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Paper No. 962. (quote when citing this arti
Eleventh World Conference on Earthquake Enginee
ISBN: 0 08 04282

COMPARATIVE ASSESSMENT OF SEISMIC ISOLATION DEVICES USING MATSUNOHAMA VIADUCT

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ABSTRACT

Various seismic isolation devices are assessed using the analytical model developed for a seismically isolated highway viaduct near Osaka which experienced the Hyogoken-Nanbu (Kobe) earthquake of January 17, 1995. As a segment of the Hanshin Expressway Public Corporation Route 5, this viaduct is seismically isolated using lead-rubber bearings and is instrumented with strong motion accelerographs. Ground motion and response records during the Kobe earthquake provided valuable information for studying the real performance of a seismically isolated bridge. In fact, this viaduct is one of the very few seismically isolated bridges in the world which are instrumented and experienced a moderate to strong earthquake. In this study, the seismic response of this bridge is numerically simulated and compared with the records. Once the accuracy of the bridge model is calibrated, a comparative assessment is performed, using the bridge model, among several typical and popular seismic isolation devices including the lead-rubber bearings, friction-pendulum bearings, and high-damping-rubber bearings. The parameter values governing the dynamic characteristics of these isolation devices are carefully determined to produce the same base shear force on the bridge substructures under certain earthquakes. Based on this criterion, the isolation effectiveness, including the response acceleration of the superstructure, the shear forces on the substructures, and the displacements of the isolators, are evaluated and compared. Although the Matsunohama viaduct was subjected to moderate shaking during the Kobe earthquake, a variety of earthquake ground motions with different frequency components and intensities, especially the damaging level intensities, are used for the numerical simulation analysis to examine the sensitivity of the isolation effectiveness to the variations in the ground motion characteristics. This study represents, in the authors' opinion, the first attempt that has provided highly useful comparative information regarding the seismic performance of different bridge isolation devices.

KEYWORD

comparative assessment; seismic isolation; Matsunohama viaduct; bridge; lead-rubber bearing; friction-pendulum bearing; high-damping-rubber; Hyogoken-Nanbu earthquake; Kobe earthquake

INTRODUCTION

Despite a growing number of seismic isolation devices installed in new bridge construction and retrofit projects, questions remain about their true effectiveness. In the US, there are two seismically isolated bridges which have gone through an earthquake to date: One is the Sierra Point bridge in the south of San Francisco, which was retrofitted in 1986 with lead-rubber bearings and became the first isolated bridge in the US; The other is the Eel River bridge on Route 101 in Northern California, which was retrofitted in 1988 with lead-rubber bearings (Prendergast, 1995). In Japan, Matsunohama viaduct, a segment of the Hanshin Expressway Route 5, became the first and the only seismically isolated bridge which experienced an earthquake (the Kobe earthquake of January 17, 1995) and recorded the seismic response as well as ground motion. This four-span continuous steel-box-girder bridge was constructed by the Hanshin Expressway Public Corporation in 1994 with lead-rubber bearings. The bridge is located 35km away from the epicenter and was only subjected to moderate shaking during the earthquake. Nevertheless, the records provide valuable information useful in the study of seismic performance of the isolation devices for bridges.

In the recent years, many types of isolation device appeared in the market, although some of them have been used only in buildings but not with bridges. Besides the lead-rubber bearing (LRB), the sliding type friction-pendulum bearing (FPB) and the high-damping-rubber (HDR) bearing are among the typical and popular devices. While extensive study is made on each of these individual devices by its manufacturer and users, the performance and effectiveness of these devices, however, have never been assessed on a common base for comparison purposes. This kind of information, however, is highly desirable in selecting an appropriate isolation device for a particular bridge to be newly constructed or to be retrofitted.

In this study, the response of the Matsunohama viaduct to the Kobe earthquake is numerically simulated and compared with the records. The analytical model of the bridge is calibrated through this process of comparison. Once the accuracy of the bridge model is confirmed, the performance of the bridge under various earthquakes with different frequency contents and levels of intensity is evaluated by means of numerical simulation. It is extremely important to evaluate the response of isolated bridges under very strong earthquakes to understand the ultimate behavior of the devices in view of the disastrous destruction of many bridges observed under the Kobe earthquake. Finally, the performance of the bridge using different types of isolation device including FPBs and HDRs is examined and compared.

