On the influence of earthquakes and soil characteristics on seismic response and performance of isolated bridges

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Abstract

Seismic isolation technology is an effective means of reducing seismic risk and enhancing the structural seismic performance. However, some parameters, such as earthquake inputs and soil characteristics, affect and mitigate the efficiency of this technology. The main purpose of this study is to investigate the simultaneous effects of different records and flexible soils on isolated bridges. To this end, an isolated bridge is assumed to be at different distances from the ruptured fault (R_{rup}) in order to represent near-fault (NF) and far-field (FF) situations. These records are extracted on different soils, which are categorized based on their shear velocity, to represent different soil behaviours and characteristics. Nonlinear time history analysis (NTHA) is carried out on a typical isolated bridge model using the SAP2000 software. Responses in terms of deck acceleration, base shear, displacement of the isolation system, and the performance of the isolation units are studied. Results demonstrate that for NF zones, the soil effects must absolutely be taken into account. In soft soils, all seismic responses are amplified, leading to higher forces and displacement demands. In such zones, failing to consider this fact during the design process results in largely underestimated seismic displacement and force demands for the isolated bridge system, seriously harming its seismic performance. Likewise, the amplification of responses in soft soils is observed for FF records and it should be considered for these prone areas. However, despite their importance, these records are not as destructive as NF records for isolated bridges on soft soils.

Keywords Seismic isolation · Earthquake characteristics · Near-fault · Far-field · Soil effects · Bridges

Introduction

Seismic isolation technology is based on decreasing the fundamental structural vibration frequency to a value less than the predominant energy-containing frequencies of the earthquake in order to reduce the seismic force demand to or near the elastic capacity of the structural members, thereby eliminating or drastically reducing inelastic deformations. Numerous experimental and analytical research studies have compared the seismic responses of conventional and isolated structures and have shown that seismic isolation technology plays a great role in reducing the seismic responses of infrastructures (Ghobarah and Ali 1988; Soneji and Jangid 2008; Tongaonkar and Jangid 2003; Tsopelas et al. 1996). The long-term benefit of these technologies lies in its preservation of the serviceability of the structure after an earthquake and thus eliminating the cost of reconstruction (Guizani 2003; Guizani and Chaallal 2011).

Bridges rank among the most important infrastructures in modern societies because they are the vital artery in transportation systems, especially in crisis conditions, such as the period following a strong earthquake. It should be mentioned that even when just a part of a bridge collapses, the stability of the whole structure is affected, because failure at a particular point, such as a span failure due to an inadequate support length at the joints, or a failure in a pier, will interrupt the operation of the whole bridge, which is a key component of the land communication system (Andrawes and DesRoches 2005; Forcellini 2017).

To ensure that reliable installations are available to respond to damaging earthquakes, all effective parameters of the performance of isolated bridges must be taken into account at the

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design stage. According to recent studies, and based on evidence from past earthquakes, record characteristics and soil effects are two of the most important parameters affecting the seismic performance of isolated structures (Beresnev and Wen 1996; Castaldo and Tubaldi 2018). Ground motion records obtained in major earthquakes have shown that the characteristics of NF are particularly different from FF records. NF and FF ground motions differ in the distance to the ruptured fault so that if the structure under consideration is inside the specified distance of a fault (10–20 km), it can be classified as NF. Ground motions having a source-to-site more than the abovementioned distance are classified as FF motions (Billah et al. 2013; Bray and Rodriguez-Marek 2004). NF records often contain strong and long-period velocity pulses that could cause severe structural damage (Chouw and Hao 2005; Neethu and Das 2019). Studies on the effect of NF records and isolated bridges showed that in the NF zone, records contain a higher PGV/PGA ratio, velocity pulse, and input energy than FF records and that these records lead to a greater ductility demand and a larger base shear on structures (Liao et al. 2000; Shen et al. 2004).

Furthermore, NF records amplify the seismic responses of the isolated bridge when the pulse period is close to the effective period of the isolation system and the ratio of the energy dissipated by the isolation system to the total input energy is slightly influenced by the NF effect (Shen et al. 2004). Several important factors are highlighted in the literature, showing that NF records cause severe damage to conventional and isolated bridges and produce high story drift values, which force the structure to behave in the inelastic range and lead to severe damage (Attalla et al. 1998; Malhotra 1999; Ordaz et al. 1995).

It has been shown in the literature that the frequency contents of the seismic waves transform while the waves are passing through the different soil layers (Saritaş and Hasgür 2014; Worku 2014). These changes are drastic where the underlying soil is soft, resulting in a higher displacement and shear forces (Kulkarni and Jangid 2003; Saritaş and Hasgür 2014; Worku 2014). For this reason, isolated bridges located on soft soils have a greater potential for severe damage, while the isolation system provides a better efficiency on rocks or stiff soils during earthquakes (Dicleli and Buddaram 2006; Kulkarni and Jangid 2003).

Often, a rigid base is assumed in seismic structural design, while soil effects or soil-structure interaction (SSI) effects are either ignored or considered separately, whereas they are indeed coupled, and ignoring the soil and its effects lead to erroneous assessments (Stehmeyer and Rizos 2008). Studies have shown that while neglecting soil effects is not consequential for all bridges, in the case of heavier bridges in particular, as well as for soft soil conditions, such neglect leads to an underestimation of the bridge damage potential (Castaldo and Ripani 2016; Stehmeyer and Rizos 2008).

Various methods and software programs used by researchers to study soil and SSI effects provide reliable soil models and structural behaviours. Developing numerical models is quite challenging since soil materials exhibit a diverse range of complex constitutive behaviours (Beresnev and Wen 1996). Methods used for seismic analysis of soils and structures are based on analytical, experimental, and numerical procedures, combined with observations of physical behaviour and lessons learned from past events. The finite element method (FEM), the boundary element method (BEM), and the coupled BEM_FEM are among the most popular numerical techniques used for the rigorous modeling of soil effects on bridges (Stehmeyer and Rizos 2008).

The effect of SSI on the response of an isolated cable-stayed bridge was investigated by Soneji and Jangid (2008). Springs and dashpots were used to simulate the SSI effect and the bridge was subjected to a series of NF records. Results showed that the soil has significant effects on the responses of isolated bridges and that bearing displacements may be underestimated if SSI effects are ignored. Further, it was found that nonlinear soil modeling is essential in properly reflecting the dynamic behaviour of the soil-pile system.

