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PERFORMANCE OF SEISMIC-ISOLATED BRIDGES IN NEAR-FAULT ZONES

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ABSTRACT

This paper investigates the performance of seismic-isolated bridges (SIBs) subjected to near-fault (NF) earthquakes with forward rupture directivity effect (FRDE) in relation to the isolator, substructure and NF earthquake properties and examines some critical design clauses in AASHTO. It is found that the SIB response is a function of the number of velocity pulses, magnitude of the NF ground motion and the distance from the fault. It is also found that the characteristic strength and post-elastic stiffness of the isolator may be chosen based on the characteristics of the NF earthquake. Furthermore, some of the AASHTO clauses are found to be not applicable to SIBs subjected to NF ground motions.

Introduction

The seismic isolation of bridges is a simple design approach based on limiting the magnitude of the seismic forces transferred to the substructures through yielding of the isolators. It has gained worldwide acceptance as a viable tool for protecting bridges from earthquakes only within the last two decades. Parallel to the rising demand for the seismic-isolation design of bridges in the USA, the second edition of AASHTO Guide Specification for Seismic Isolation Design was introduced in 1999 (AASHTO, 1999). The development of this specification and the design experience gained by bridge engineers over the years were mostly based on the performance of seismic-isolated structures subjected to far-field ground motions. Near-fault (NF) ground motions with forward rupture directivity effect (FRDE) are generally characterized by one or more, intense, long-period velocity pulses (Makris and Chang, 1998), which may be detrimental to seismic-isolated bridges (SIBs). As most of the experience gained by bridge engineers is based on the performance of SIBs subjected to far-field effects, further research is required to study the effect of isolator and substructure properties on the response of SIBs in relation to the characteristics of NF ground motions with FRDE and identify critical issues with regard to the design of such bridges subjected to NF ground motions.

Research Objectives and Methodology

The main objectives of the research is to; (i) study the effect of substructure and isolator properties on the response of SIBs subjected to NF ground motions with FRDE, (ii) investigate the effect of the characteristics of the NF ground motion on the response of SIBs (iii) examine the critical design clauses in AASHTO (1999), (iv) make recommendations for the design of SIBs located near active faults. To

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achieve the above stated objectives, a parametric study involving more than 400 nonlinear time history (NLTH) analyses of simplified structural models representative of typical SIBs, are conducted. The effects of several parameters, such as substructure stiffness, characteristic strength and post-elastic stiffness of the isolator and the number, intensity and period of the velocity pulse (or magnitude and distance from the fault) of the NF ground motion on the performance of SIBs are considered both individually and in terms of three dimensionless parameters (Makris and Black 2004). Furthermore, the impact of important AASHTO (1999) design clauses on the performance of SIBs is studied in relation to the NLTH analyses results and recommendations for the design of SIBs are outlined.

In the present study, the performance of SIBs is measured by the maximum isolator force and displacement (MIF and MID). The MIF represents the magnitude of the seismic force transferred to the substructures. Thus, it has a remarkable effect on the design of the substructures. The MID is generally used to determine the isolator size as well as the width and type of the expansion joints and in some cases, the widths of the substructures. Accordingly, for a given NF ground motion, smaller isolator force and displacement are indicative of superior seismic performance.

Isolator Properties Considered in this Study

Fig 1(a) illustrates a typical single bridge substructure and an isolator supporting a tributary bridge superstructure. Fig. 1(b) demonstrates the force-displacement hysteresis relationship of most isolators idealized as bilinear for design purposes and is used in NLTH analyses. In the figure, Q_d is the characteristic strength, k_u is the elastic stiffness, k_d is the post-elastic stiffness, F_y and u_y are respectively the yield force and displacement and F_i and u_i are respectively the maximum force and displacement. In the parametric study, a total of 11 different combinations of isolator's stiffness values are considered to cover a broad range of rubber-based and sliding-based isolator types. Furthermore, the characteristic strength of the isolators is varied to obtain typical Q_d/W ratios ranging between of 0.025 and 0.15 where W is the tributary weight acting on the isolator. Overall, 66 isolators with various properties are considered.

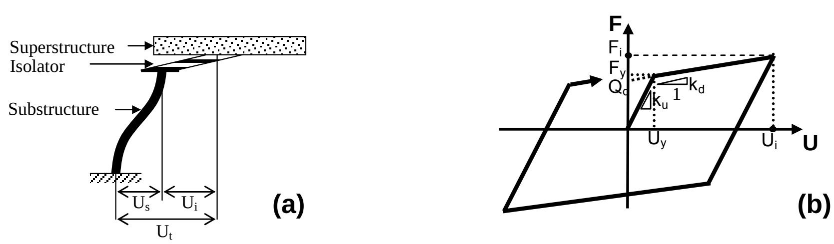

Figure 1. (a) Typical SIB substructure, (b) Idealized hysteresis loop of a typical isolator.

