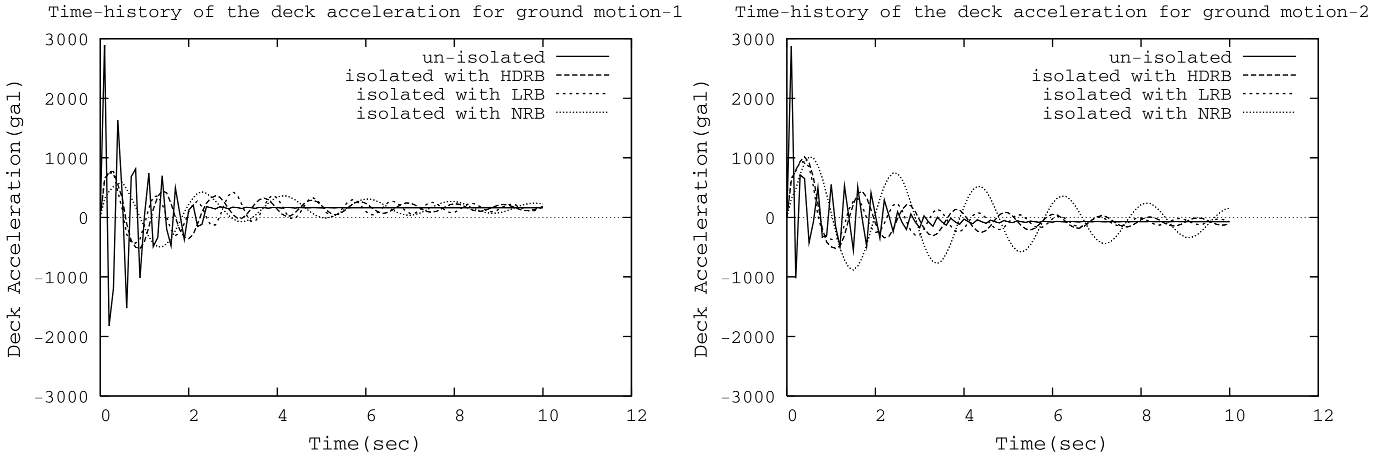


Figure 6. Time variation of Deck Acceleration for two earthquake ground motions (a) El Centro -1 (b) El Centro – 2

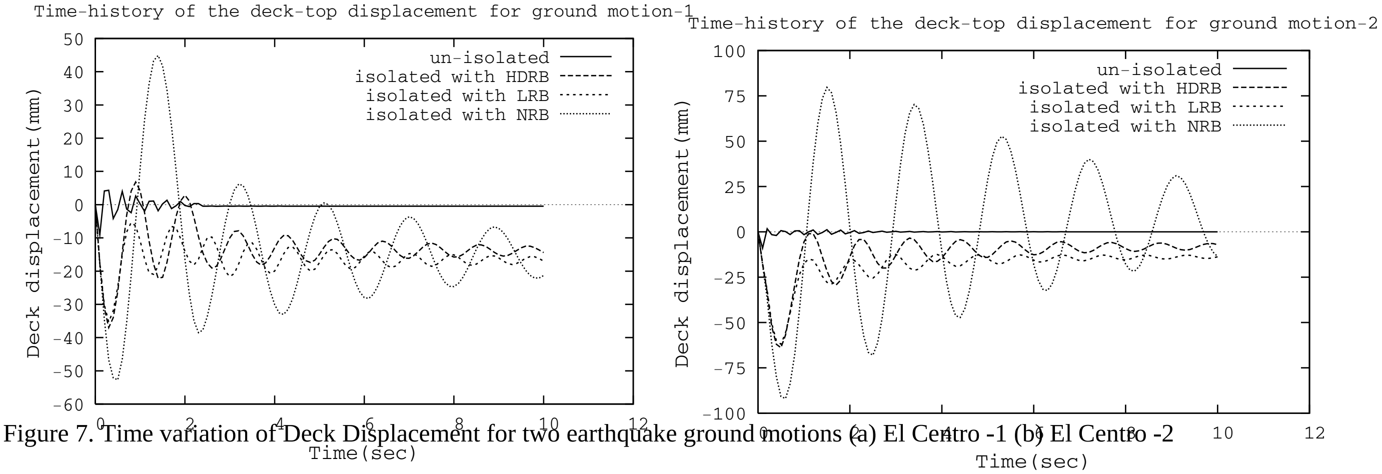


Figure 7. Time variation of Deck Displacement for two earthquake ground motions (a) El Centro -1 (b) El Centro -2

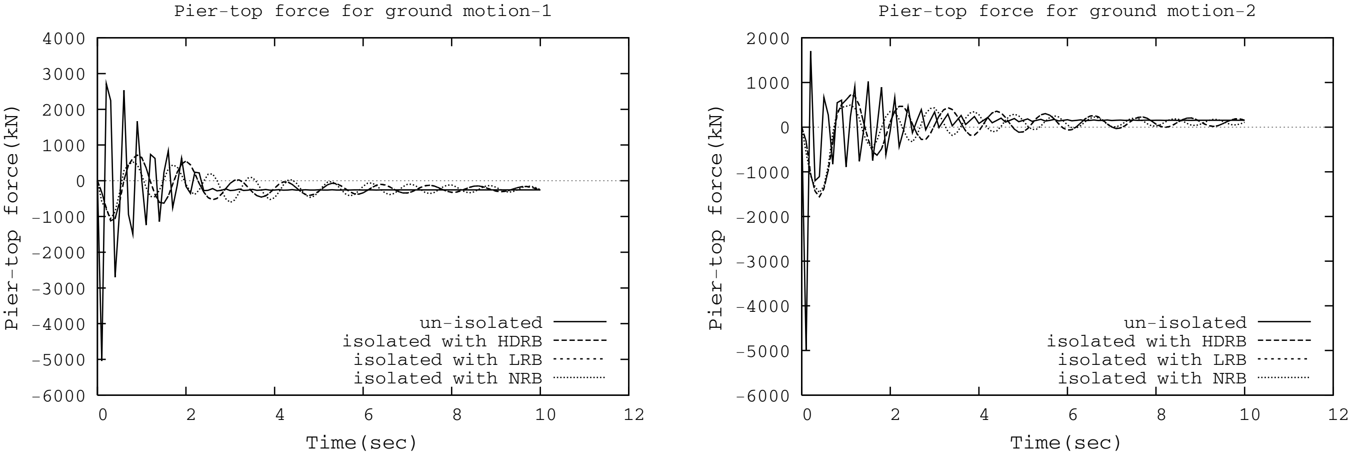


Figure 8. Time variation of Pier Top Force for two earthquake ground motions (a) El Centrio-1 (b) El Centro - 2

Table 5: Peak Response Quantities of the Bridge for both Isolated and Nonisolated Conditions

Response	Non-isolated	Isolated			Remarks
		HDRB	LRB	RB	
Base Shear (kN)	28094.24	7783.46	7438.59	8559.48	El Centtro-1
	27813.02	10367.64	9742.59	9931.38	El Centtro-2
Deck Acceleration (mm/sec^2)	2892.67	770.56	749.6	589.35	El Centtro-1
	2874.06	1014.56	932.28	1015.78	El Centtro-2
Pier top Force (kN)	5042.24	1117.57	1050.31	911.05	El Centtro-1
	4998.11	1559.44	1464.76	1408.5	El Centtro-2
Deck Displacement (mm)	9.10	37	35.32	52.70	El Centtro-1
	9.01	63.89	61.98	91.94	El Centtro-2

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