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Seismic Behavior of Bridges with Isolation Bearings of Different Properties Under Long and Short Earthquake Durations

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ABSTRACT

This paper evaluates the structural behavior of bridges subjected to seismic excitation of short and long durations. The bridge is of three spans and of continuous deck. It is studied under two cases of properties for the lead rubber isolation bearings. One of the bearings is of yield strength 500 MPa and the second is of yield strength 150 MPa. Dynamic nonlinear time history analysis is performed using three short-duration and three long-duration earthquakes all of which are matched to the response spectrum of the Egyptian loading code. Three dimensional finite element modeling is made for the bridge. The studied behavior items for the isolation bearings are maximum bearing longitudinal displacement, maximum bearing vertical displacement, and maximum bearing vertical residual displacement. Also, the base shear of piers, the maximum displacement at the top of the piers, and the maximum deck acceleration at locations top of the piers are studied. The analysis revealed that the two types of used bearings have small effect on the base shear, both the longitudinal pier displacements and deck accelerations were similar for all the cases, short duration earthquakes result in higher vertical displacements for the bearings, and the two types of bearings produce small residual displacements.

Keywords: *Bridges, seismic analysis, isolation bearings & time history analysis.*

1. Introduction

Seismic isolation bearings for bridges are used to control the damage during earthquakes. This is due to their decoupling of the deck and piers. There are considerable ranges of these bearings. It is common to use lead rubber bearing and friction pendulum system for seismic isolation of bridges. The use of shape memory alloy wire-based lead rubber bearing is increasing over the last years (1, 2, 3 & 4). A brief discussion for some of the isolation bearings developments will be presented. Yuan et al. (2021) developed a steel reinforced polyurethane isolation bearing. The steel part is an innovative four C-shaped dampers which reinforces the bearing. Thus, the bearing combines polyurethane elastomer and hysteretic steel. The bearing was used for a continuous bridge, which was numerically studied and proved its promising rule. Nguyen and Guizani (2021) studied analytically the behavior of natural rubber bearing combined with U-shaped dampers of superior seismic performance. They developed a numerical model to evaluate the behavior of this type of bearing. The U-shaped dampers showed similar performance for the in-plane and out-of-plane loadings. Their behavior is affected by material properties and geometric shape. This type of bearing system showed a stable behavior in all directions. Tubaldi et al. (2018) studied the seismic behavior of three-span bridge with steel-reinforced natural rubber bearings. They reported that the bearing vertical stiffness is very important and affects the seismic performance. They also compared the simplified and advanced bearing models. Filipov et al. (2013) used bridge isolation bearings to have certain seismic response. They showed models for estimating bridge systems. A finite element model for a bridge prototype was performed. Pushover analyses were performed in two directions. They concluded that the abutments provide good force resistance in the longitudinal direction. Choi et al. (2006) reported that lead-rubber isolation bearings may suffer from permanent deformations in the case of large earthquakes. A new isolation bearing with wires of shape memory alloy places in the elastomeric bearing is developed. This bearing is used with a three-span steel bridge and showed its good recovering ability. The current research utilizes lead rubber isolation bearings.

Long-duration earthquakes have caused lots of damage in different locations of the world (10). However, current seismic design codes do not cover these earthquakes. For complete study of the performance of bridges under earthquakes' loads, both long-duration and short-duration earthquakes are to be considered. Typically, short-duration earthquakes have been used in the seismic studies of bridges. However, the long-duration earthquakes, which are quite less studied, are also to be considered in this research.

There are three methods of analysis for statically indeterminate bridges, which have continuous deck. These are modal pushover analysis, secant mode superposition, and dynamic analysis. The dynamic method of analysis is the general and time-consuming method. This is the method used in the current research. A finite element program called Seismostruct (11) will be used to perform the analytical study. This program has been verified by many researchers such as references 12 and 13.