Near-Fault Ground Motions Considered in this Study

Two sets of NF ground motions with FRDE are considered. The first set involves a suite of 36 simulated NF ground motions used to relate the performance of SIBs to the number, intensity and period of the velocity pulse of the NF ground motion. For their generation, the NF zone is assumed to be within 20 km of the fault (Somerville et al., 1997). The simulation is performed for moment magnitudes (M_w) ranging between 6.0 and 7.5 and fault distances (r) ranging between 3 and 18 km. For the assumed range of M_w and r, the peak ground velocity, V_p, and the velocity pulse period, T_p, of the simulated NF ground motions are obtained using the following relationships (Somerville, 1998);

$$\ln(V_p) = -2.31 + 1.15M_w - 0.5\ln(r) \tag{1}$$

$$Log_{10}(T_p) = -2.5 + 0.425M_w \tag{2}$$

For the simulation of NF ground motions, the model presented by Agrawal and He (2002) is used. This model simulates the velocity time history of NF ground motions by a decaying sinusoid as follows;

$$\dot{u}_g = se^{-\zeta_p \omega_p t} \sin \omega_p \sqrt{1-\zeta_p^2}\, t \tag{3}$$

$$\ddot{u}_g = se^{-\zeta_p \omega_p t} \left(-\zeta_p \omega_p \sin \omega_p \sqrt{1-\zeta_p^2}\, t + \omega_p \sqrt{1-\zeta_p^2} \cos \omega_p \sqrt{1-\zeta_p^2}\, t \right) \tag{4}$$

where ζ_p is the decaying factor, ω_p is the frequency of the sinusoid, s is the initial amplitude of the velocity pulse and t is the time in seconds. The decaying sinusoids with ζ_p =10%, 20% and 40% resembles NF ground motions with multiple, forward-and-backward and forward velocity pulses respectively.

The second set of ground motions contains five NF earthquakes tabulated in Table 1. These earthquakes are used for further studying the response of SIBs subjected to NF ground motions.

Table 1. Important features of earthquake records used in the analyses.

Earthquake	Station / Component	M_w	r (km)	A_p (g)	V_p (cm/s)	T_p (s)
Northridge, 1994	Rinaldi, DWP Sta. 77	6.7	7.1	0.84	166.1	1.25
Loma Prieta, 1989	Gilroy, Arr. #02,CDMG Sta. 47380, 90°	6.9	12.7	0.32	39.1	1.40
Northridge, 1994	Sylmar, Olive View Hosp., CDMG Sta. 24514, 360°	6.7	6.1	0.84	116.3	2.60
Imperial Valley, 1979	Elcentro, Array # 05, USGS Sta. 952, 230°	6.5	1.0	0.38	90.5	3.90
Landers, 1992	Lucerne, SCE Sta. 24, 275°	7.3	1.1	0.72	97.6	5.00

Parameters Considered in this Study

The seismic response of SIBs subjected to pulse type excitations is governed by many variables which are the bridge mass, m, the properties, Q_d, k_d, of the isolator and the properties, M_w and r (or V_p and T_p), of the NF ground motion. All of these parameters are considered to examine their effects individually on the performance of SIBs. In addition, three of the four dimensionless terms proposed by Makris and Black (2004) are used to study the performance of SIBs subjected to NF earthquakes. These terms are; $P_1=u_i/ApT^2_p$, $P_2= A_p/Xg$ where $X=Q_d/W$, and $P_4= T_p/T_s$, where T_s is the period of the structure based on its post-elastic stiffness and all the other variables are as described before.

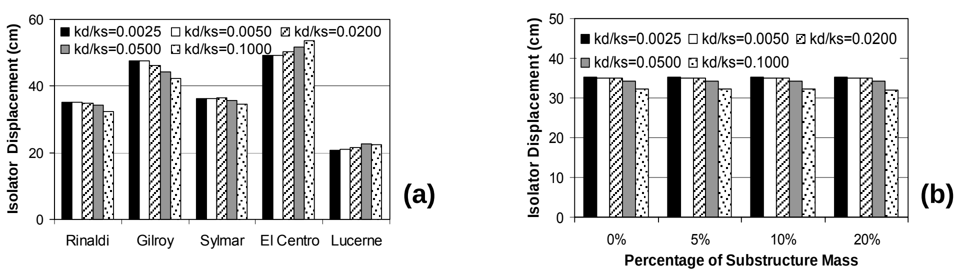

Figure 2. Isolator displacement (a) for various k_d/k_s ratios and earthquakes (b) for various k_d/k_s ratios and percentage of substructure mass (Rinaldi Earthquake).