Similar studies have been conducted by using springs and dashpots to model the SSI effects and show that SSI causes higher isolation system drifts and higher pier shears as compared with fixed pier bridges (Ates and Constantinou 2011; Bi et al. 2011; Ucak and Tsopelas 2008; Zhang and Makris 2002). As well, numerous studies have shown that seismically isolated bridges are very sensitive to NF records and soft soil effects (Castaldo and Tubaldi 2018; Chouw and Hao 2005).

Despite the difficulties inherent in modeling soils and structures in the direct method, many related studies have been conducted by researchers using different methods such as FEM, BEM, and the finite difference method (FDM) to show the effect of different soils and records on infrastructures.

The SSI effect for a historical masonry arch bridge using full three-dimensional (3D) nonlinear time history analysis and the FEM approach was studied by Güllü and Jaf (2016). A comparison of the results with the 3D model showed that the influence of SSI becomes relatively prominent on the displacement, acceleration, rotation, frequency, modal shape, base shear, and overturning moment responses.

Another approach to investigate the influence of soil characteristics in terms of frequency content on the seismic performance of isolated bridges was used by Castaldo and Tubaldi (2018). A series of artificial ground motions corresponding to the stiff, medium, and soft soil conditions was used to assess the seismic responses of an isolated bridge and define the optimal isolator properties. Results revealed the importance of different soil characteristics in the design of the isolator's parameters and the need to consider the frequency and characteristics of the records at the design stage.

While most of the studies focused on the NF records or compared the NF and FF records, a seismically isolated highway bridge pier was evaluated by considering the SSI effect subjected to FF records. Spring and dashpot components for SSI and laminated rubber bearings for the isolation system were modeled. The results showed that SSI effects play an important role in increasing the responses of seismically isolated bridges constructed on soft soils, which should be carefully considered in such conditions (Alam and Bhuiyan 2013).

Many studies have examined different record characteristics, such as NF and FF records, soil effects, and SSI effects on conventional and isolated bridges. Most such studies have focused on either the record characteristics or the soil characteristics with or without isolation systems, but limited attention has been paid to the concurrent effects of both characteristics on isolated bridges for prone areas. For this reason, this study aims to investigate the simultaneous effects of record characteristics, including NF and FF, and the effect of different soil properties on isolated bridges. Real earthquake records on different soil layers are extracted and seismic responses of a bridge with and without an isolation system are studied. The purpose of this study is to understand the effect of soil layers on the propagation of different record characteristics and the performance of isolation systems. Reaching a more advanced comprehension of the responses of isolated bridges leads to better and more optimal bridge designs in future projects. Additionally, this understanding allows posing more accurate diagnostic and finding more efficient isolation solutions for retrofit projects, considering the effects of site conditions. More details about the records, soil categories, and isolation systems will be presented in the next sections.

Selected records and record properties

Twenty-one ground motion records of the Northridge 1994, Kobe 1995, and Parkfield 2004 earthquakes were extracted from the strong motion database of the Pacific Earthquake Engineering Research Center (PEER 2013). These earthquakes were chosen for two major reasons. First, they are among the most destructive earthquakes ever recorded, and second, there is a rich database of records for these earthquakes at different distances from the epicenter (R_{rup}) representing NF and FF situations, and different soil types, to represent the soil effects. It is important to note that for all three earthquakes, records were chosen to cover nearly the same distances and soil classes. Real captured records were used in order to study the trend of real changes in NF and FF record characteristics by passing through the different soil layers instead of using software predictions and simulations. Records and site classes were classified according to Canadian Highway Bridge Design Code (CSA 2014). Nine of the 21 records were within 10 km of the epicenter (R_{rup} less than 10

km) and were considered as NF records (CSA 2014). As earlier stated, NF records have higher characteristic values, especially in terms of Peak Ground Velocity (PGV), specific energy density, and damage index (Liao et al. 2000; Shen et al. 2004). These features cause higher seismic responses, and such signals impose very high input energy on the structure at the early stages of the records (Liao et al. 2004). Different site classes were categorized based on the shear wave average velocity (Vs), which is shown in Table 1, while the record properties are shown in Table 2. It should be noted that since this study aims mainly to investigate the simultaneous effects of NF and FF records on different soils, the effect of different source mechanisms such as directivity effects, focal mechanisms (strike-slip, normal or reversing faulting), rupture duration, and slip duration is not considered.

Table 2 shows that NF records have higher characteristics, especially in PGV, Arias intensity (AI), and specific energy density. Arias intensity (AI), which is a cumulative ground motion intensity measure (IM), provides a quantitative and instrumental measure of the severity of seismic shaking. According to Table 2, this parameter has a higher amount for soft soil records in NF areas (Wilson 1993).

A term used for the amount of energy stored in a system is "specific energy density," which is the square of velocity at any given time integrated over the entire time range (Sandeep and Prasad 2012). Obviously, for NF records, this parameter should carry a high value, and as is shown in Table 2, for soft soils in NF zones, the parameter has a higher amount of specific energy density. As a constant rule, all parameters are amplified in soft soils, as compared with stiff soils. The damping effect of soil in FF areas is clearly observed in records characteristics by passing through the soil so that by increasing the distance from the fault, a higher reduction is observed in all the intensity parameters.

Spectral accelerations of the Kobe, Northridge, and Parkfield for NF records on different soil types are shown in Fig. 1 to illustrate the effects of different soil frequencies on the characteristics of records (PEER 2013). Drastic changes in the maximum response acceleration and period elongation in soft soils are observed, which illustrates the importance of considering soil classes for seismic bridge analysis.

Case study bridge model and isolation system properties

The selected case study bridge model is a regular conventional bridge with a uniform solid slab deck, 7 m wide and 0.7 m thick. In this study, the bridge is symmetric with two equal spans supported on a circular 30 MPa concrete pier. In total, four different conventional bridge models are analysed in which each pier's dimensions provide a bridge with a specified fundamental period of 0.63, 0.43, 0.24, and 0.16 s, which

Table 1 Site classifications for seismic site response

Site class	Ground profile name	Average properties in top 30 m		
		Shear wave average velocity, $\overline{V}_s$ (m/s)	Standard penetration resistance, $\overline{N}_{60}$	Soil undrained shear strength, s_u
A	Hard rock	$\overline{V}_s > 1500$	Not applicable	Not applicable
B	Rock	$760 < \overline{V}_s \leq 1500$	Not applicable	Not applicable
C	Very dense soil and soft rock	$360 < \overline{V}_s \leq 760$	$\overline{N}_{60} > 50$	$s_u > 100$ kPa
D	Stiff soil	$180 < \overline{V}_s \leq 360$	$15 \leq \overline{N}_{60} \leq 50$	$50 < s_u \leq 100$ kPa
E	Soft soil	$\overline{V}_s < 180$	$\overline{N}_{60} \leq 15$	$s_u < 50$ kPa
		Any profile with more than 3 m of soil with the following characteristics: • Plastic index, PI > 20; • Moisture content, $W \geq 40\%$; and • Undrained shear strength, $s_u < 25$ kPa		
F	Other soil	Site-specific evaluation required		

are referred to in this study as BR-1, BR-2, BR-3, and BR-4, respectively. Table 3 illustrates the dimensions and the period of each conventional bridge.