2. Earthquakes Used in the Analysis

Three short duration earthquakes and three long duration earthquakes are used in the time history analysis. The duration of each earthquake is shown in Table 1. These six records are matched to the response spectrum of the Egyptian loading code (14) assuming peak ground acceleration of 0.3g and soil class C. The importance factor is taken 1.3 assuming main bridge and the response reduction factor is taken equal to 1.0 as for piers with elastomeric bearings.

Table 1 Utilized Earthquake Records :

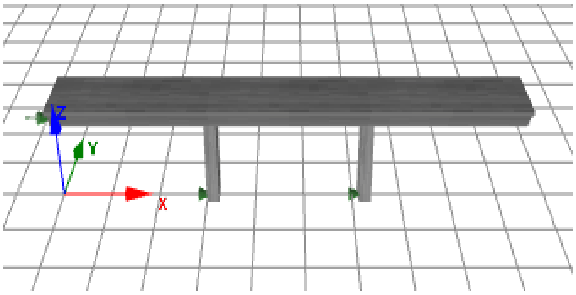
Earthquake	**Date**	**Recording Station**	**Duration (sec)**
Loma Prieta (USA)	October 1989 ،18	Corralitos	16.9
Loma Prieta (USA)	October 1989 ،18	Emeryville	20.53
Trinidad (USA)	August 1983 ،24	CDMG 090	21.4
Hollister (USA)	1989	Hollister	60.0
Century City (USA)	1994	Century City, Lacc North	60.0
Yermo (USA)	1992	Fire -Yermo Station	80.0

3. Studied Bridge

The studied bridge in this research has a box type continuous deck of three equal spans. Each span is ten meters long. The bridge is supported on two abutments at the beginning and at the end and on two middle piers. The piers are of rectangular hollow section. Each pier is of five meters height. The deck of the bridge in this structural system acts as a diaphragm which makes all piers move similarly. The deck and piers are made of reinforced concrete which has a concrete of cylinder compressive strength equals to 30 MPa and steel reinforcement of yield strength equals to 420 MPa. Rubber lead bearings are used between the deck and piers.

4. Modeling of the Bridge

A commercial nonlinear 3D finite element software which is fiber based and called SeismStruct is used in the analysis. The deck is modeled using elastic frame element assuming that it will be elastic during earthquake and the piers are modeled using inelastic nonlinear force-based frame elements. The layout of the bridge is shown in Figure 1. The model used for concrete is the one of Mander et al. (15) and for steel reinforcement is Menegotto-Pinto model (16). Rigid connections are assumed between the deck and the bearings on top of the piers. The piers are assumed fixed at the base while the bases of the abutments are fixed except that they allow for rotation about y-axis. The bearings are modeled using zero-length link element. The response curve of the link is taken as asymmetric bilinear Takeda curve (takeda-asm) where different values are specified for tension and compression as shown in Figure 2. Table 2 gives the values of the six parameters which define the behavior of bearing 2 (500) and bearing 1 (150) (bearing 2 (500) of yield strength 500 MPa and bearing 1 (150) of yield strength 150 MPa). The assumed loads on the bridge are the own weights of its components and a uniformly distributed load on the deck equals to 3.33 ton/m^2 noting that the deck width is 3.8 m. The scaled natural earthquakes are applied in the longitudinal direction of the bridge. Figure 3 shows the input parameters for one of the bearings and Figures 4 & 5 show the dimensions of the deck and pier, respectively. The dimensions of the bridge deck and pier are taken from the literature associated with the program SeismoStruct.