Effect of Substructure Stiffness on Bridge Performance

In this section, the effect of substructure stiffness on the performance of SIBs is investigated. For this purpose, a single bridge substructure and an isolator supporting a tributary bridge superstructure with infinite in-plane rigidity is considered. The NLTH analyses of the SIB are then conducted for $P_2= A_p/Xg$ =12 and for substructure mass ranging between 0% and 20% of the superstructure mass using the five NF earthquakes considered in this study. In the analyses, the ratio, k_d/k_s, of the post-elastic stiffness of the isolator to the lateral stiffness of the substructure is varied between 0.0025 and 0.1 (stiff and flexible) by changing the substructure stiffness. Fig. 2(a) presents the MID, u_i, in a bar-chart form for the five NF earthquakes and for various k_d/k_s ratios neglecting the mass of the substructure. Although discrepancies in the total displacement of the bridge as a function of the substructure stiffness are observed, the variations among the MIDs are modest. Fig. 2(b) presents the MIDs as a function of the substructure mass and for various, k_d/k_s ratios. In the figure the plots for various substructures' mass are nearly identical. This demonstrates that the variation of the MID as a function of the k_d/k_s, ratios is generally negligible for a wide range of substructure mass values. Thus, for the remainder of this study, the SIBs are idealized as isolators placed on rigid supports and supporting a rigid mass. However, for bridges with tall, heavy piers the above observations may not be true.

Effect of Near Fault Ground Motion Characteristics

NF ground motions are generally characterized by the number, amplitude and period of the velocity pulse. The amplitude and period of the velocity pulse are functions of the moment magnitude (M_w) and distance from fault (r) (see Eqns. 1 and 2). In this section, the effect of these NF ground motion parameters, namely, the number of velocity pulses, moment magnitude, distance from fault and intensity, on the performance of SIBs is investigated.

Effect of Number of Velocity Pulses

In this section, the effect of the number of NF ground motion velocity pulses on the performance of SIBs is studied considering a SIB with typical isolator properties of k_u=200 kN/cm, k_d=20 kN/cm and Q_d/W=0.05. The analyses are conducted using simulated NF ground motions with various decaying factors to replicate those with one, two, three and four velocity pulses. Fig. 3(a) presents the MID, u_i, as a function of the number of velocity pulses of the simulated NF ground motions for fault distances ranging between 3 and 18 km. It is observed that the MID increases with the number of velocity pulses. This results from the higher energy content of NF ground motions with larger number of velocity pulses. The effect of the number of velocity pulses is more pronounced for SIBs located closer to the fault. Thus, an accurate estimation of the characteristics of the NF ground motion for the design of SIBs located in the vicinity of the fault becomes very important. If adequate NF ground motion data is not available for the bridge site, the number of velocity pulses may be assumed to be at least equal to three for the design of the SIB. As nearly 50 percent of the NF ground motions recorded to date contain only two velocity pulses (Rodriguez-Marek, 2000), two velocity pulses are assumed for the remainder of this study.

Effect of Ground Motion Magnitude, Fault Distance and Intensity

In this section, the effect of the magnitude, fault distance (or T_p and V_p) and intensity (A_p or V_p) of the NF ground motion on the performance of SIBs is studied The analyses are conducted using the 36 simulated NF ground motions considered in this study.

Fig. 3(b) displays the relationship between the MID and the magnitude of the NF ground motion for $3 < r < 18$ km. It is observed that for the particular SIB considered in the analyses, the MID increases up to M_w=6.6 and then increases at a slower rate up to M_w= 7.2. For M_w>7.2 a decline in the MID is observed.

The variation of MID as a function of the distance from the fault is displayed in Fig. 3 (c). It is observed that the MID increases as the distance to the fault decreases. The MID may be in the order of 0.5-3 m in the vicinity of the fault, depending on the properties of the isolator. This clearly demonstrates that the design of SIBs near active faults should be performed by taking special measures to improve the seismic performance of the bridge. Such measures will be explored in the subsequent sections

To investigate the effect of NF ground motion intensity on the performance of SIBs, the MID is plotted as a function of the dimensionless parameter $P_2 = A_p/Xg$ in Fig. 3(d) for NF ground motions with various magnitudes. The figure demonstrates that for a NF ground motion with a specific velocity pulse period, the MID is linearly proportional to P_2. Thus, it seems that the seismic performance of a SIB is a linear function of the characteristic strength of the isolator relative to the intensity of the ground motion.

