A comparative study on aseismic performances of base isolation systems for multi-span continuous bridge

Kyu-Sik Park, Hyung-Jo Jung, In-Won Lee *

Structural Dynamics & Vibration Control Lab, Department of Civil Engineering, Korea Advanced Institute of Science and Technology, 373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, South Korea

Received 9 October 2000; received in revised form 21 January 2002; accepted 4 February 2002

Abstract

Various base isolation systems (BISs) such as the pure-friction, laminated rubber bearing, lead rubber bearing, resilient-friction base isolator and electricité de France systems, which have been used or are considered to have considerable potential for wide applications, are systematically compared and discussed for aseismic performances of multi-span continuous bridge in this study. Sensitivity analyses of the bridge employed the devices are carried out to choose the appropriate design parameters of various devices. It is possible to recommend the appropriate ranges of the natural period and the friction coefficient of the various BISs. Therefore, the recommended ranges of the design parameters are presented in this study. The design parameters such as the first natural period of the isolated bridge and the friction coefficient of the bearing are determined by the reciprocal relationship between the peak deck displacement and the peak overturning moment of the bridge in the recommended ranges, and then the relative effectiveness of the bearings is described for the selected design parameters under the different ground motions. The peak responses of the bridge with the friction-type bearing are less sensitive to substantial variations in the frequency range and the intensity of the ground excitation than those with the rubber-type bearing due to characteristics of the friction element within the range of this study. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Base isolation system; Bridge structure; Aseismic performance; Sensitivity analysis; Design parameter; Comparative study

1. Introduction

Many aseismic construction designs and technologies have been developed over the years in attempt to mitigate the effects of earthquakes on buildings, bridges and potentially vulnerable contents. The design method using base isolation systems (BISs) is a relatively recent, and evolving technology of this kind. The seismic isolation differs fundamentally from the conventional seismic design approaches in the method by which the period lengthening (detuning) and hysteretic energy-dissipating mechanisms are provided, as well as in the philosophy of how the earthquake attack is withstood. In the conventional approaches, it is accepted that considerable earthquake forces and energy will be transmitted to the structure from the ground. In the seismic isolation, however, the fundamental aim is to substantially reduce the transmission of the earthquake forces and energy into the structure. Therefore, the seismic isolation is an innovative aseismic design approach aimed at protecting structures against damage from the earthquake by limiting the earthquake attack rather than resisting it.

The seismic isolation consists essentially of the installation of mechanisms, which decouple the structure and/or its contents from potentially damaging earthquake induced ground or support motions. This decoupling is achieved by increasing the flexibility of the system, together with providing appropriate damping. Although it is a relatively recent technology, the seismic isolation has been well evaluated and reviewed [7–9,22]; has been the subject of international workshops [12–14]; is included in the programs of international, regional and national conferences on earthquake engineering [15–18]; and has been proposed for specialized applications [21]. In these many researches, it is widely accepted that the seismic isolation is very effective to mitigate the influence of earthquakes on structures. However, there are...
few comparative studies on aseismic performances of various BISs for the critical design parameters. Furthermore, most of previous studies are focused on buildings [3,9–11]. On the other hand, there are few studies on bridges in spite that BISs are widely used for them.

To evaluate aseismic performances of BISs and suitable earthquake-resistance design of the bridge, the sensitivity analysis for variations in the design parameters of devices is required. Therefore, a comparative study on aseismic performances of different BISs for multi-span continuous bridge is accomplished in this paper. Various BISs such as the pure-friction (P-F), laminated rubber bearing (RB), lead rubber bearing (LRB), resilient-friction base isolator (R-FBI) and electricité de France (EDF) systems are considered. Sensitivity analyses for variations in the first natural period of the isolated bridge and the friction coefficient of the bearing are also performed under the different ground motions. The recommended ranges of the design parameters are presented in this study. The two design parameters, the first natural period of the isolated bridge and the friction coefficient of the bearing, are determined by the reciprocal relationship between the peak deck displacement and the peak overturning moment of the bridge. The peak responses of the bridge with BISs are obtained, and then the relative effectiveness of different BISs is evaluated for the selected design parameters of devices.