3D structural modeling of the bridge and NTHA is performed in SAP2000 program. The concrete bridge deck and pier are modelled by frame elements with an assumed elastic behaviour during the earthquake excitation because in general the bridge piers in seismic isolated bridges are designed to perform in an elastic or nearly elastic manner (Ucak and

Tsopelas 2008). Table 4 indicates the value of the density, concrete's compressive strength, modulus of elasticity, and Poisson's ratio of the sections used for modelling.

As it is shown in Fig. 2, boundary conditions are assigned as roller for free movements of the superstructure in the longitudinal direction for both spans and pin-type connections in the transverse direction. In addition, the base of the pier is restrained in all directions of translation and rotation.

Table 2 NF and FF earthquake records on different soils based on V_s

Records	Soil type	R_{rup} (km)	PGA (g)	PGV (cm/s)	PGD (cm)	Arias intensity (m/s)	Specific energy density (cm²/s)
Northridge-1	A	7.0	0.43	30.0	5.5	0.73	489
Northridge-2	C	7.2	0.43	51.0	10.5	1.80	1812
Northridge-3	C	31.7	0.06	5.3	2.4	0.04	27
Northridge-4	C	81.7	0.05	2.9	0.6	0.03	12
Northridge-5	D	7.5	0.55	76.0	14.3	3.10	5281
Northridge-6	D	29.7	0.10	13.6	5.7	0.22	417
Northridge-7	D	85.4	0.05	4.0	0.8	0.03	15
Kobe-1	B	0.9	0.31	31.0	8.6	0.82	1031
Kobe-2	C	7.0	0.48	46.8	8.4	3.35	1978
Kobe-3	C	50.0	0.09	5.3	2.8	0.11	41
Kobe-4	C	119.0	0.02	1.1	1.9	0.01	6
Kobe-5	D	0.9	0.83	91.1	21.2	8.40	7597
Kobe-6	D	31.7	0.30	24.5	8.1	1.40	1778
Kobe-7	D	95.7	0.14	15.1	3.1	0.37	420
Parkfield-1	B	5.3	0.24	14.6	1.4	0.17	54
Parkfield-2	C	4.9	0.37	14.1	1.9	0.74	105
Parkfield-3	C	22.0	0.02	3.6	2.0	0.01	33
Parkfield-4	C	69.0	0.01	0.7	0.2	0.002	1
Parkfield-5	D	5.2	0.31	20.2	3.7	0.95	292
Parkfield-6	D	29.4	0.02	4.3	1.7	0.03	87
Parkfield-7	D	68.5	0.02	0.9	0.2	0.01	4

Fig. 1 Spectral acceleration of **a** Kobe, **b** Northridge and **c** Parkfield for NF records on different soils, $R_{rup} < 10$ (km)
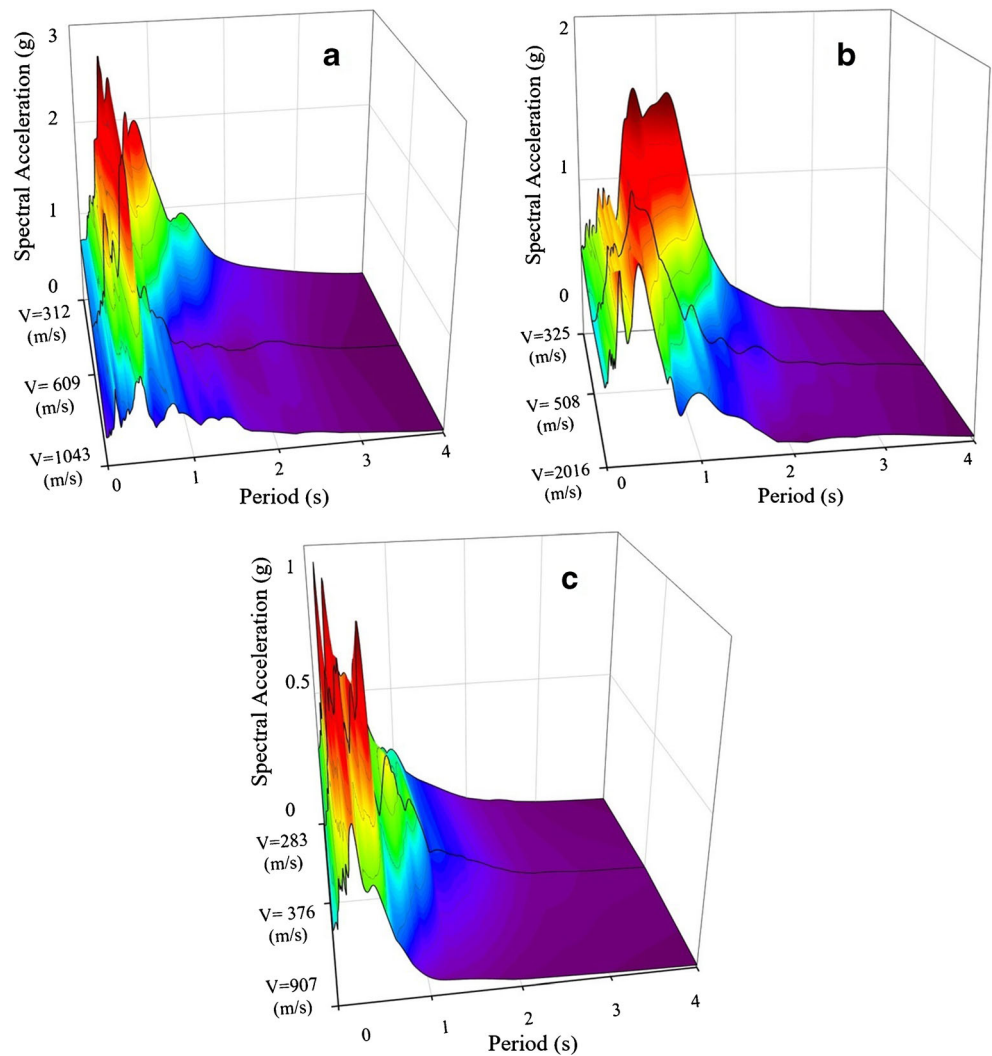
Table 3 Period and the dimension of conventional bridges