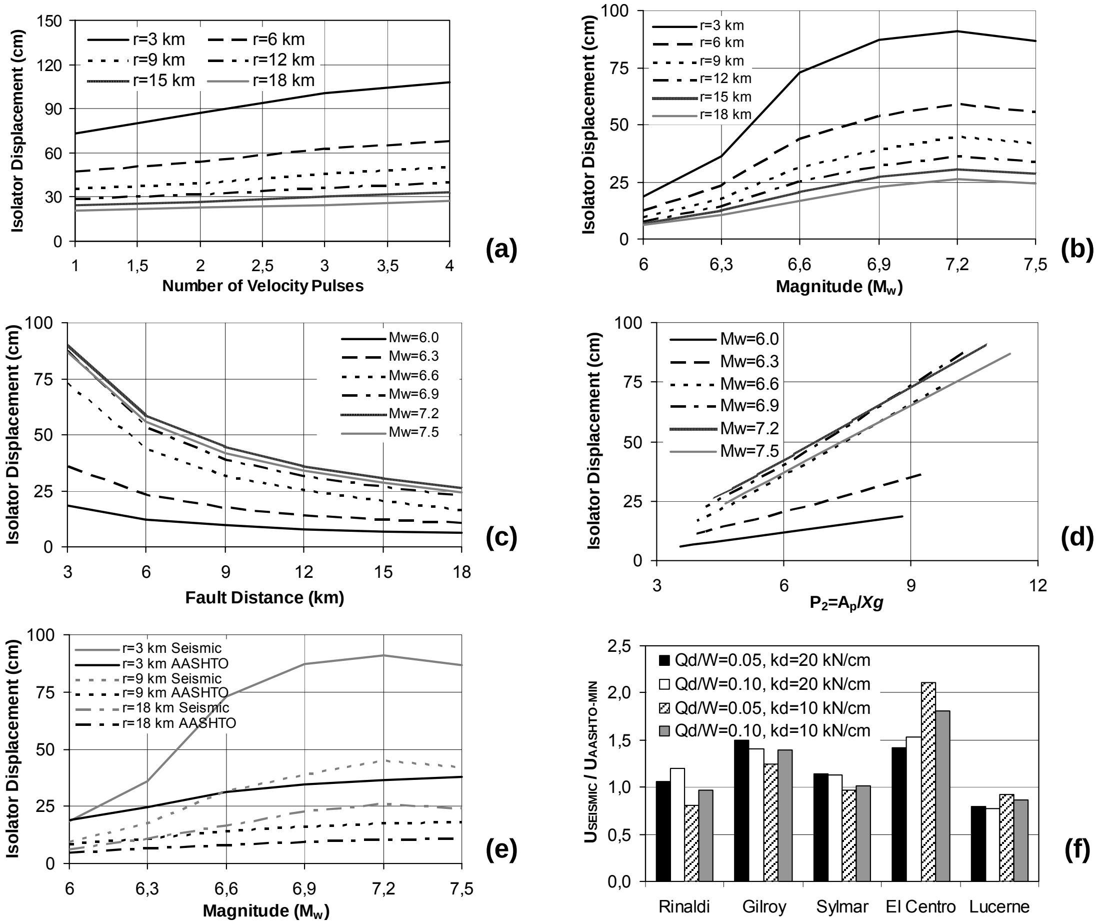

Figure 3. (a) Isolator displacement as a function of number of velocity pulses (b) Isolator displacement as a function of magnitude (c) Isolator displacement as a function of distance from the fault (d) Relationship between isolator displacement and P_2 (e) Comparison of isolator displacement with minimum displacement per AASHTO as a function of M_w (f) Ratio of isolator displacement to minimum displacement per AASHTO for various earthquakes and isolator characteristics.

AASHTO's Minimum Isolator Displacement Versus NF Ground Motions

AASHTO (1999) requires the isolators to have a minimum displacement capacity, u_{min}, given in mm as:

$$u_{\min} = \frac{200 A_p S_i T_{eff}}{B} \quad (5)$$

where, S_i is the site coefficient, T_{eff} is the effective period of the SIB and B is the damping factor. The purpose of this requirement is to guard against analysis procedures that produce excessively low isolator displacements. The applicability of this requirement to SIBs subjected to NF earthquakes is investigated in this section. For this purpose, assuming an AASHTO soil type II and using the MIDs obtained from NLTH analyses, u_{min} are calculated. The calculated u_{min} and those obtained from NLTH analyses using simulated NF ground motions are presented as functions of M_w for r = 3, 9 and 18 km in Fig. 3(e). As observed from the figure, the isolator design displacement capacity is not governed by Eqn. 5 for any of the cases considered. This is also confirmed by Fig. 3(f) where the ratios of MIDs to those calculated using Eqn 5 are presented for various recorded NF ground motions and isolator properties. It is observed that for the majority of the cases considered, the calculated ratios are nearly equal or larger than 1.0. Thus, either NLTH analysis needs to be recommended or a new AASHTO's minimum isolator displacement capacity requirement needs to be developed for SIBs subjected to NF ground motions.