2. Aseismic BISs

A variety of the seismic isolation and energy-dissipation devices has been developed over the years all over the world. The components in BISs are specially designed, distinct from the structural member, and installed at or near the base of the structure. In bridges, however, where the aim is to protect relatively low-mass piers and their foundations, they are more commonly between the top of the piers and the superstructure. The basic features of such devices consist of the horizontal flexibility and the energy dissipative capacity. The most important feature of the seismic isolation is that its increased flexibility lengthens the natural period of the structure. Because the period is increased beyond that of the earthquake, the resonance and near-resonance are avoided and the seismic acceleration response is reduced. However, the increased period and consequent increased flexibility also affects the horizontal seismic displacement of the structure. These excessive displacements are counteracted by the introduction of increased damping and/or energy-dissipation. Because of these characteristics of BISs, they can attenuate the harmful horizontal acceleration transmitted to the superstructure and reduce the sectional force of the substructure. The seismic isolation concept for the protection of structures from earthquakes has been proposed in various forms at numerous times this century. Here, various leading BISs, which have been used or are considered to have considerable potential for wide applications, are briefly described. Various systems have used RBs (elastomeric bearings) with and without lead plugs, damping being provided either by the use of high-loss rubber or neoprene materials in the construction of bearings or by auxiliary viscous dampers. There have been a number of applications of friction sliding systems, both with and without provision of the elastic centering action.

2.1. The P-F system [5,8,9]

The P-F or sliding-joint system is classified as the simplest device because it uses only the stick-slip mechanism. A schematic diagram of the P-F system is shown in Fig. 1(a). When there is a sliding in the friction plates, the P-F system limits a maximum acceleration transmitted from the substructure to a certain value according to the friction coefficient. However, there may be an excessive deflection or a residual deformation in the friction surface after the seismic event, because the P-F system has no recovering force. Furthermore when the P-F system does not slide, it acts as a fixed one. In this case, the P-F system cannot provide a certain amount of protection. Because of these reasons, the friction element is used with RBs instead using alone. Nevertheless, the P-F system may be used economically in the simple or small-scale structure.

Whenever the structure sticks to the P-F system, the non-sliding condition

\[ \dot{x}_b(t) = 0 \]  

holds as long as

\[ |M\ddot{x}_b(t) + \sum_{n=1}^{N} m_n a_n| < \mu Mg \]  

(2)

where \( x_b(t) \) is the displacement of base raft relative to the ground, \( M \) is total mass on the device, \( \dot{x}_b(t) \) is the horizontal ground acceleration, \( m_n, a_n \) are mass and acceleration of the \( n \)th degree of freedom, \( \mu \) is the Coulomb friction coefficient and \( g \) is the acceleration of gravity, respectively. As soon as the stick condition given by Eq. (2) fails, a sliding will occur and the equation of motion is stated as

\[ M\ddot{x}_b(t) + \mu Mg \text{sgn}[\dot{x}_b(t)] + \sum_{n=1}^{N} m_n a_n = -M\dot{x}_b(t) \]  

(3)

Here, \( \text{sgn}[\dot{x}_b(t)] \) indicates the sign according to the direction of velocity of the device.

2.2. The RB system [2,6,8,9,20]

Another method of seismically isolating structures is by mounting them on RBs. These bearings are fully
developed as commercial products whose main application has been for bridges. More recently, their use has been extended to the seismic isolation of buildings and other structures. The RB system consists of alternating layers of rubber and steel with the rubber being vulcanized to the steel plates for the horizontal flexibility and the vertical stiffness. The dominant feature of this device is the parallel action of spring and dashpot as shown schematically in Fig. 1(b). Because the damping capacity of the RB system is relatively small, it mainly shifts the natural period of the isolated structure to avoid the detrimental earthquake energy. The equation of motion is stated as

\[ M\ddot{x}_b(t) + C_b\dot{x}_b(t) + K_b x_b(t) = 0 \] (4)

where \( C_b \) and \( K_b \) are damping and stiffness coefficients of the RB system, respectively.