MATSUNOMAHA BRIDGE AND ITS INSTRUMENTATION

The Matsunohama viaduct is located 35km away from the epicenter of the Kobe earthquake. As shown in Fig. 1, this is a four-span continuous bridge with a total length of 211.5m. The superstructure using steel-box girders is supported on the middle three reinforced concrete piers (Piers B, C, and D) through rectangular lead-rubber bearings (four for each pier) and on the two piers at the end (Piers A and E) through pivot roller bearings. The seismic isolation is designed to function in the longitudinal direction only, and thus the movement of the lead-rubber bearings in the transverse direction is constrained by stopper plates with the clearance of approximately 10mm. The design details of the bridge and the isolators are given in (Hiromatsu, *et al.*, 1994).

Four servo-type strong motion accelerographs are installed at the locations indicated in Fig. 2: one on the ground (2 horizontal and one vertical components), one near the bridge footing (2 horizontal components), one on the top of Pier D (2 horizontal components), and one on the bridge deck (longitudinal component only). The recorded peak accelerations during the Kobe earthquake are listed in Table 1 and several typical time histories in the longitudinal direction are shown in Fig. 4 (Horie, *et al.*, 1995).

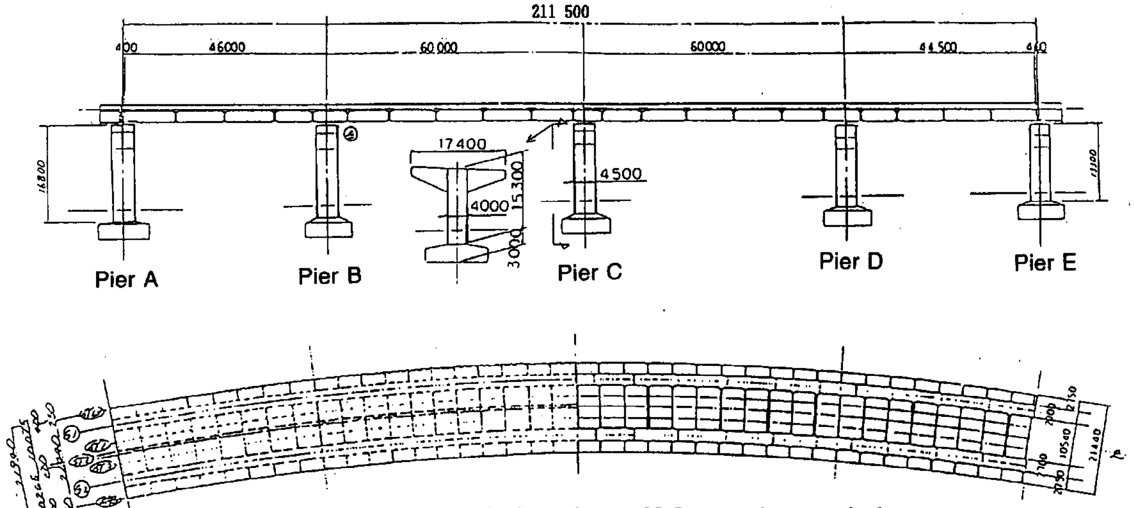


Fig. 1 Elevation and plan view of Matsunohama viaduct

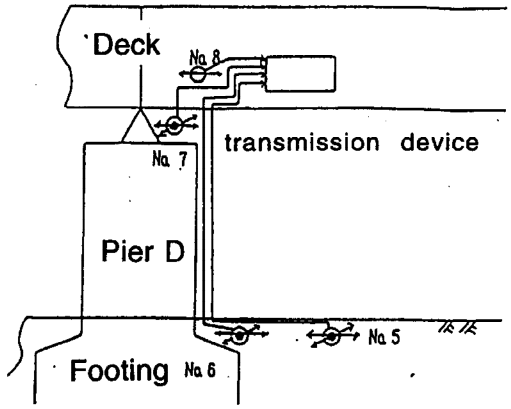


Fig. 2 Instrumentation of Matsunohama viaduct

Table 1. Recorded Peak Accelerations

Sensor No.	Direction	Peak Acc. (gal)
No. 5	X	144.0
	Y	136.2
	Z	119.4
No. 6	X	105.1
	Y	127.0
	Z	71.0
No. 7	X	200.0
	Y	357.9
	Z	76.3
No. 8	X	188.0