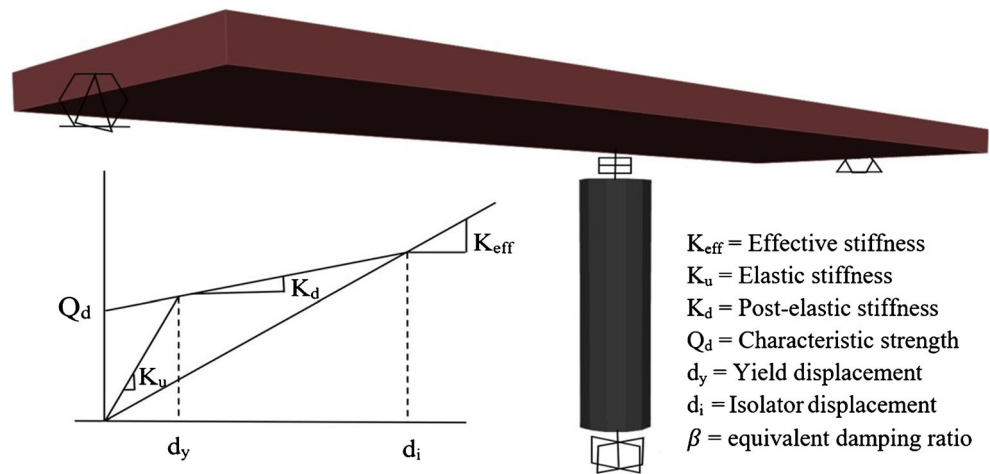| Bridge	T (s)	Pier diameter (m)	Pier height (m)	Span length (m)	Deck width (m)	Deck thickness (m)
BR-1	0.63	0.8	6.0	10	7.0	0.7
BR-2	0.43	1.0	6.0	10	7.0	0.7
BR-3	0.24	1.5	6.0	10	7.0	0.7
BR-4	0.16	2	6.0	10	7.0	0.7

Considering the bridge is located in Montreal, Canada, the isolation system is designed for three periods of $T = 1$, 2, and 3 s, referred to as ISO-1, ISO-2, and ISO-3, with a displacement capacity of 3, 5.5, and 10 cm, respectively. For implementing seismic isolation, the isolation system is lumped between the deck and the pier, and only the longitudinal direction is studied. Bilinear behaviour model of the isolation system is based on the rubber isolator property and it is assigned as a link element in SAP2000 (Wilson 2017). The hysteresis parameters, the behaviour of the seismic isolation system (SIS), and

Table 4 Material properties

Material name	Density (kN/m³)	Compressive strength (MPa)	Modulus of elasticity (MPa)	Poisson ratio
Concrete	24	30	24,000	0.2

Fig. 2 Isolated bridge model and primary hysteresis curve parameters for SIS

K_{eff} = Effective stiffness
K_u = Elastic stiffness
K_d = Post-elastic stiffness
Q_d = Characteristic strength
d_y = Yield displacement
d_i = Isolator displacement
β = equivalent damping ratio

the bridge 3D model are shown in Fig. 2, while the SIS parameters are presented in Table 5.

Four different conventional bridges in order to represent different structural flexibility parameters, and three isolation systems to show the effect of different isolation characteristics, in total, 16 bridges are analysed. These bridges are subjected to 21 records that contain NF and FF captured on different soil types at different ruptured faults distances. NTHA for all cases is conducted in SAP2000 and structural responses, including the maximum acceleration on top of the deck, the maximum displacement of the isolator, and the maximum base shear, are studied, and the results are discussed in the following sections (Wilson 2017).

Results

Maximum acceleration response

As can be seen in the maximum acceleration responses shown in Table 6, increasing the isolation period leads to fewer responses in all bridges, with different natural periods and all subjected records, including NF and FF on stiff to soft soils. The highest reduction factor among the isolation systems is related to ISO-2, by a factor of 2 compared with ISO-1. This factor is almost 1.5 for ISO-3 compared with ISO-2. By increasing the isolation system period, the acceleration responses tend to approach the same value, especially in the stiffer bridges, BR-3 and BR-4.

Acceleration responses of isolated bridges are higher in NF records than in FF records, and among NF records, it is higher on soft soils. This trend shows the destructive effect of NF records, particularly on softer soils. The average increasing factor in the maximum acceleration responses for NF records on soft soils is 2, 1.8, and 1.5, respectively, as compared with NF records on stiff soil for the Kobe, Northridge, and Parkfield records, respectively.

Comparisons of FF records show that there is a drastic decrease in acceleration responses for all bridges in the case of stiffer soils (type C). This reduction is more significant for records at higher distances from the ruptured fault. In softer soils (type D), the amplification of responses is observed compared with the records in stiffer soils, while in general, the lowest acceleration responses are related to FF records.

The maximum acceleration responses of all records along with the increasing factor of the maximum acceleration are shown in Figs. 3 and 4. It should be mentioned that the higher seismic responses in NF records and also the amplification of responses in soft soils have been reported in previous studies (Shen et al. 2004; Stehmeyer and Rizos 2008).

Maximum seismic isolation system displacement

The maximum isolation system displacements are 29.4, 23.7, and 4.34 cm for Kobe, Northridge, and Parkfield records, respectively. All the maximum responses are related to NF records ($R_{rup} < 10$ km), on soft soils (soil type D). For the Kobe and Northridge records, the isolator displacements are nearly 6, 5, and 3 times and 8, 3, and 2 times greater than the isolator

Table 5 Isolation properties

Isolation name	T (s)	K_{eff} (kN/m)	K_u (kN/m)	K_d (kN/m)	Q_d (kN)	β
ISO-1	1	9750	30000	3000	225	0.2
ISO-2	2	2400	12000	1200	70	0.2
ISO-3	3	1100	8000	800	30	0.2