2.3. The LRB system [8,9,20]

The RB system may not be able to resist the required displacements for the seismic isolation. A lead-plug insert provides hysteretic energy-dissipation, therefore, the damping required for a successful seismic isolation system can be incorporated in a single compact component with the RB system. Thus, one device is able to support the structure vertically, to provide the horizontal flexibility together with the restoring force, and to provide the required hysteretic damping.

To determine properties of the LRB system, the bilinear model of characteristic curve is used. The effective stiffness coefficient, \( K_{\text{eff}} \), is obtained with reference to sheaf force versus displacement hysteresis loop shown in Fig. 2. In general, the concept of this effective value is a gross approximation, but it works surprisingly well [20].

The equation of motion, which uses the effective and equivalent values, is stated as

\[ M\ddot{x}_b(t) + C_{\text{eq}}\dot{x}_b(t) + K_{\text{eff}} x_b(t) + \sum_{n=1}^{N} m_n a_n = 0 \] (5)

\[ -M\ddot{x}_b(t) \]

Here, \( C_{\text{eq}} \) is the linearized equivalent damping coefficient given by Eq. (6) and \( \xi_{\text{eq}} \) is the linearized equivalent damping ratio given by Eq. (7), respectively.

\[ C_{\text{eq}} = 2\xi_{\text{eq}} \sqrt{MK_{\text{eff}}} \] (6)

![Fig. 2. Characteristic curve of the LRB system: bilinear model.](image-url)
\( \xi_{eq} = \Delta E / (2\pi K_{eq} D_d^2) \)  

where \( \Delta E \) is the total dissipated energy that is area of the characteristic curve and \( D_d \) is the design displacement, respectively. In this study, the peak deformation of the RB system is used as a design displacement of a LRB unit. When the bilinear isolator has a high degree of nonlinearity, the seismic responses of higher modes are often much greater than the responses which occur with the above equivalent linear modes.

### 2.4. The R-FBI system [8,9,11]

The R-FBI system makes use of the parallel action of resiliency of rubber and the friction of Teflon coated plates. Similar to the P-F system, it does not slide below the frictional resistance. Unlike the P-F system, however, it has an additional resistance to an increase of deformation and a recovering force by rubber after sliding.

Initially, when the bearing starts from rest or whenever the friction plates are sticking to each other through the frictional force, the non-sliding condition given by Eq. (1) holds as long as

\[ |M\ddot{x}_g(t) + K_b x_b(t) + \sum_{n=1}^{N} m_a a_n| < \mu M g \]  

(8)

As the ground acceleration is increased, the stick condition given by Eq. (8) fails and a sliding in the friction plates will occur. Then, the equation of motion is given by Eq. (9).

\[ M\ddot{x}_b(t) + C_p \dot{x}_b(t) + \mu M g sgn[x_b(t)] + K_b x_b(t) \]

\[ + \sum_{n=1}^{N} m_n a_n = -M\ddot{x}_g(t) \]  

(9)

### 2.5. The EDF system [8,9,19]

The EDF system consists of the elastomeric bearing and the friction plates in series. During a low-intensity earthquake, therefore, it behaves as a RB unit and returns to its original position after the seismic event. However, when the frictional resistance is exceeded, a sliding will occur and the EDF system may have a residual deformation in the friction surface during a high-intensity earthquake. Owing to the slip in the friction plates, the EDF system limits a maximum acceleration like a P-F unit.

Whenever the frictional resistance is not exceeded, the equations of motion are governed by

\[ M\ddot{x}_{b2}(t) + C_p \dot{x}_{b2}(t) + K_b x_{b2}(t) + \sum_{n=1}^{N} m_n a_n = 0 \]  

(10a)

\[ -M\ddot{x}_g(t) \]

\[ x_{b1}(t) = x_{b2}(t), x_{b1}(t) = x_{b2}(t) \]  

(10b)

and hold as long as

\[ |M[x_g(t) + x_{b2}(t)] + \sum_{n=1}^{N} m_n a_n| < \mu M g \]  

(11)

As soon as this condition fails, a sliding will occur and the equations of motion are stated as

\[ C_p \dot{x}_{b1}(t) + K_p x_{b1}(t) = \mu M g sgn[x_{b2}(t) - x_{b1}(t)] \]  

(12a)

\[ M\ddot{x}_{b2}(t) + \mu M g sgn[x_{b2}(t) - x_{b1}(t)] + \sum_{n=1}^{N} m_n a_n = -M\ddot{x}_g(t) \]  

(12b)

In these equations, \( x_{b1}(t) \) is the deflection experienced by Neoprene pad and \( x_{b2}(t) \) is the displacement of the base raft relative to the ground as shown in Fig. 1(e).