Effect of Isolator's Post-Elastic Stiffness on SIB Performance

Post-Elastic Stiffness

In this section, the effect of the post-elastic stiffness (or period) of the isolator on the performance of SIBs is studied. Figs. 4(a) and 4(b) display respectively the variation of the MID and MIF as functions of the magnitude of the NF ground motions for various post-elastic periods of SIB at a fault distance of 6.0 km. It is observed that the seismic response of SIBs is a function of its post-elastic period in relation to the magnitude of the NF ground motion. The variation of the MIDs as a function of the post-elastic period of the bridge is generally small for NF ground motions with small magnitudes. This variation becomes more significant at larger NF ground motion magnitudes. Nevertheless, as observed from Fig. 4 (b), the opposite is true for the variation of MIF as a function of the post-elastic period of the SIB and magnitude of the NF ground motion. That is, the difference between the MIFs for various post-elastic periods is noticeable for NF ground motions with small to moderate magnitudes and is practically insignificant for NF ground motions with large magnitudes (M_w > 7.2).

Post Elastic Stiffness Versus Velocity Pulse Period

In this section, the dependency of the seismic response of the SIB on its post-elastic period, T_s, in relation to the velocity pulse period, T_p, (or magnitude) of the NF ground motion is further investigated. For this purpose, the MID normalized with respect to the intensity and velocity pulse period of the NF ground motion (P_1) is plotted as a function of $P_4=T_s/T_p$ in Fig. 4(c). It is observed that the peak value for P_1 occurs at P_4=1. This confirms that SIB subjected to NF ground motions behave like an equivalent elastic structure with a period equal to the post-elastic period of the SIB. Thus, the post elastic stiffness of the isolator may be chosen in relation to the velocity pulse period (or magnitude) of the NF ground motion to minimize the isolator displacements. For NF ground motions with large magnitude, isolators with large post elastic stiffness must be used to avoid resonant response. Conversely, for NF ground motions with small magnitude, isolators with small post-elastic stiffness may be chosen to minimize the isolator displacements and forces transferred to the substructures.

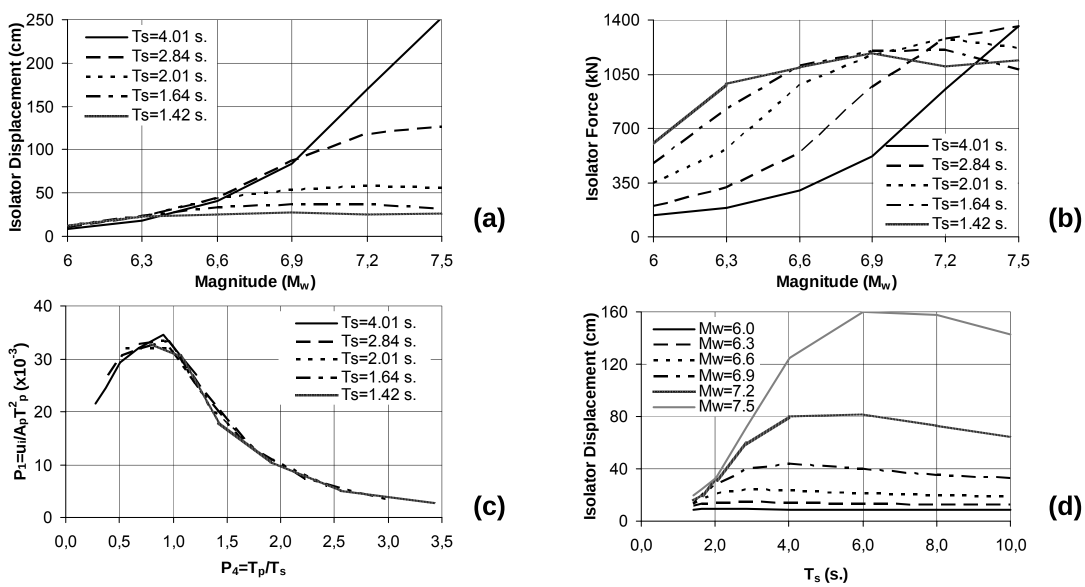

Figure 4. (a) Isolator displacement as a function of magnitude for various post-elastic periods. (b) Isolator force as a function of magnitude for various post-elastic periods. (c) The dimensionless parameter P1 as a function of the ratio of the post-elastic period of the SIB to the velocity pulse period of the NF ground motion (d) Isolator displacement as a function of post-elastic period for Q_d/W=0.125.