Note: X: longitudinal; Y: transverse; Z: vertical

COMPARATIVE ANALYSIS

As shown in the records, the Matsunohama viaduct only experienced moderate ground shaking during the Kobe earthquake. How would this isolated bridge perform under strong ground shaking? How would this bridge behave if it was isolated by different types of isolation device? These are very important questions many practicing engineers would ask when applying the isolation devices to real bridges whether for new construction or for seismic retrofitting. This study attempts to answer these questions through numerical simulation using the analytical model of the Matsunohama viaduct.

First, the analytical model is developed and its accuracy is confirmed by comparing the simulated bridge response to the recorded one under the recorded ground motion during the Kobe earthquake. Then numerical simulation is performed to examine the response of the Matsunohama viaduct to a variety of seismic ground motions and to study the seismic performance of the same bridge if the existing LRB isolators are assumed to be replaced by FPB or HDR isolators.

Analytical model of Matsunohama viaduct

The bridge motion in the longitudinal direction is simulated, since the isolation is designed only for this direction. For this purpose, the lumped-mass model shown in Fig. 3 is expected to be accurate enough to describe the bridge motion. The equations of motion are

$$\ddot{u}_S + \frac{1}{m_S}\sum_{i=B}^{D} f_i = -\ddot{x}_G \qquad (1)$$

$$\ddot{u}_i + 2\xi_i\omega_i\dot{u}_i + \omega_i^2 u_i - \frac{1}{m_i} f_i = -\ddot{x}_G \qquad (2)$$

where u_S is the relative displacement of the superstructure with respect to the ground; u_i ($i = B, C, D$) is the relative displacement of Piers B, C, and D to the ground; x_G is the displacement of the ground; m_S is the mass of the superstructure; m_i, ω_i, and ξ_i ($i = B, C, D$) are the mass, frequency, and damping of Piers B, C, and D; f_i ($i = B, C, D$) is the force by the isolation bearings on top of Piers B, C, and D.

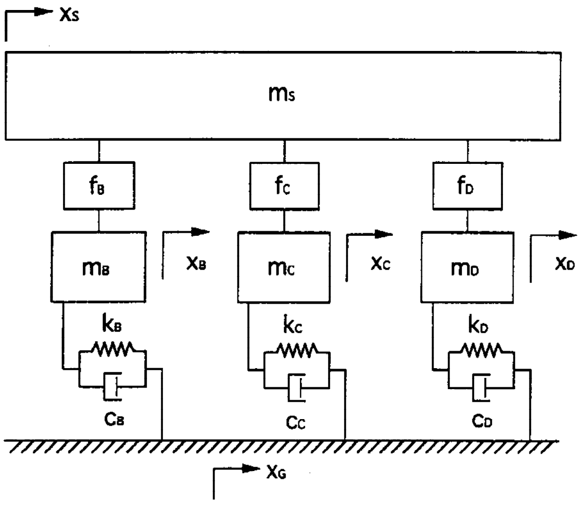
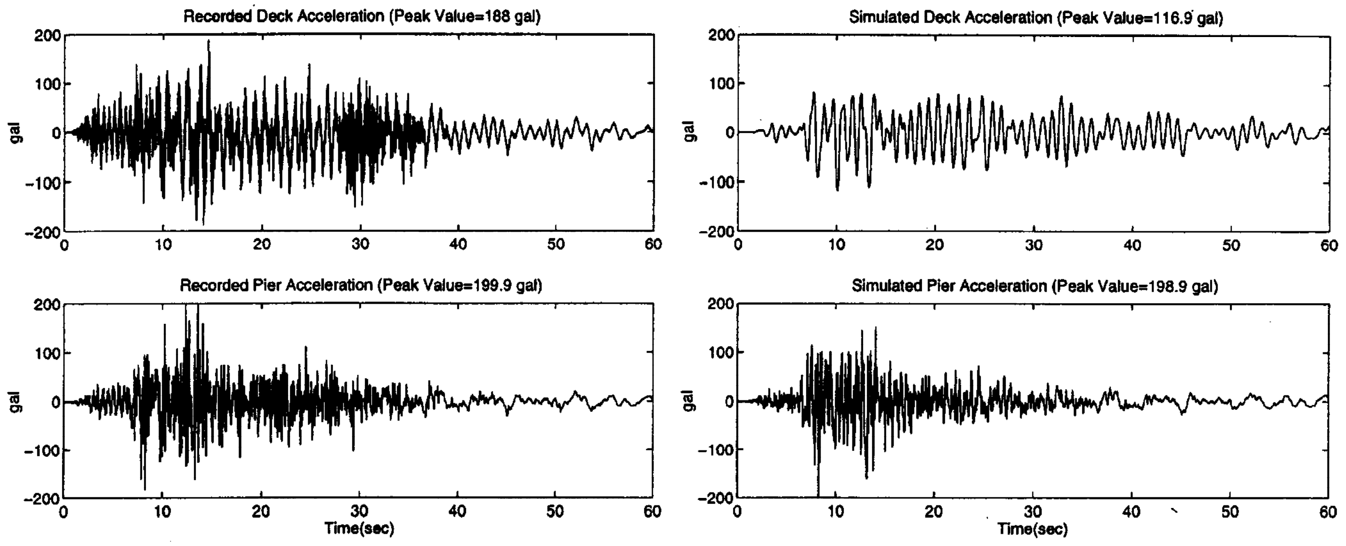