### 3. Sensitivity analysis

#### 3.1. Analysis model

For the sensitivity analysis of various aseismic BISs, the Dong-Jin Bridge (Fig. 3, Table 1) is used. It is a continuous bridge with 15 spans and has been constructed in the western coast expressway in Korea. The span length of the bridge is 725 m and the width of the superstructure is 12.15 m. The longitudinal slope is 0.03%. The schematic diagram of the Dong-Jin Bridge is shown in Fig. 3. The superstructure and the substructure are modeled by beam elements. Since, general prestressed concrete bridge has structural damping ratios of 2–3%, Rayleigh damping with \( \xi = 2\% \) is used in the modeling of the Dong-Jin Bridge.

The calculation of several design properties is the most important in the modeling of BISs. The horizontal and vertical translational stiffness of devices are calculated by Eqs. (13) and (14) [4].

\[ k_{trans} = \frac{G A_r}{t_r} \]  

(13a)

\[ k_{vert} = \frac{E A_r}{t_r} \]  

(13b)

\[ k_{hr} = n k_{trans} \]  

(14a)

\[ k_{vt} = n k_{vert} \]  

(14b)

Here, \( k_{trans}, k_{vert} \) are the horizontal and vertical translational stiffness of each bearing, \( G, E \) are the shear modulus and Young’s modulus of rubber, \( A_r, t_r \) are area and rubber thickness of each bearing, and \( k_{hr}, k_{vt} \) are total horizontal and vertical translational stiffness for \( n \) bearings, respectively. The rotational stiffness of bearings about the vertical axis is found by adding the individual bearing contribution when a unit rotation is applied to
Table 1
Pier length (H2) of the Dong-Jin Bridge

<table>
<thead>
<tr>
<th>Pier No.</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2 (m)</td>
<td>0.94</td>
<td>1.09</td>
<td>1.21</td>
<td>1.33</td>
<td>1.46</td>
<td>1.57</td>
<td>1.98</td>
</tr>
<tr>
<td>Pier No.</td>
<td>P8</td>
<td>P9</td>
<td>P10</td>
<td>P11</td>
<td>P12</td>
<td>P13</td>
<td>P14</td>
</tr>
<tr>
<td>H2 (m)</td>
<td>2.13</td>
<td>2.08</td>
<td>2.13</td>
<td>2.32</td>
<td>2.36</td>
<td>2.40</td>
<td>2.48</td>
</tr>
</tbody>
</table>

The entire group [4]. As shown in Fig. 4, it is assumed that bearings are connected with a rigid link that transmits forces from the individual bearing to the point where the moment, which produces the unit rotation, is applied. It is calculated that the horizontal force acting on each pad and the moment about the centerline produced by the force at each bearing by Eq. (15)

\[ V_i = k_{\text{trans}} \theta d_i \] (15a)
\[ M_i = V_i d_i \] (15b)

where \( d_i \) is the distance from the center of the superstructure to the \( i \)th bearing. The spring constant for rotation is calculated by summing the moments and dividing by rotation

\[ k_{\text{rot}} = \frac{2 \sum_{i=1}^{n} M_i}{\theta} = 2k_{\text{trans}} \sum_{i=1}^{n} d_i^2 \] (16)

Rotation has been released about an axis parallel to the strong direction of pier because the stiffness in this direction is considered negligible [4]. The damping coefficient of bearings is calculated by Eq. (17)

\[ c_{\text{ht}} = 2\xi \sqrt{m} k_{\text{ht}} \] (17)

where \( \xi \) is the damping ratio of rubber. Generally, the damping ratio of rubber is 10% and this value is used in this study.