Layout of the Bridge :**Figure 1**

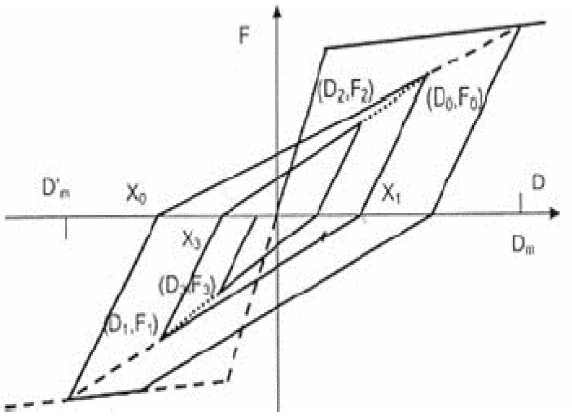
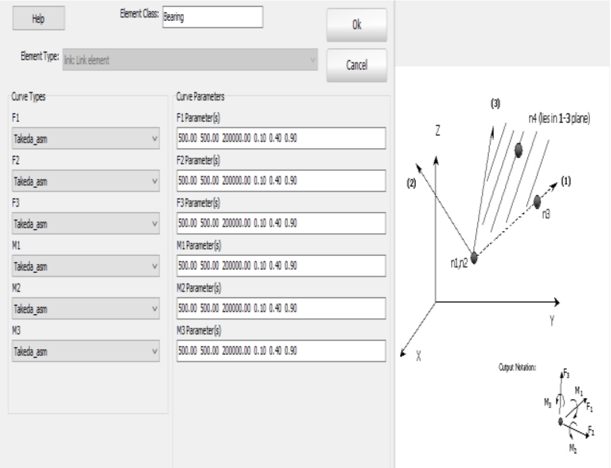


Figure 2: Asymmetric Bilinear Takeda Curve for the Link Member

Table 2: Parameters which Define the Link Elements

Parameter	Bearing 2 (500)	Bearing 1 (150)
positive yield ((+)Fy)	MPa 500	MPa 150
negative yield ((-)Fy)	MPa 500	MPa 150
stiffness at beginning (Ky)	e5 N/mm2	e5 N/mm2
post-yield/stiffness at beginning ratio (α)	0.10	0.10
stiffness reduction factor for outer loop (β_o)	0.40	0.40
stiffness reduction factor for inner loop (β_1)	0.90	0.90



Element Class: Bearing

Element Type: link: Link element

Curve Types

F1: Takeda_asm

F2: Takeda_asm

F3: Takeda_asm

M1: Takeda_asm

M2: Takeda_asm

M3: Takeda_asm

Curve Parameters

F1 Parameter(s): 500.00 500.00 200000.00 0.10 0.40 0.90

F2 Parameter(s): 500.00 500.00 200000.00 0.10 0.40 0.90

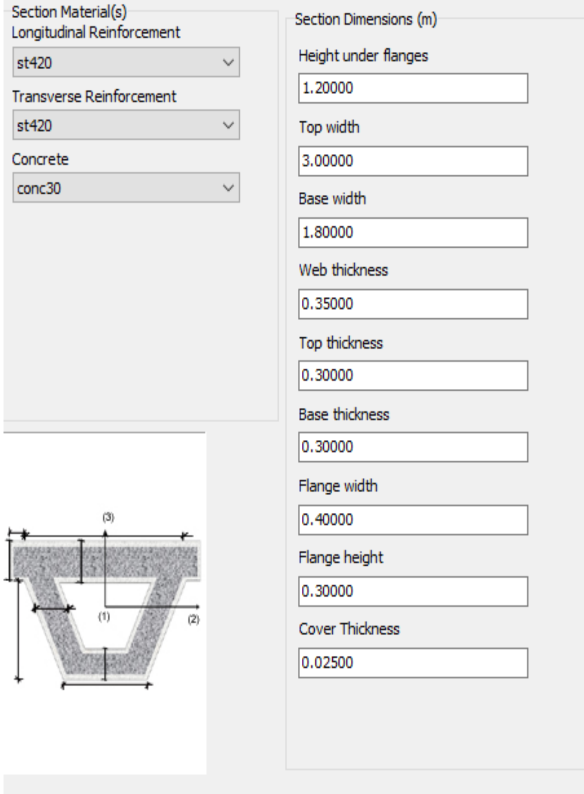
F3 Parameter(s): 500.00 500.00 200000.00 0.10 0.40 0.90