Fig. 3 Analytical model

The values of frequencies ω_i and damping ratios ξ_i of the bridge piers are determined based on the results of a dynamic testing of a bridge pier during the construction (Hiromatsu, *et al.*, 1994). In an LRB, the reinforced rubber provides the flexibility to lengthen the structural period and the lead cores are used to dissipate the seismic energy. The force-displacement relationship of the LRB is modeled by a bilinear model with the initial and after yielding stiffness as well as the yielding forces determined based on the results of a loading test of a bearing before it was installed on the bridge (Hiromatsu, *et al.*, 1994).

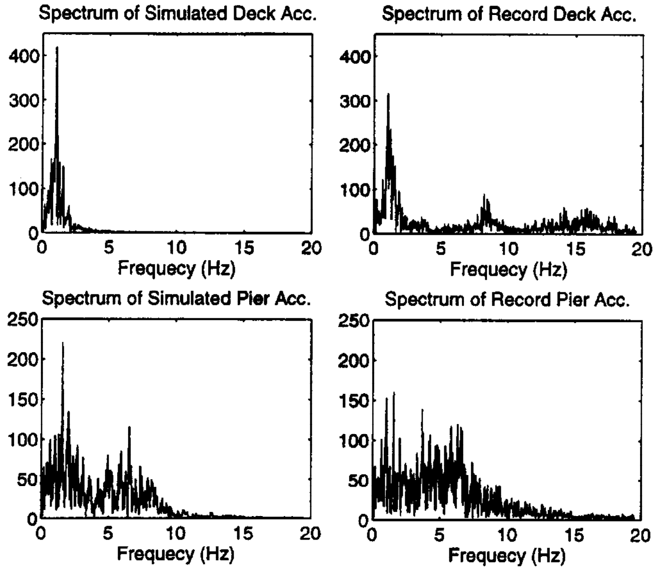
Using this analytical model, the response of the bridge to the input ground motion recorded during the Kobe earthquake at the bridge site is numerically simulated. Figure 4 shows time histories of the simulated deck acceleration and acceleration of Pier D, together with the recorded ones. Figure 5 compares their frequency spectra. In the deck acceleration record, there are some high-frequency components which are believed to be caused by the collision of the stopper plates with the LRBs in the transverse direction. In fact, scratches were observed on the stopper plates after the earthquake by the first author of this paper and by Horie (1995). Except for those high-frequency components in the deck acceleration, the simulation results agree with the records very well in both time and frequency domain, thus establishing the confidence in the analytical model.