Minimum Post-Elastic Stiffness Based on Restoring Force Provisions of AASHTO

In this subsection, the AASHTO (1999) criterion for preventing the cumulative seismic isolator displacements is examined. This provision requires the isolator to be configured such that the post-elastic period, T_d, of the SIB is smaller than 6 s. Figs. 3 (d) presents the MIDs as a function of the post-elastic period of the SIB for various NF ground motion magnitudes for Q_d/W=0.125. The figures reveal that the variation of MIDs as a function of post-elastic period of the SIB is generally steady for NF ground motions with relatively small magnitude ($M_w \leq 6.3$), modest for those with intermediate magnitude ($6.3 < M_w < 7.2$) and large for those with large magnitude ($M_w \geq 7.2$). Furthermore, it is observed that MIDs are within practical limits for post-elastic periods smaller than 3 s. Thus, the maximum limit of Ts=6 s. required by AASHJTO (1999) to provide a minimum restoring force does not seem to be applicable to SIBs subjected to NF ground motions. A maximum post-elastic period limit of T_s=3 s. seem to produce MIDs within practical range of engineering design when combined with a characteristics strength to tributary weight ratio of at least Q_d/W=0.10. Thus, for SIBs located within the NF zone, a maximum post-elastic period limit of T_s=3 s. and a minimum characteristics strength to tributary weight ratio of at least Q_d/W=0.10 may be recommended in future editions of AASHTO (1999).

Isolator's Characteristic Strength Versus SIB Performance

The effect of the isolator's characteristic strength on bridge performance is studied with respect to two parameters; (i) the Q_d/W ratio,. (ii) $P_2 = A_p/Xg$ ratio described earlier. Details are presented in the following subsections.

Q_d/W versus Ground Motion Magnitude

Fig. 5(a) displays the MID as a function of the magnitude of the NF ground motion for Q_d/W ratios ranging between 0.025 and 0.150 and r= 9 km. The figure reveals that isolators with large Q_d result in smaller isolator displacements. Furthermore, the magnitude of Q_d becomes more effective in reducing the isolator displacements for ground motions with larger magnitude. Moreover, in Fig 5(a), the difference between the shapes of the curves for Q_d/W=0.025-0.100 and Q_d/W=0.125-0.150 reveals that the dependency of the seismic performance of the SIB on its post elastic period in relation to the magnitude of the NF ground motion diminishes for isolators with large characteristic strength.

Fig. 5(b) displays the same information as in Fig. 5(a) but for MIF. The figure reveals that isolators with large characteristic strength generally result in larger isolator forces for NF ground motions with small magnitudes (M_w < 6.3). However, the opposite is true for NF ground motions with larger magnitudes (M_w > 6.3).

In the light of the above observations, it is generally recommended that for SIBs built within the NF zone, if the magnitude of the NF ground motion is expected to be small (M_w < 6.3) isolators with a small Q_d/W ratio most be used to minimize the forces transferred to the substructures while keeping the displacements within reasonable ranges. However, for NF ground motions with larger expected magnitudes, isolators with Q_d/W ratio of at least equal to 0.10 must be used to limit the magnitude of the MIDs and MIFs and to reduce the dependency of the seismic response of the SIBs on its post elastic period in relation to the magnitude (or velocity pulse period) of the NF ground motion.

Q_d/W versus Fault Distance

Figs. 5(c) and (d) display respectively the MID and MIF as functions of the distance from the fault for Q_d/W ratios ranging between 0.025 and 0.150 and M_w= 7.2. It is observed that isolators with larger Q_d result in smaller isolator displacements and forces for the range of fault distances considered. The trends of the curves in Figs. 5 (c) and (d) reveal that increasing the magnitude of the Q_d becomes more effective in reducing the MIDs and MIFs for SIBs located very near (r < 6 km) active faults. Thus, isolators with large Q_d must be used for SIBs located close to the fault to reduce the magnitude of both MIDs and MIFs.