Table 6   Maximum acceleration responses

Record	Conventional bridges				Isolated bridge (ISO-1)				Isolated bridge (ISO-2)				Isolated bridge (ISO-3)			
	(m/s2)				T = 1 (s)				T = 2 (s)				T = 3 (s)			
	BR-1	BR-2	BR-3	BR-4	BR-1	BR-2	BR-3	BR-4	BR-1	BR-2	BR-3	BR-4	BR-1	BR-2	BR-3	BR-4
Kobe-1	3.50	8.40	4.10	4.90	1.31	1.57	1.60	1.60	0.70	0.79	0.83	0.84	0.52	0.55	0.56	0.56
Kobe-2	7.90	21.20	15.60	8.17	1.37	1.50	1.50	1.50	0.70	0.79	0.81	0.82	0.46	0.50	0.52	0.52
Kobe-3	0.81	0.96	2.20	1.94	0.23	0.58	0.65	0.68	0.23	0.24	0.32	0.33	0.15	0.15	0.14	0.14
Kobe-4	0.21	0.22	0.42	0.48	0.07	0.14	0.29	0.24	0.05	0.10	0.16	0.13	0.05	0.07	0.08	0.08
Kobe-5	16.60	22.80	12.10	10.60	2.80	2.80	2.80	2.80	1.60	1.70	1.70	1.70	0.95	1.05	1.10	1.14
Kobe-6	4.20	5.70	12.60	8.80	1.02	1.10	1.20	1.20	0.46	0.47	0.52	0.53	0.32	0.34	0.34	0.35
Kobe-7	5.80	3.50	1.90	1.57	1.17	1.20	1.18	1.18	0.43	0.46	0.46	0.46	0.23	0.25	0.46	0.26
Northridge-1	4.80	9.80	6.80	8.60	1.30	1.40	1.48	1.40	0.58	0.67	0.71	0.71	0.36	0.38	0.41	0.40
Northridge-2	10.5	9.20	7.97	6.10	1.50	1.60	1.82	1.80	0.79	0.83	0.84	0.84	0.52	0.55	0.56	0.56
Northridge-3	0.91	1.01	1.18	1.40	0.21	0.35	0.58	0.73	0.18	0.24	0.26	0.26	0.13	0.13	0.13	0.13
Northridge-4	0.52	0.54	0.60	1.08	0.46	0.30	0.59	0.56	0.24	0.30	0.25	0.25	0.12	0.15	0.15	0.15
Northridge-5	13.7	6.30	8.75	6.70	2.30	3.10	3.40	3.40	0.95	1.04	1.10	1.11	0.66	0.70	0.72	0.72
Northridge-6	2.20	5.70	7.19	12.98	0.80	1.10	1.16	1.10	0.38	0.40	0.46	0.47	0.23	0.22	0.22	0.21
Northridge-7	0.51	0.85	1.16	0.89	0.26	0.63	0.50	0.48	0.22	0.26	0.29	0.28	0.14	0.14	0.13	0.13
Parkfield-1	2.10	3.60	5.30	3.30	0.44	0.60	1.01	1.05	0.31	0.31	0.34	0.35	0.17	0.18	0.19	0.19
Parkfield-2	2.50	4.30	7.60	9.40	0.67	0.88	1.05	1.06	0.36	0.34	0.36	0.37	0.20	0.20	0.21	0.21
Parkfield-3	0.57	0.57	0.53	0.45	0.31	0.48	0.49	0.52	0.28	0.31	0.29	0.29	0.16	0.16	0.15	0.15
Parkfield-4	0.20	0.18	0.19	0.20	0.04	0.10	0.29	0.24	0.03	0.07	0.11	0.13	0.02	0.05	0.07	0.08
Parkfield-5	4.37	3.10	6.10	11.40	1.06	1.13	1.23	1.24	0.43	0.50	0.49	0.51	0.25	0.26	0.27	0.27
Parkfield-6	0.75	0.54	0.37	0.34	0.40	0.80	0.51	0.60	0.32	0.32	0.33	0.34	0.18	0.15	0.16	0.16
Parkfield-7	0.25	0.20	0.35	0.49	0.16	0.20	0.32	0.30	0.16	0.17	0.19	0.22	0.09	0.11	0.11	0.10

displacement capacity for ISO-1, ISO-2, and ISO-3, respectively. In the case of the Parkfield records, the maximum isolator displacement in ISO-1 is higher than the designed displacement and the responses of other isolation systems are in the designed range.

This shows that the isolation displacement demand is higher in NF zones, especially on soft soils, and so it must therefore be taken into account in the design process by increasing the isolation period or the designed displacement.
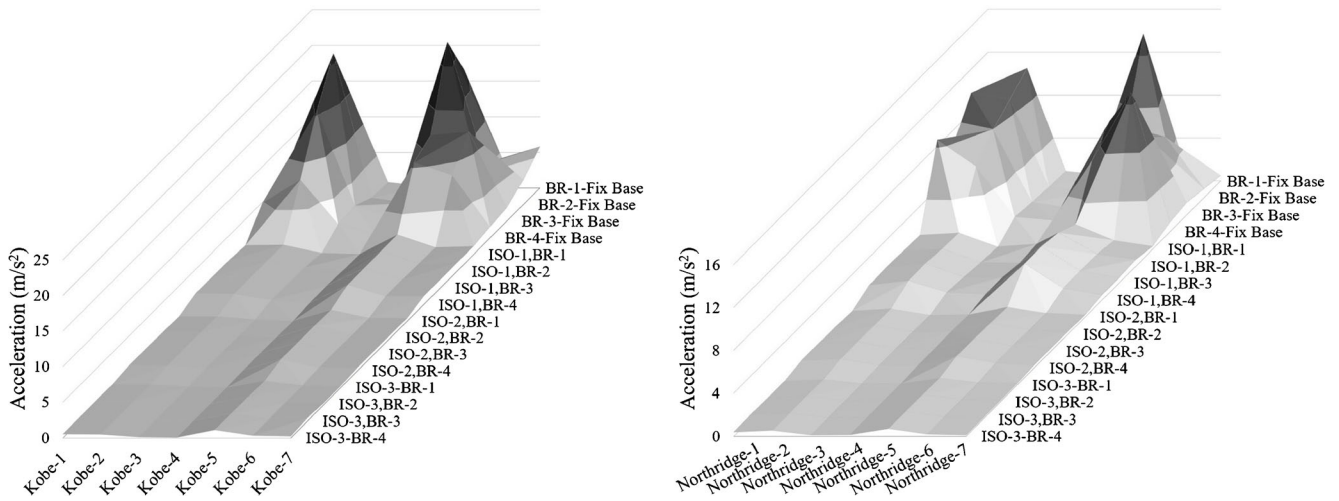
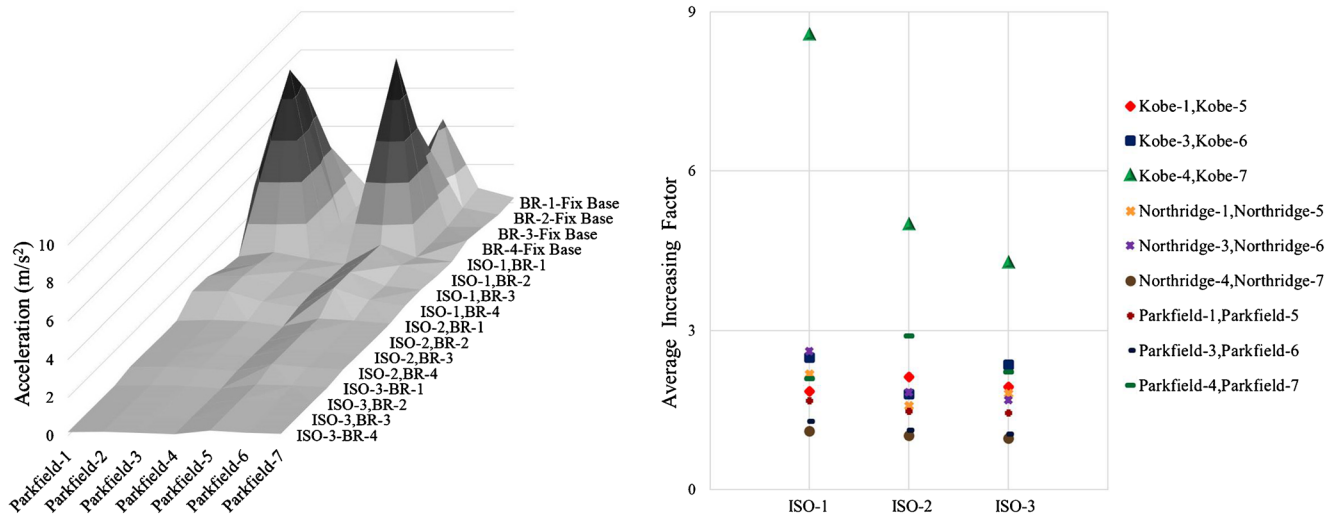**Fig. 3**   Maximum acceleration responses: (left) Kobe records and (right) Northridge records