(a) Recorded

(b) Simulated

Fig. 4 Recorded & simulated response time histories



(a) Recorded

(b) Simulated

Fig. 5 Recorded & simulated response spectra

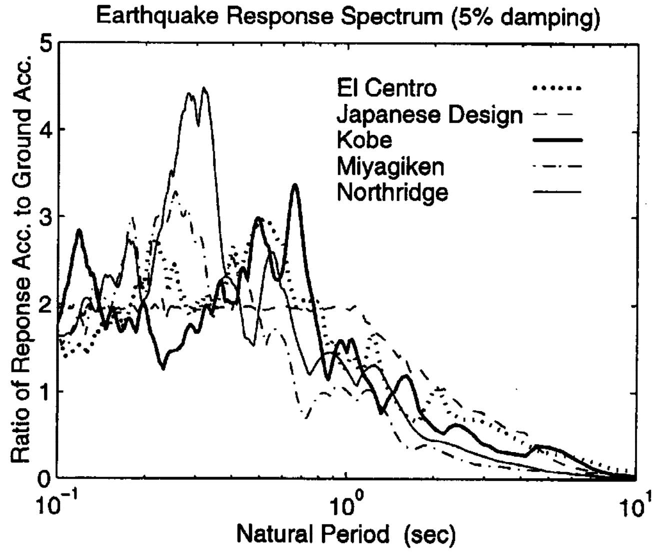


Fig. 6 Response spectra of ground motions

Ground motions

In addition to the ground motion recorded in the Matsunohama viaduct site during the Kobe earthquake, three earthquake ground motion records, El Centro (1940, EW), Miyagiken Oki (1978, EW), and Northridge (New Hall site, 1994, EW) as well as the Japanese design earthquake for bridges (Level 1) are chosen for the simulation. As shown in the response spectra (normalized by their peak ground accelerations) in Fig. 6, these seismic ground motions represent potential acceleration time histories with a wide range of frequency characteristics expected of the natural earthquake. Using these earthquakes, the sensitivity of the isolation effectiveness to the variations in the frequency content of the ground motion can be studied. The intensities of the ground motion are linearly adjusted to different levels in the numerical simulation.

FPB and HDR isolators

The FPB is a sliding steel bearing which has a spherical surface and works on the principle of the pendulum. The radius of curvature of the spherical surface determines the period of the isolated bridge, and the friction on the sliding surface dissipates the seismic energy. The FPB force is modeled as (Al-Hussaini, *et al*, 1994)

$$f_i = \frac{W}{R}(u_S - u_i) + \mu W \operatorname{sgn}(\dot{u}_S - \dot{u}_i) \tag{3}$$

where $i = B, C, D$; W is the weight supported by the bearing; R is the radius of curvature; μ is the friction coefficient.

The HDR is a reinforced rubber bearing using the synthetic rubber with high damping. Although the analytical model for the HDR is usually complicated (Clark, et al., 1995), the following simple model is considered adequate when the bearing deformation is within a certain range

$$f_i = k(u_S - u_i) + c(\dot{u}_S - \dot{u}_i) \tag{4}$$

where $i = B, C, D$; k and c are the stiffness and damping coefficient of the high-damping rubber bearing.

Comparison criterion

It is difficult to choose the parameter values for different types of isolation device for the comparison purpose, since each device has its unique isolation mechanism with correspondingly unique dynamic parameters. In an LRB device, as mentioned before, the initial and post-yielding stiffness as well as the yielding force are the key parameters determining the isolation performance such as the period shifted by the isolator and the amount of energy dissipated. In an FPB device, the radius of curvature of and the friction coefficient on the spherical sliding surface are the significant parameters (see Eq. 3). Finally, in an HDR device the stiffness and damping coefficient are the important parameters (see Eq. 4). Those parameter values need to be determined on the basis of a comparison criterion.

Table 2. Parameters of different isolators

LRB	FPB200	FPB400	HDR200	HDR400
k11=3657.0 tonf/m	R=1.5 m	R=1.5 m	k=1828.5 tonf/m	k=1462.8 tonf/m
k12=1125.3 tonf/m	μ=0.085	μ=0.13	c=252.45 tonf*sec/m	c=224.4 tonf*sec/m
q=61.74 tonf				

One of the major purposes to use seismic isolation devices either for new construction or for seismic retrofit of bridges is to protect the bridge substructures from seismic damage. Therefore, the parameter values of different isolation devices are determined to produce the same shear force of the substructure of the LRB-isolated Matsunohama viaduct under the Kobe earthquake with the peak ground acceleration linearly adjusted to a certain level. Two levels of ground motion intensity are tentatively considered: 200 gal for the retrofit and

400 gal for the new construction purposes. Table 2 listed the parameter values of the isolation devices designed on the basis of the same substructure shear force, where LRB uses the same values as built in the Matsunohama viaduct. FPB200 and FPB400 respectively represent the FPB devices designed to achieve the same pier shear force as the LRB-isolated bridge under 200 gal and 400 gal Kobe earthquakes, while HDR200 and HDR400 are the HDR devices that produce the same pier shear forces.