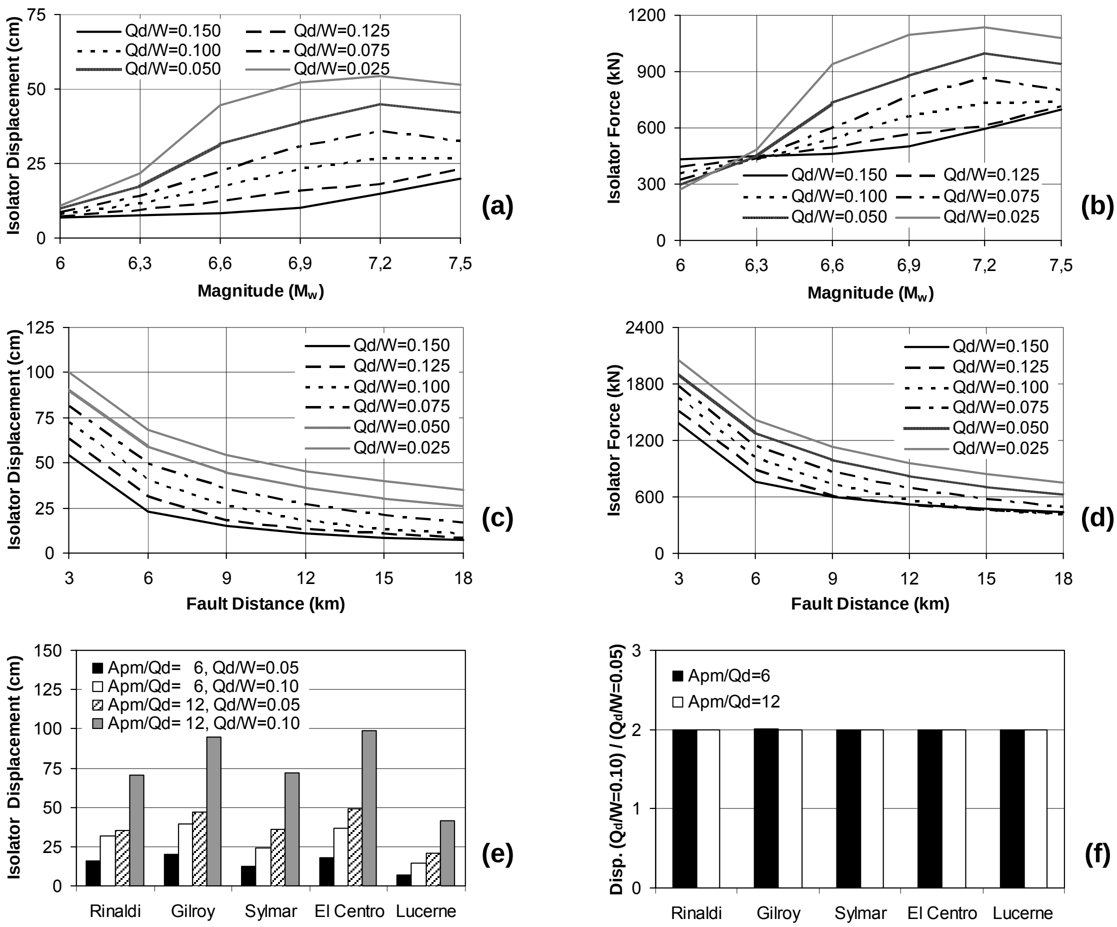

Figure 5. (a) Isolator displacement as a function of magnitude for various Q_d/W ratios (b) Isolator force as a function of magnitude for various Q_d/W ratios (c) Isolator displacement as a function of distance from the fault for various Q_d/W ratios (d) Isolator force as a function of distance from the fault for various Q_d/W ratios (e) Comparison of isolator displacement for various A_p/Xg and Q_d/W ratios (f) Ratio of isolator displacement for Q_d/W=0.10 to that for Q_d/W=0.05 (k_d=20 kN/cm, k_u=200 kN/cm).

Effect of A_P/Xg Ratio on the Seismic Performance of the Bridge

Fig. 5(e) presents the MIDs for various recorded NF ground motions for two different A_p/Xg ratios of 6 and 12 calculated using Q_d/W ratios of 0.05 and 0.10. It is observed that for the same A_p/Xg ratio, the displacement amplitudes for Q_d/W=0.10 are twice the ones for Q_d/W=0.05. Fig. 5(f) demonstrates the ratio of the MID for Q_d/W=0.10 to that for Q_d/W=0.05 for A_p/Xg=6 and 12 and for all the earthquakes considered in this study. As observed from the figure, all the MID ratios are equal to 2.0. This clearly demonstrates that the isolator displacement is proportional to the ratio of the peak ground accelerations (2.0) used to calculate the same A_p/Xg ratios for Q_d/W=0.05 and 0.10. Thus, when both the NF ground motion and Q_d are scaled by a factor f, the isolator displacement changes by the same factor. This proves that for the same A_p/Xg ratio, the isolator displacement is linearly proportional to the magnitude of the peak ground acceleration (see Fig. 3(d)). Consequently, if the ground motion is scaled by a factor f, the characteristic strength needs to be increased by a factor much larger than f to keep the MID within a prescribed limit. Thus, isolators with large Q_d must be used to limit the MIDs for SIBs located closer to the fault and subjected to NF ground motions with large magnitudes.