Fig. 4 (Left) maximum acceleration responses of Parkfield records. (Right) average increasing factors in NF and FF records

In FF records, the displacement responses are also negligible as compared with NF records and the highest responses are related to records on soft soils. The maximum displacements of the isolation systems for FF records are 6.8, 4.0, and 2.1 cm for Kobe, Northridge and, Parkfield records, respectively, all of them related to records on soft soils (soil type D). For Kobe FF records on soft soils (soil type D), the maximum isolator displacement in ISO-1 is higher than the designed displacement by only 2 mm while the responses of other FF records for all three isolation systems are less than the designed displacement. These results are in agreement with previous studies and show that the isolation systems are more effective for stiffer soils while less effective for moderate to soft soils if the effect of the soil is neglected (Castaldo and Ripani 2016; Stehmeyer and Rizos 2008; Worku 2014). The maximum displacement of isolation systems is shown in Figs. 5 and 6.

It should be stated that the pier displacement in flexible bridges is greater than that in stiffer bridges. This means that the flexible pier is partly responsible for the displacement in isolated bridges, and this prevents the isolation system from acting perfectly. As is shown in Fig. 6, in the stiffer bridge, BR-4, the pier

displacement is less than 10 percent, making its contribution lower, and in that case, the isolation system is more efficient.

The isolation hysteresis loops for BR-1 and BR-4 subjected to Kobe records and obtained from NTHA are shown in Figs. 7, 8, and 9. They illustrate that the isolator displacement and energy dissipation are higher in soft soils and NF records. In FF areas, the farther the distance away from a ruptured fault, the higher the responses and displacement demands on soft soils. A comparison of the same isolation system on 2 different bridges, BR-1 and BR-4, shows that in stiffer bridges, the maximum isolation displacement is higher than the displacement in softer bridges. This is because, in softer bridges, a part of the displacement occurs in the pier, and based on the contribution percentage in Fig. 6, the isolation performance increases in stiffer bridges.

Base shear responses

The maximum base shear responses are shown in Figs. 10 and 11. The isolation systems noticeably reduce the base shear of
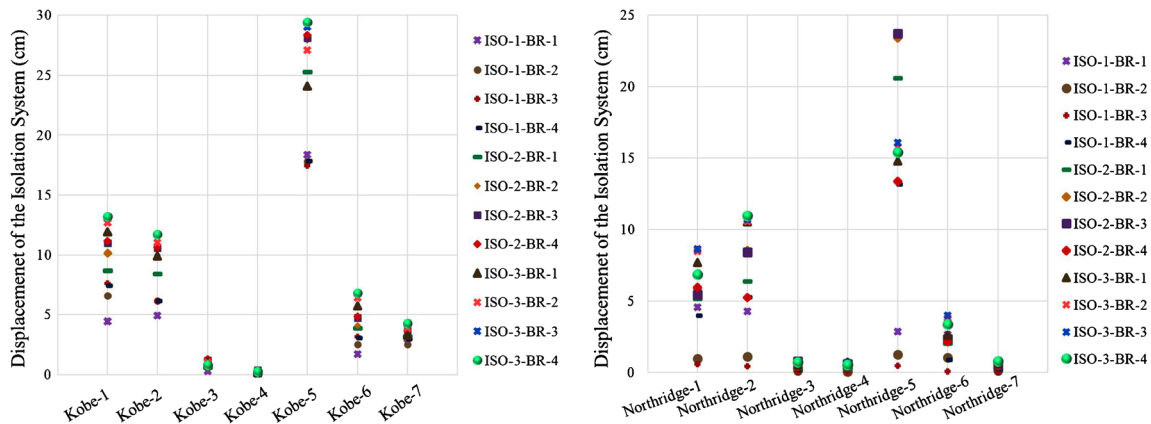

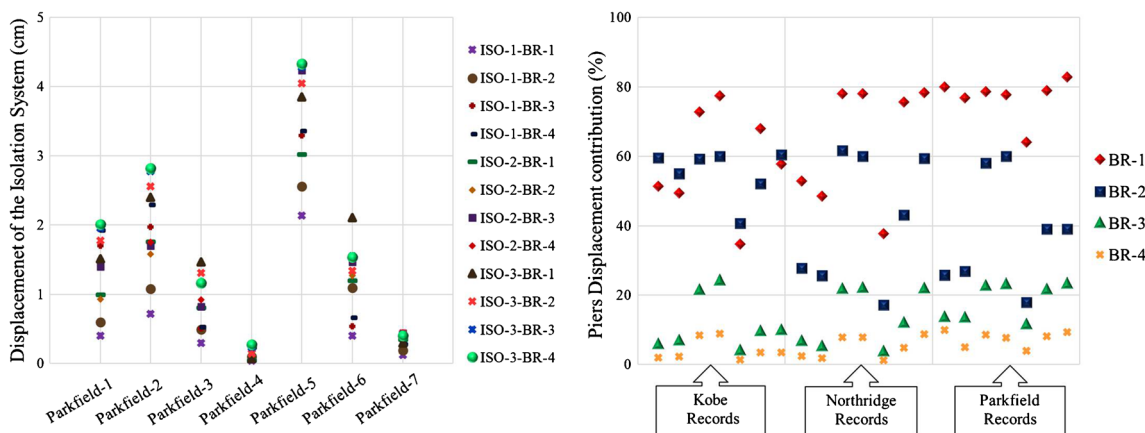**Fig. 5** Maximum isolation displacements: (left) Kobe records and (right) Northridge records