3.2. Sensitivity analysis

For the sensitivity analysis on variations in the design parameters of devices, a number of different earthquake excitations are used. Among several major earthquake excitations, El Centro (N00W component, 1940), San Fernando (S16E component, 1971) and Mexico City (N90W component, 1985) earthquakes are used as the ground acceleration. These earthquake records have a variety of peak ground acceleration (PGA) and cover various forms of the frequency range as shown in Figs.
5 and 6. The El Centro accelerogram is typical of those to be expected on the ground of moderate flexibility during a major earthquake. It must also be recognized that occasionally earthquakes give their strongest excitation at long periods. The likelihood of these types of motions occurring at a particular site can sometimes be foreseen, such as with deep deposits of soft soil which may amplify low-frequency earthquake motions, the old lake bed zone of Mexico City being the best known example.

Fig. 5. Time histories of the historical earthquakes.

Mexico City earthquake has considerable energy at low frequencies of about 0.5 Hz. Therefore, this earthquake is used to evaluate performances of BISs in the severe input excitation condition.

The commercial finite element analysis program, automatic dynamic incremental nonlinear analysis (ADINA) [1], developed by K.J. Bathe is used for the numerical analysis. The method of nonlinear time history analysis is used instead of the response spectrum analysis and the relative effectiveness of different BISs according to variations in the design parameters is studied.

The most important parameters that control performances of aseismic devices are the natural period of the isolated structure and the friction coefficient of the device. Aseismic performances of bearings are influenced by the natural period and the friction coefficient according to the frequency range and PGA of the input ground motions. To obtain variations in the natural period of the isolated bridge, the size of the bearing is changed and it leads to variations in the spring constants and damping coefficient of the bearing as shown Eqs. (13)–(17).

The natural period of the isolated structure should be long enough to avoid the frequency range on which earthquake energy concentrates and is short enough to resist the ambient vibration such as traffic or wind induced one. The friction coefficient of the bearing should be large enough to resist the ambient vibration and small enough to have an additional aseismic effect by sliding in the friction plates of the device. Considering these reasons and manufacturing conditions of devices, the first natural period of the isolated bridge is changed from 1.0 to 6.0 s with interval 1.0 s and the friction coefficient of the bearing is changed from 0.02 to 0.30 with interval 0.04 in this sensitivity analysis.

The main seismic attack on most structures is the set of horizontal inertial forces acting on the structural masses, these forces being generated as a result of horizontal ground accelerations. For most structures, vertical seismic loads are relatively unimportant in comparison with horizontal seismic loads. Therefore, in this study the structure is excited in the horizontal (longitudinal) direction. The responses of the bridge with aseismic devices have similar trend at abutment and pier because bearings installed at them have the same properties in general. Therefore, the peak responses of the center pier (pier 7) in the longitudinal direction are calculated and compared. The peak deck displacement and the peak overturning moment are obtained to check the serviceability and the design sectional force.

3.2.1. Variations in the first natural period of the isolated bridge

One of the most important features of BISs is to shift the natural period of the isolated structure to longer one in order to avoid the dominant frequency range of the
earthquake ground excitations. Therefore, parameters such as spring constants of the bearing must be selected very carefully to achieve this goal. In this section, therefore, the sensitivity of the peak responses to variations in the first natural period of the bridge with aseismic bearings, $T_1$, is analyzed. Variations of the peak responses of the isolated bridge according to the first natural period are shown in Figs. 7–9.

Fig. 7 shows that the peak responses of bridge with the rubber-type bearing, such as the RB and LRB systems, have similar trend to the response spectrum of each earthquake because of the linearity of the device. As a whole, the peak deck displacement is increased as the first natural period is increased whereas the peak overturning moment is decreased because the horizontal flexibility of the bridge is increased. Most of the deck displacement is the deformation of the device, therefore the deformation of pier is negligible as the first natural period is increased. The peak overturning moment is decreased a little when the first natural period is longer than 4.0 s. The peak responses of the bridge subjected to Mexico City earthquake are amplified in the first natural period of about 2.0–3.0 s because earthquake energy is dominant in this range therefore the resonance is occurred. For Mexico City earthquake, flexible mountings with moderate damping increase rather than decrease the structural response. The provision of high damping as part of the isolation system gives an important defense against the unexpected occurrence of such motions. This concept is presented well in Fig. 7(b), due to the additional energy dissipative capacity of a central lead core the peak responses of the bridge with

Fig. 7. Variations of the peak responses with the first natural period: rubber-type bearing.