Conclusions and Recommendations

The effects of isolator and substructure properties as well as the characteristics of the NF ground motion on the performance of SIBs are studied. Additionally, important design clauses in AASHTO are examined. The conclusions and recommendations derived from this study are presented below.

The effect of the bridge substructure stiffness on the magnitude of the MID is found to be practically negligible for SIBs subjected to NF ground motions provided that the columns remain elastic. However, this may not be true if the bridge substructures are very flexible and/or have significant mass.

It is observed that MID increases with increasing number of velocity pulses. Thus, an accurate estimation of the characteristics of the NF ground motion for the design of SIBs located in the vicinity of the fault becomes very important. If adequate NF ground motion data is not available for the bridge site, the number of velocity pulses may be assumed to be at least equal to three for the design of the SIB.

It is found that the MID increases as the distance to the fault decreases. The MID may be in the order of 0.5-3 m in the vicinity of the fault, depending on the properties of the isolator. This clearly demonstrates that the design of SIBs near active faults should be performed by taking special measures to improve the seismic performance of the bridge.

The response of a SIB is found to be a function of its post-elastic period (T_s) in relation to the magnitude (or T_p) of the NF ground motion. The variation of MIDs as a function T_s is generally small for NF ground motions with small magnitudes and becomes more significant at larger magnitudes. Nevertheless, the opposite is true for the variation of MIF as a function T_s and magnitude of the NF ground motion. That is, the difference between the MIFs for various T_s values is noticeable for NF ground motions with small to moderate magnitudes and is practically insignificant for NF ground motions with large magnitudes. Furthermore, the general behavior of a SIB subjected to NF ground motions is observed to be similar to that of an elastic structure with a period equal to the post-elastic period of the SIB. Consequently, similar to the resonant response of elastic structures, the maximum response of the SIB is found to occur at a T_s/T_p=1.0. Thus, the post elastic stiffness (k_p) of the isolator may be chosen in relation to the velocity pulse period (or magnitude) of the NF ground motion to minimize the isolator displacements. For NF ground motions with large magnitude, isolators with large k_p must be used to minimize isolator displacements. Conversely, for NF ground motions with small magnitude, isolators with small k_p may be chosen to minimize the isolator displacements and forces transferred to the substructures.

It is found that isolators with large characteristics strength (Q_d) result in smaller isolator displacements. This finding is more pronounced for ground motions with larger magnitude and at distances closer to the fault. Moreover, it is observed that the dependency of the performance of the SIB on its post elastic period in relation to the magnitude of the NF ground motion (or T_p) diminishes for isolators with large Q_d. Furthermore, isolators with large Q_d generally result in larger isolator forces for NF ground motions with small magnitudes (M_w < 6.3). However, the opposite is true for NF ground motions with larger magnitudes (M_w > 6.3). Thus, it is recommended that for SIBs built within the NF zone, if the magnitude of the NF earthquake is expected to be small (M_w<6.3) isolators with a small Q_d/W ratio must be used to minimize the forces transferred to the substructures while keeping the MIDs within reasonable ranges. However, for NF ground motions with larger expected magnitudes, isolators with Q_d/W at least equal to 0.10 must be used to limit the magnitude of the MIDs and MIFs and to reduce the dependency of the seismic response of the SIBs on its post elastic period in relation to the magnitude of the NF ground motion.

It is observed that for the same A_p/Xg ratio, the MID is linearly proportional to the magnitude of the peak ground acceleration. Consequently, if the ground motion is scaled by a factor f, Q_d needs to be increased by a factor much larger than f to keep the magnitude of the MID within a prescribed limit.

Specific AASHTO clauses are studied in relation to SIBs subjected to NF ground motions. It is found that AASHTO's minimum displacement capacity requirement is generally not applicable to SIBs in NF zones. This was expected since AASHTO (1999) was never intended for NF ground motions throughout its development. Thus, either NLTH analysis needs to be recommended or a new AASHTO's minimum isolator displacement capacity requirement needs to be developed for SIBs subjected to NF ground motions. Furthermore, AASHTO's maximum limit of T_s=6 s. developed considering far field effects does not seem to apply to SIBs in NF zones. A maximum post-elastic period limit of T_s=3 s. seem to produce MIDs within practical range of engineering design when combined with a characteristics strength to tributary weight ratio of at least Q_d/W=0.10. Thus, for SIBs located within the NF zone, a maximum post-elastic period limit of T_s=3 s. and a minimum characteristics strength to tributary weight ratio of at least Q_d/W=0.10 may be recommended in future editions of AASHTO (1999).

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