M1 Parameter(s): 500.00 500.00 200000.00 0.10 0.40 0.90

M2 Parameter(s): 500.00 500.00 200000.00 0.10 0.40 0.90

M3 Parameter(s): 500.00 500.00 200000.00 0.10 0.40 0.90

Figure 3: Input Parameters for One of the Bearings



Section Material(s)

Longitudinal Reinforcement: st420

Transverse Reinforcement: st420

Concrete: conc30

Section Dimensions (m)

Height under flanges: 1.20000

Top width: 3.00000

Base width: 1.80000

Web thickness: 0.35000

Top thickness: 0.30000

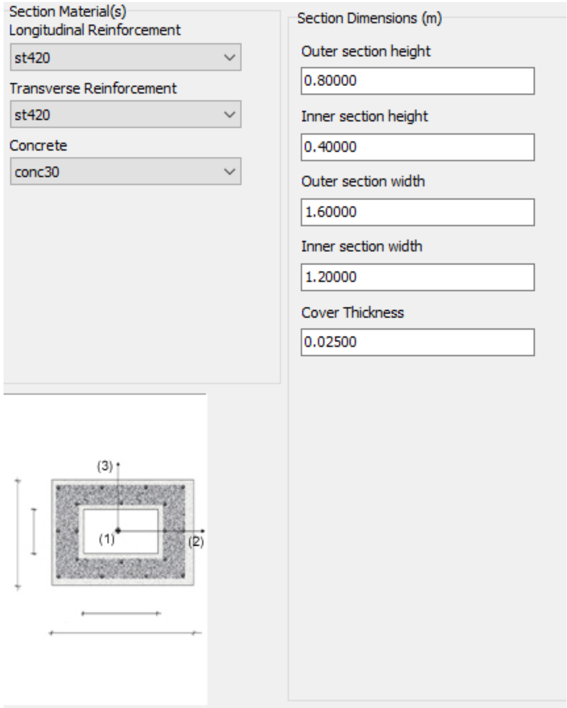
Base thickness: 0.30000

Flange width: 0.40000

Flange height: 0.30000

Cover Thickness: 0.02500

Dimensions of the Deck :**Figure 4**



Section Material(s)

Longitudinal Reinforcement: st420

Transverse Reinforcement: st420

Concrete: conc30

Section Dimensions (m)

Outer section height: 0.80000

Inner section height: 0.40000

Outer section width: 1.60000

Inner section width: 1.20000

Cover Thickness: 0.02500

Figure 5: Dimensions of the pier

5. Finite Element Results

5.1 Maximum Acceleration of the Deck

Similar seismic forces result in similar deck accelerations. This is proved by Table 3 and Figure 6 for all the cases, which gave an average maximum acceleration of 9.52 m/s^2.

Table 3: Deck Acceleration on Top of Pier

Earthquake	Type of Bearing	max deck acc. top of pier (^{2}m/s)
Corralitos 16.90	**(bearing 1 (150**	10.154
	(bearing 2 (500	9.935
Emeryville 20.53	**(bearing 1 (150**	9.26
	(bearing 2 (500	9.637
Trinidad 21.4	**(bearing 1 (150**	9.668
	(bearing 2 (500	9.093
60 1-Hollister	**(bearing 1 (150**	10.519
	(bearing 2 (500	11.327
60 1-Lacc_nor	**(bearing 1 (150**	8.445
	(bearing 2 (500	8.633
80.0 1-Yermo	**(bearing 1 (150**	8.564
	(bearing 2 (500	9.051