Fig. 8. Variations of the peak responses with the first natural period: R-FBI system.

Fig. 9. Variations of the peak responses with the first natural period: EDF system.
the LRB system are much reduced when compared with a RB unit.

For the R-FBI and EDF systems, the natural period and the friction coefficient are the important design parameters simultaneously. Fig. 8 shows the peak responses of the bridge with the R-FBI system versus the first natural period of the isolated bridge according to the friction coefficient of the device. It is observed that the peak responses of the bridge are similar to the response spectrum of each earthquake for the small value of friction coefficient. As the friction coefficient is increased, the peak responses are not sensitive to variations in the first natural period due to characteristics of friction elements. In the friction-type bearing which uses the friction elements in parallel i.e., the R-FBI system, insensitivity to the natural period may be obvious because the natural period is relatively not an important design parameter. The maximum peak deck displacement of three earthquakes is more reduced when compared with the rubber-type bearing due to the frictional resistance of friction elements.

In Fig. 9, the peak responses of the bridge with the EDF system show similar trend to those with the rubber-type bearing as the friction coefficient is increased. If there is no sliding in the friction plates, the responses of the bridge are the same as those with a RB unit. However, the peak deck displacement is larger when compared with the rubber-type bearing due to the sliding of the friction plates.

3.2.2. Variations in the friction coefficient of BIS

For the friction-type bearing, such as the P-F, R-FBI, EDF systems, the friction coefficient is more important design parameter than the natural period. In this section, therefore, the sensitivity of the peak responses to variations in the friction coefficient of the bearing, \( \mu \), is discussed. Variations of the peak responses of the isolated bridge according to the friction coefficient of the bearing are shown in Figs. 10–12.

It is observed that an increase of friction coefficient of the P-F system, generally, leads to a decrease of the peak deck displacement whereas it leads to an increase of the peak overturning moment because of influence of the superstructure. The most portion of displacement is the sliding deformation of the P-F system and the deformation of pier is negligible. As the friction coefficient is increased, a sliding seldom occurs in the P-F system, therefore the deformation of pier is increased. The P-F system subjected to El Centro earthquake slides less than 1 cm for \( \mu \geq 0.18 \) and sliding does not occur for \( \mu \geq 0.18 \) about Mexico City earthquake as shown in Fig. 10. The P-F system has an excessive deformation when the value of friction coefficient is small and a residual deformation because there is no recovering force as shown Figs. 10 and 17.

For the R-FBI and EDF systems, the sensitivity of the
peak responses to variations in the friction coefficient of the bearing according to the first natural period of the isolated bridge is obtained. Fig. 11 shows the peak responses of the bridge with the R-FBI system versus the friction coefficient according to the first natural period. The R-FBI system subjected to El Centro earthquake slides less than 1 cm for \( m/H_1 = 0.22(T_1 = 1.0 \text{ s}) \) and \( m/H_1 = 0.18(T_1 = 2.0 \text{ s}) \) and these results are similar to those of a P-F unit. However, the R-FBI system gives an additional resistance to an increase of deflection by the parallel action of stiffness and damping. Thus, the peak deck displacement is smaller than that with a P-F unit whereas the peak overturning moment is similar. For Mexico City earthquake, the R-FBI system does not slide for \( m/H_1 = 0.18(T_1 = 1.06 \text{ s}) \). It is observed that the peak responses of the bridge are similar to those with a P-F unit. However, the peak overturning moment is decreased as the friction coefficient is increased for \( T_1 = 2.0 \text{ s} \) opposite to the rubber-type bearing. This is why an increase of friction coefficient for \( T_1 = 2.0 \text{ s} \) reduces the resonance of the isolated bridge and the R-FBI system still provides a certain amount of protection.