Fig. 6 (Left) maximum isolation displacements for Parkfield records. (Right) displacement contribution of piers
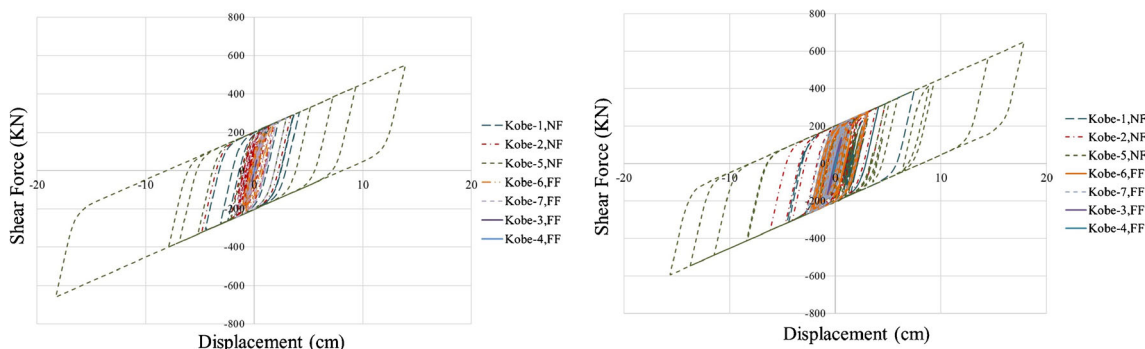

Fig. 7 Isolation hysteresis loops: (left) BR-1, ISO-1 and (right) BR-4, ISO-1

conventional bridges by an average factor of 4, 8, and 8.5 for ISO-1, ISO-2, and ISO-3, respectively. For all isolated bridges, the maximum responses are seen in the NF records on soft soils, which is almost twice as much as the responses of stiffer soils. In the case of isolated bridges, while all three isolation systems reduce the base shear, the reduction with ISO-2 is twice as much as that with ISO-1, and ISO-3 reduces it by 1.5 times more than ISO-2. Thus, the overall reduction factor in ISO-2 is the greatest. For all isolation systems, base shear responses show the increasing trend from BR-1 to BR-4,

meaning that stiffer structures endure stronger base shear forces.

In FF records, the base shear responses are much lower than NF records. Comparisons of soil types C and D show that the highest responses are related to records on softer soils (soil type D), showing amplification in responses by passing through these soils. These results are in agreement with the fact that ignoring the soil effects does not lead to an accurate prediction of the base shear in the design stage for soft soils (Soneji and Jangid 2008). Besides, it shows that the isolation
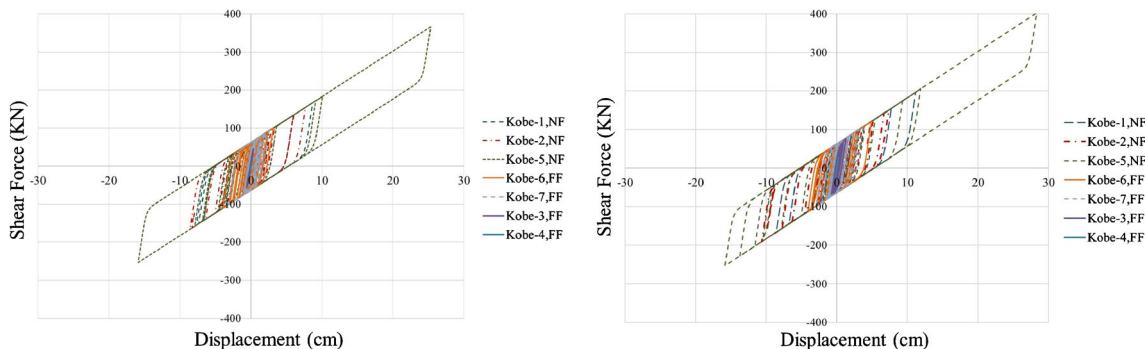

Fig. 8 Isolation hysteresis loops: (left) BR-1, ISO-2 and (right) BR-4, ISO-2
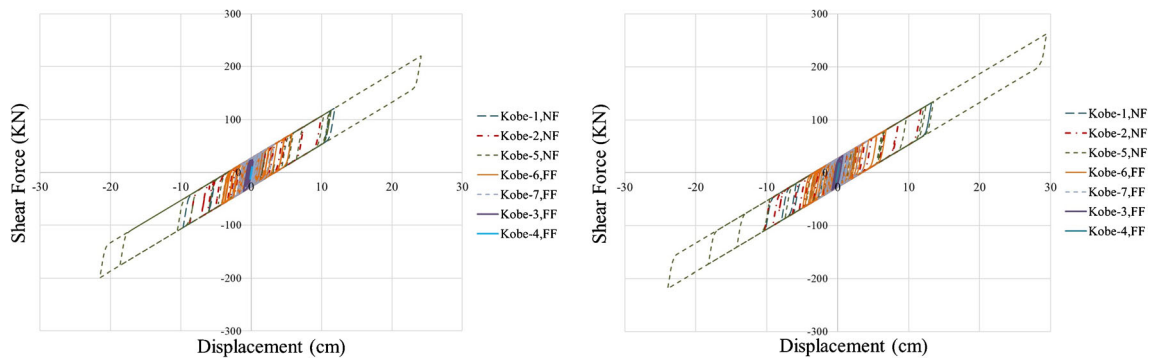
Fig. 9 Isolation hysteresis loops: (left) BR-1, ISO-3 and (right) BR-4, ISO-3

systems are sensitive to NF records and soft soil effects. Thus, these parameters will cause a higher pier shear in structural responses (Ates and Constantinou 2011; Bi et al. 2011; Ucak and Tsopelas 2008).