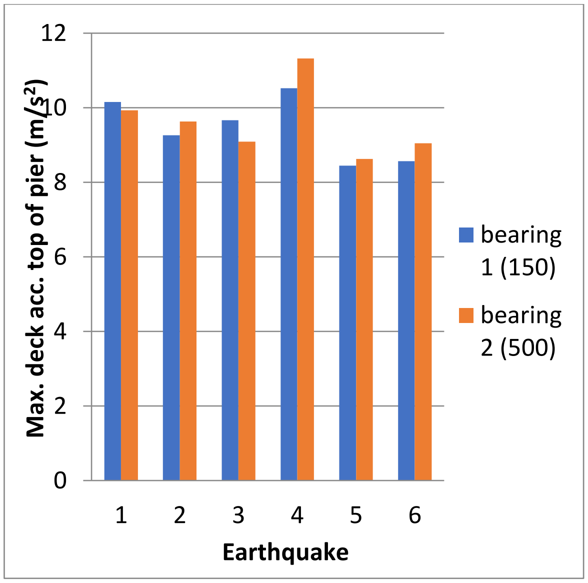


Figure 6: Deck acceleration for top of piers (“1” refers to the earthquake Corralitos 16.90 and go on)

5.2 Maximum Base Shear

Table 4 and Figure 7 show the maximum total base shear for the bridge piers considering the cases of bearing 1 (150) and bearing 2 (500). The given base shears are due to the six considered earthquakes. The average obtained base shear for the bridge with bearing 1 (150) and bearing 2 (500) under long duration earthquakes are 178.2 kN and 195.2 kN, respectively. These values are smaller than the corresponding ones for the case of short duration earthquakes, which are 217.3 kN and 208.2 kN. Generally, the differences are small comparing the bridges with bearing 1 (150) and bearing 2 (500).

Table 4: Base Shear for the Bridge Piers

Earthquake	Type of Bearing	base shear (kN)
Corralitos 16.90	**(bearing 1 (150**	225.6
	(bearing 2 (500	207.3
Emeryville 20.53	**(bearing 1 (150**	218.5
	(bearing 2 (500	233.4
Trinidad 21.4	**(bearing 1 (150**	207.8
	(bearing 2 (500	183.9
60 1-Hollister	**(bearing 1 (150**	186.3
	(bearing 2 (500	213.7
60 1-Lacc_nor	**(bearing 1 (150**	153.5
	(bearing 2 (500	174.9
80.0 1-Yermo	**(bearing 1 (150**	194.8
	(bearing 2 (500	196.9

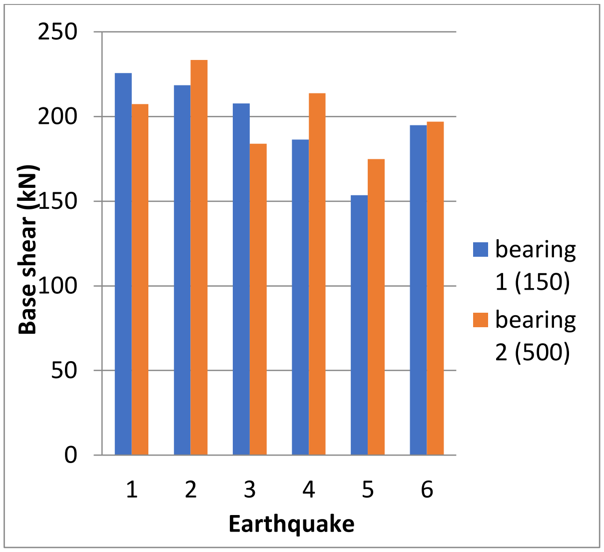


Figure 7: Base shear on the bridge piers (“1” refers to the earthquake Corralitos 16.90 and go on)

5.3 Maximum Displacement of the Pier

The maximum recorded longitudinal displacement for the bridge piers under the six considered seismic loads are given in Table 5 and Figure 8. All the cases gave approximately similar maximum longitudinal displacement for the piers with an average of 0.86mm.