Fig. 12 shows the peak responses of the bridge with the EDF system versus the friction coefficient according to the first natural period. The EDF system subjected to El Centro earthquake does not slide for \( \mu = 0.30(T_1 = 1.0 \text{ s}) \), \( \mu \geq 0.14(T_1 = 2.0 \text{ s}) \), \( \mu \geq 0.10(T_1 = 3.0 \text{ s}) \), \( \mu \geq 0.06(T_1 = 4.0 \text{ and } 5.0 \text{ s}) \) and \( \mu \geq 0.10(T_1 = 6.0 \text{ s}) \). For Mexico City earthquake, sliding does not occur for \( \mu = 0.30(T_1 = 3.0 \text{ s}) \), \( \mu \geq 0.10(T_1 = 4.0 \text{ s}) \) and \( \mu \geq 0.06(T_1 = 5.0 \text{ and } 6.0 \text{ s}) \). For San Fernando earthquake, sliding does not occur for \( \mu \geq 0.22(T_1 = 3.0 \text{ s}) \), \( \mu \geq 0.14(T_1 = 4.0 \text{ and } 5.0 \text{ s}) \) and \( \mu \geq 0.10(T_1 = 6.0 \text{ s}) \). When there is no sliding in the upper plate of the EDF system, it behaves like the rubber-type bearing and the peak responses of the bridge remain constant for variations in the friction coefficient. For Mexico City earthquake, when the first natural period is 2.0 s, the peak responses of the bridge are amplified like those with the rubber-type bearing.

Figs. 13 and 14 present the peak responses of the bridge with the R-FBI and EDF systems according to the first natural period and the friction coefficient simultaneously.

It is impossible to elect the optimal values of the natural period and the friction coefficient for the various BISs, because the optimal design parameters vary depending on the various design conditions such as soil type, structure type and possible input ground motion. It is possible, however, to recommend the appropriate ranges of the natural period and the friction coefficient. Therefore, within the range of the above sensitivity analyses of the design parameters, it is recommended
using the first natural period shorter than 4.0 s to avoid an excessive deck displacement with suitable overturning moment. Furthermore, the use of adequate friction element is effective in reducing deck displacement. It is recommended using the friction coefficient smaller than 0.18. If the value of friction coefficient is larger than 0.18, there is little advantage of reducing deck displacement whereas overturning moment is monotonously increased.

3.2.3. Comparative study for different earthquakes with the selected design parameters

Practical BISs must trade off between the extent of force isolation and acceptable relative displacements across the isolation system during the earthquake motion. The design parameters determined by the reciprocal relationship between the peak deck displacement and the peak overturning moment of the bridge is used for comparisons and analyses of aseismic performances of various BISs with the fixed design parameters instead of the conventionally recommended ones [9]. San Fernando earthquake has a general feature in the response spectrum and it is possible to examine the characteristic of sliding of the friction-type bearing owing to relatively large intensity of the ground motion. The first natural period of the isolated bridge and the friction coefficient of the device are determined by using sensitivity analysis results of San Fernando earthquake. Importance of the deck displacement or the overturning moment is different according to various design conditions such as soil type, structure type and possible input ground motion. Therefore, the design parameters of the device are determined by following procedure in this paper.
First, it is calculated that the ratio of the peak deck displacement and the peak overturning moment to average value according to the first natural period and the friction coefficient, respectively. To consider the influence of small values of results, the average value is used instead of a maximum one.

\[
D_{\text{ratio}} = \frac{D}{D_{\text{average}}} \quad (18a)
\]
\[
M_{\text{ratio}} = \frac{M}{M_{\text{average}}} \quad (18b)
\]

The curves of \(\alpha D_{\text{ratio}}\) and \((1-\alpha)M_{\text{ratio}}\) are plotted in Fig. 15, for example. The \(\alpha\) is a factor that indicates the relative importance of the peak deck displacement. The \(\alpha\) varies from 0 to 1 and \(\alpha = 0.5\), which means same importance of the peak deck displacement and the peak overturning moment, is used in this study. One can consider a different relative importance of the peak deck displacement and the peak overturning moment using the factor \(\alpha\) according to various design conditions as shown in Fig. 15. Finally, the crossing point of two curves is selected as the design first natural period of the isolated bridge and/or the friction coefficient of the device. As shown in Fig. 15, if \(\alpha\) is increased from \(\alpha_1\) to \(\alpha_2\), then the selected first natural period is decreased from \(T_{\text{select1}}\) to \(T_{\text{select2}}\), whereas the selected friction coefficient is increased from \(\mu_{\text{select1}}\) to \(\mu_{\text{select2}}\). Therefore, the peak deck displacement will be decreased with \(T_{\text{select2}}\) and/or \(\mu_{\text{select2}}\). Table 2 shows the selected first natural period and the friction coefficient determined by above procedure.