Comparative assessment

Computer simulation is performed on the Matsunohama viaduct equipped with these different types of isolation device (with the parameter values as chosen in Table 2) and subjected to various earthquake ground motions (with different frequency contents and intensity levels as shown in Fig. 6). Simulation result is shown in Fig. 7, plotting the peak pier deformation (a measure of shear force), deck acceleration, and isolator bearing displacement of the bridge, under the assumption that the deformation of the bridge substructures is within the linear range even under strong ground motions. The seismic response of the bridge without any isolation devices (the deck is fixed on Piers B, C, and D) is simulated as well for the comparison purpose. Under the Kobe earthquake with the peak acceleration linearly adjusted to 1000gal, the peak deck acceleration is 1372gal and the peak pier deformation is 3.07cm for the non-isolated Matsunohama viaduct.

The following are observed:

(1) Any of the three types of isolation device can significantly reduce not only the deck acceleration but also the pier deformation, relative to the corresponding values associated with the non-isolated bridge. For example, under the 1000gal Kobe earthquake, the deck acceleration is reduced to a range between 29% and 52% of that without isolation and the pier deformation is reduced to a range between 23% and 38% of that without isolation. The reduction in the pier deformation is very encouraging, since the protection of bridge substructures from the seismic damage is one of the major purpose for using seismic isolation devices. In fact, the dramatic reduction in the pier deformation shown in this simulation absolves the commonly held concern: Can an isolation device really protect the bridge substructure when it is installed on top of the substructure?

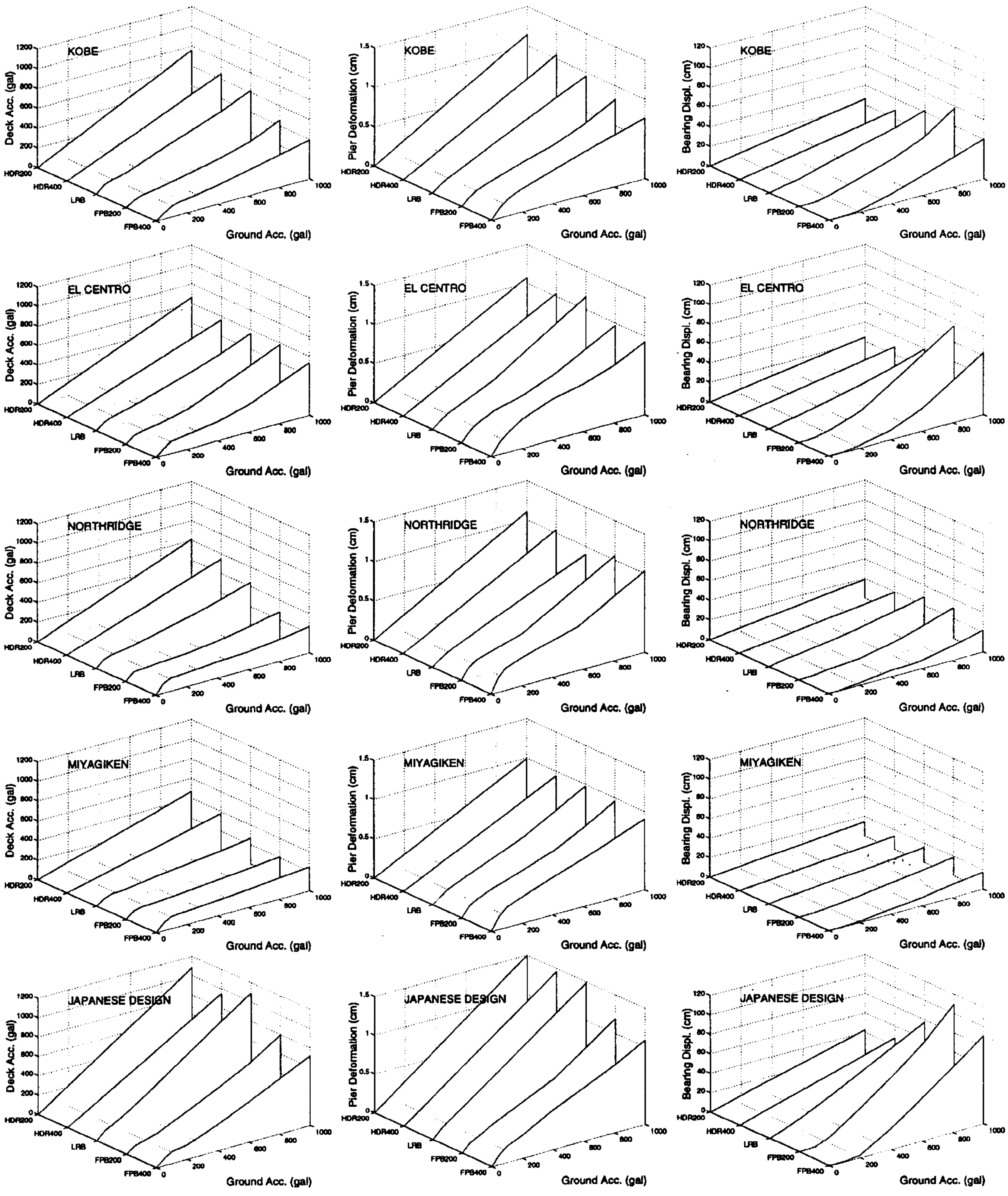
(2) The response of the bridge isolated by any of the devices considered above is sensitive to the frequency content of ground motions. For obvious reasons, the isolation effectiveness of all these devices deteriorates under the ground motion with low frequency contents such as the Japanese design earthquake.