Table 5: Longitudinal Displacement for the Bridge Pier

Earthquake	Type of Bearing	max disp. for pier (mm)
Corralitos 16.90	Bearing 1 (150)	0.90
	Bearing 2 (500)	0.79
Emeryville 20.53	Bearing 1 (150)	0.87
	Bearing 2 (500)	0.97
Trinidad 21.4	Bearing 1 (150)	0.96
	Bearing 2 (500)	0.92
60 1-Hollister	Bearing 1 (150)	0.74
	Bearing 2 (500)	0.93
60 1-Lacc_nor	Bearing 1 (150)	0.67
	Bearing 2 (500)	0.76
80.0 1-Yermo	Bearing 1 (150)	0.84
	Bearing 2 (500)	0.92

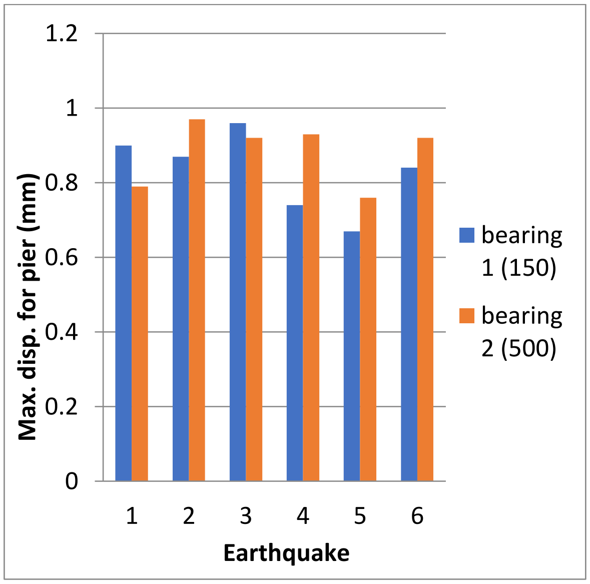


Figure 8: Max. displacement at the bridge pier ("1" refers to the earthquake Corralitos 16.90 and go on)

5.4 Bearing Vertical Displacement and Residual Displacement

The performance of the two types of bearings can be compared using the maximum bearing vertical displacement and the maximum bearing vertical residual displacement shown in Tables 6 and 7, and Figures 9 an 10. The maximum bearing vertical displacement was recorded for bearing 1 (150) under the short duration earthquakes with an average of 2.5 mm. The next value was recorded for bearing 2 (500) under the short duration earthquakes with an average of 2.33 mm. The long duration earthquakes resulted in an average of 2.15 mm for both types of bearings. It is clear that the short duration earthquakes result in higher maximum vertical displacement for the bearings. The values of Table 7 give an indication on the capability of both types of bearings to re-center after earthquakes. The residual deformation of bearing 1 (150) was better than that for bearing 2 (500) under both short duration and long duration earthquakes. The values of maximum bearing vertical residual displacements for bearing 1 (150) were 0.132 mm and 0.023 mm under the short and long duration earthquakes, respectively. The corresponding values for bearing 2 (500) were 0.389 mm and 0.026 mm. Thus, bearing 1 (150) was more effective in recovering the vertical deformation. Generally, the two types of bearings were successful in limiting the maximum vertical displacement and reducing the residual displacement.

Table 6: Maximum Bearing Vertical Displacement

Earthquake	Type of Bearing	maximum bearing vertical displacement at top of pier (mm)
Corralitos 16.90	(bearing 1 (150	2.2
	(bearing 2 (500	1.6
Emeryville 20.53	(bearing 1 (150	2.6
	(bearing 2 (500	2.6
Trinidad 21.4	(bearing 1 (150	2.7
	(bearing 2 (500	2.8
60 1-Hollister	(bearing 1 (150	2.1
	(bearing 2 (500	2.1
60 1-Lacc_nor	(bearing 1 (150	1.9
	(bearing 2 (500	2.1
80.0 1-Yermo	(bearing 1 (150	2.6
	(bearing 2 (500	2.1