The peak responses of the bridge with various BISs, which are designed by the selected parameters of Table 2.
Fig. 15. Selection of values of the design parameters.

Table 2
The selected values of the design parameters

<table>
<thead>
<tr>
<th>BIS</th>
<th>The first natural period (s)</th>
<th>Friction coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>RB system</td>
<td>3.0</td>
<td>N/A</td>
</tr>
<tr>
<td>LRB system</td>
<td>3.0</td>
<td>N/A</td>
</tr>
<tr>
<td>P-F system</td>
<td>N/A</td>
<td>0.14</td>
</tr>
<tr>
<td>R-FBI system</td>
<td>3.0</td>
<td>0.14</td>
</tr>
<tr>
<td>EDF system</td>
<td>4.0</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Fig. 16. Aseismic performances of various BISs for the selected values of the design parameters.

2, are shown in Fig. 16. As shown in the figure, the performance of BISs varies depending on the input ground motions. While the peak deck displacement with the friction-type bearing is generally smaller than that with the rubber-type bearing, the peak overturning moment is larger due to the friction element. The P-F system has a residual deformation after the seismic event as shown in Fig. 17, because it does not have the recovering force. The EDF system has a residual deformation due to the sliding in the friction plates for San Fernando earthquake like a P-F unit as shown in Fig. 17.

In Figs. 7–14, 16, the peak responses of the bridge with the friction-type bearing are less sensitive to substantial variations in the frequency range and intensity of earthquake excitation due to characteristics of the stick-slip mechanism compared to those with the rubber-type bearing.

4. Conclusions

Comprehensive sensitivity analyses of several leading BISs such as the P-F, RB, LRB, R-FBI and EDF systems, are presented. The bridge with BISs must trade off between the extent of force isolation and acceptable relative displacements across the isolation system during the earthquake motion. The recommended ranges of the two design parameters such as the first natural period of the isolated bridge and the friction coefficient of the bearing are presented in this study. The two design parameters are determined by reciprocal relationship between the peak deck displacement and the peak overturning moment. Comparisons and analyses on aseismic performances of different BISs for the selected design parameters are presented. Based on these results, the following conclusions may be drawn.

The peak deck displacement is increased as the first natural period of the isolated bridge is increased and as the friction coefficient of the device is decreased. Contrary to the peak deck displacement, the peak overturning moment is increased as the first natural period is decreased and as the friction coefficient is increased.

Several design parameters of the bearing are influenced by various design conditions such as soil type, structure type and possible input ground motion. Therefore, it is important that adequate design parameters determined by the sensitivity analysis of the bridge with BISs are used in the design of the device instead of the conventionally recommended ones. It is shown within the range of these sensitivity analyses on variations in the design parameters of the bearing and a comparative study on aseismic performances of various BISs with the selected design parameters that the peak responses of the bridge with the friction-type bearing are less sensitive to substantial variations in the frequency range and the
intensity of earthquake excitation when compared to those with the rubber-type bearing because of characteristics of friction elements.

Within the range of the parametric study of this paper, it is recommended using the first natural period shorter than 4.0 s to avoid excessive deck displacement with suitable overturning moment. Furthermore, the use of adequate friction element is effective in reducing deck displacement and it is recommended using the friction coefficient smaller than 0.18. If the value of friction coefficient is larger than 0.18, there is little advantage of reducing deck displacement whereas overturning moment is monotonously increased.

Acknowledgements

This research was supported by the National Research Laboratory (NRL) program for Aseismic Control of Structures. The financial support is gratefully acknowledged.

References

[16] Proceedings of the Ninth World Conference on Earthquake Engineering. 9WCEE organizing committee, Japan Association for Earthquake Disaster Prevention, Tokyo, Vols V and VIII; 1988.