(3) The FPB400 isolator, in general, results in smaller bridge response (deck acceleration and pier deformation) under strong ground motions than the FPB200 isolator, while the latter produces smaller bridge response under weak input ground motions. A similar trend is observed for the HDR isolators. Therefore, each type of isolation device has the flexibility to select the parameter values depending on the target intensity range of the earthquake where it is expected to be effective.

(4) Among the three types of isolator, the FPB isolator tends to produce the smallest bridge response at the expense of the largest bearing displacement, under strong ground motions especially with low frequency contents such as the Japanese design earthquake and the Kobe earthquake (recorded in the Matsunohama viaduct site). However, as expected, under weak earthquakes with seismic force less than the friction force on the sliding surface, the FPB isolator will not slide, thus producing no isolation effectiveness, although there is usually no need for the isolation device to protect the bridge from weak earthquakes.

CONCLUDING REMARKS

The performance of three types of isolation device, LRB, FPB, and HDR, has been examined by means of numerical simulation using the analytical model of the Matsunohama viaduct, a seismically isolated bridge which is instrumented and experienced the Kobe earthquake. Several major earthquake records and a design earthquake with various frequency contents and different levels of intensity are used as input ground motions. The significant effectiveness of all these isolation devices has been demonstrated not only in reducing the response acceleration of the bridge superstructure but also in protecting the substructures. At the same time, it has also been found that the isolation effectiveness is sensitive to the frequent content of ground motion. The parameter values governing the isolator's performance can be designed for a certain target intensity level of earthquake. The FPB device shows the best isolation effectiveness under strong seismic ground motion.



(a) Peak deck acceleration (b) Peak pier deformation (c) Peak bearing displacement

Fig. 7 Comparison of peak responses

As the next step of this study, comparative assessment will be made on the US vs Japan seismic isolation design procedures for bridges. In addition, the analytical model of dynamic characteristics of these isolation devices as their deformation increases under strong earthquakes must be refined on the basis of the more recent analytical and experimental research and used to enhance the accuracy of this numerical assessment.

ACKNOWLEDGMENT

The work is supported by the Federal Highway Administration through the National Center for Earthquake Engineering Research (NCEER) under Contract DTFH61-92-C-00106. The authors acknowledge technical advice and encouragement by Professor Ian Buckle, Deputy Director of NCEER.

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