Table 7: Maximum Bearing Vertical Residual Displacement

Earthquake	Type of Bearing	maximum bearing vertical residual displacement at top of pier (mm)
Corralitos 16.90	(bearing 1 (150	0.31
	(bearing 2 (500	0.27
Emeryville 20.53	(bearing 1 (150	0.061
	(bearing 2 (500	0.028
Trinidad 21.4	(bearing 1 (150	0.025
	(bearing 2 (500	0.87
60 1-Hollister	(bearing 1 (150	0.02
	(bearing 2 (500	0.021
60 1-Lacc_nor	(bearing 1 (150	0.034
	(bearing 2 (500	0.0017
80.0 1-Yermo	(bearing 1 (150	0.015
	(bearing 2 (500	0.056

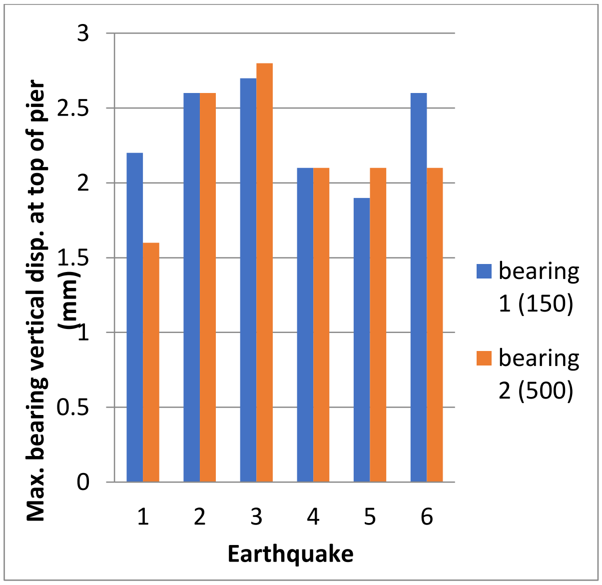


Figure 9: Max. vertical displacement for bearing (“1” refers to the earthquake Corralitos 16.90 and go on)

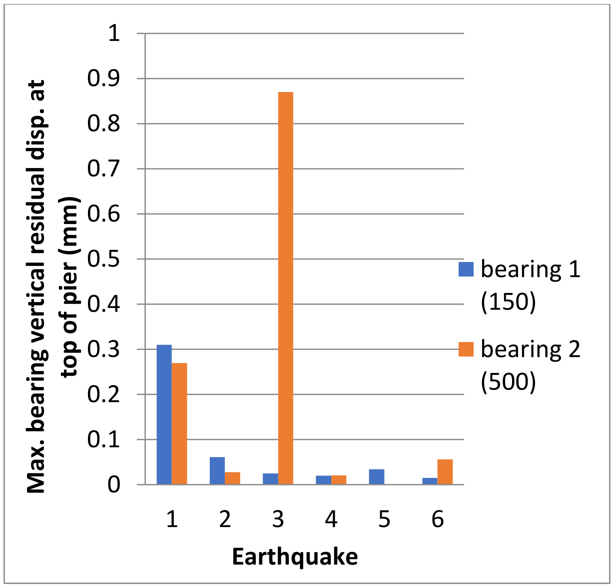


Figure 10: Max. vertical residual displacement for bearing (“1” refers to the earthquake Corralitos 16.90 and go on)

6. Conclusions

The current research proved the following:

1-Small differences in the base shear for the piers are noticed for bridges with bearing 1 (150) and bearing 2 (500).

2-Approximatelly equal longitudinal displacements for the bridge piers are recorded for the two types of bearings under the two types of earthquake.

3-The bridge deck accelerations are approximately similar for all the cases.

4-The two types of bearings under short duration seismic loads suffer higher maximum vertical displacements for the bearings compared to the case of long duration seismic loads.

5-The two types of bearings showed good capability of re-centering after earthquakes.

7. Acknowledgement

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