Conclusions

The seismic responses of four conventional bridges isolated by 3 different isolation systems subjected to real NF and FF records captured on different soil layers are examined in this paper by three-dimensional NTHA. For this task, SAP2000 software is used to study the effect of soil properties on changes in the record characteristics and structural responses, and the following results are obtained:

1. In NF records, all mentioned seismic responses are amplified for the isolated and conventional bridges. These increasing trends are more severe on soft soils, and this effect should be considered during the design stage for the bridges in NF areas and located on soft soils. In FF

zones, although the amplification of responses on soft soils is negligible compared with NF areas, soft soil effects should be taken into consideration for the design stage.

2. In the case of the isolated bridges, the concurrent effects of NF records and soft soils lead to higher demands in terms of the isolator displacements. Isolator displacements are 6, 5, and 3 times greater than the designed displacement in the case of Kobe and 8, 3, and 2 times greater than Northridge records for ISO-1, ISO-2, and ISO-3, respectively. Ignoring this issue at the design stage could lead to a large underestimation and possible failure of the isolation systems and the bridges during a strong NF earthquake on soft soil sites. Isolator displacements for FF records were less than the displacement capacity for all records except for Kobe records on soft soils, where they are exceeding the designed displacement by only 2 mm.

3. The isolation performance is better for stiffer bridges for both NF and FF records, where pile flexibility contributes
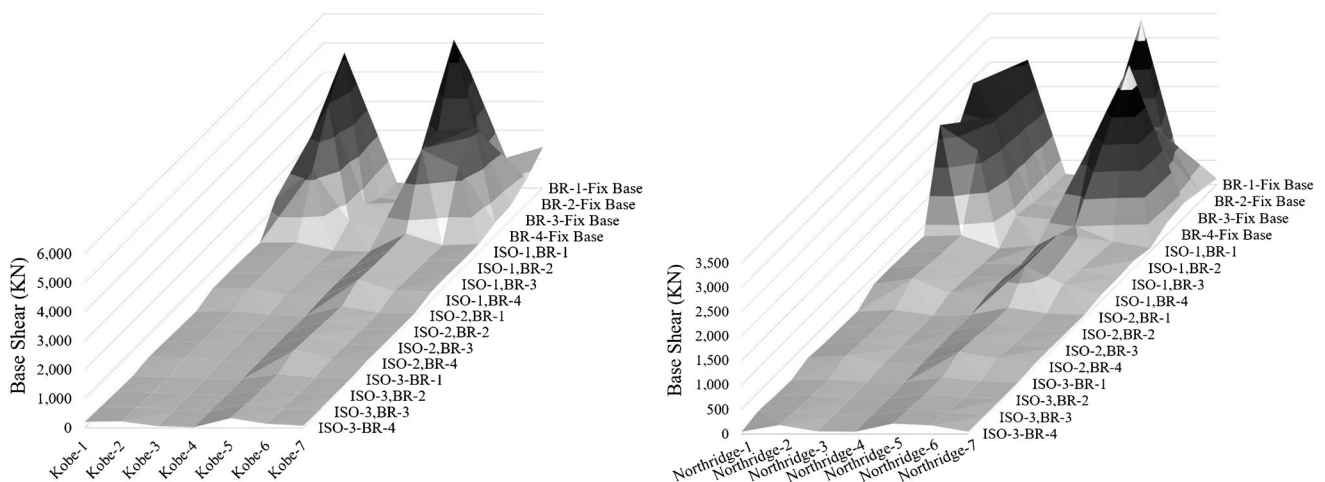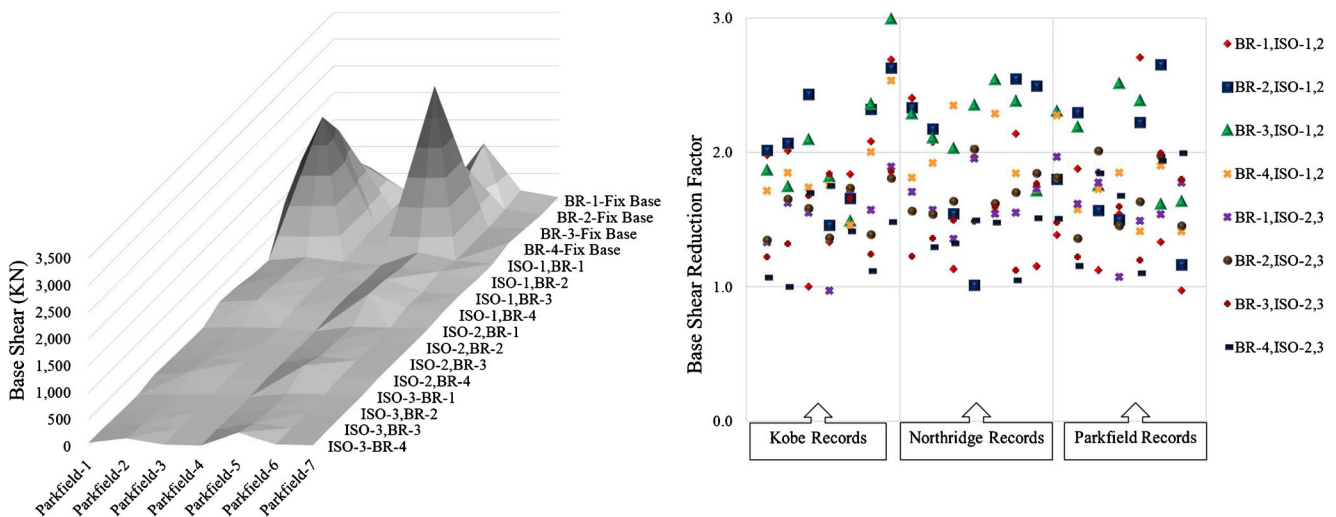

Fig. 10 Maximum base shear responses: (left) Kobe records and (right) Northridge records

Fig. 11 (Left) maximum base shear responses of Parkfield records. (Right) reduction factor for different isolation systems

very little in the total displacement, which is mainly taking place within the isolation system.

4. In soft soils, the reduction in acceleration responses of the isolated bridges is limited. The average reduction factor of all isolation systems in NF located on stiff soils is 28, 13, and 26 for Kobe, Northridge, and Parkfield, while it drops by a factor of 3, 5, and 12 for FF records on soft soils, respectively. This clearly shows that seismic isolation is more efficient for rocks or stiff soils rather than soft soils for both NF and FF records. Careful attention and scrutiny are required in designing these technologies, depending on the distance of the relevant structure from active faults and the type of soil where it is located.

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