On scaling of ground motions used in dynamic analyses of structures with lead rubber bearings

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ABSTRACT: In dynamic analyses, although there is no limitation for scale factors, the customary values vary from 0.25 to 4. However, these values are based on subjective judgments rather than a quantitative evaluation. This study focused on scaling legitimacy of acceleration time series to be used in dynamic analyses performed during the design of lead rubber bearing (LRB) isolated structures, to obtain a limit for scale factors. For this purpose, several dynamic analyses are performed with the parameters namely, isolation period and peak ground velocity. In the analyses, a recently proposed deteriorating hysteretic bilinear representation is used to model the behavior of LRBs. Limitation for scale factors is discussed through the concept of bounding analysis that intends to provide design envelopes for response quantities of isolated structures. As a result, limits for scale factors, providing that the bounding analysis fulfills its intended purpose in design of LRBs, are proposed.

1 INTRODUCTION

The generally accepted way of representing ground motions for design of earthquake resistant structures is through the use of response spectra for acceleration or displacement. Nevertheless, there can be instances involving structures with special features such as isolation systems where using the elastic response spectrum to obtain the structural response is not suitable. Then, a nonlinear response history analysis (NRHA) is needed for design or evaluation of buildings. To conduct NRHA, code procedures require scaling an ensemble of acceleration time series to be compatible with the target spectrum. There are many studies that have discussed the subject of scaling and its effects on the response of both linear and nonlinear structures (Nau and Hall, 1984; Shome et al., 1998; Bommer and Acevedo, 2004; Luco and Bazzurro, 2007; Hancock et al., 2008). In the light of the existing research outcomes, although the acceptable scale factor limits vary from 1 to 10 or more, in practice, the preferred typical values for limits on the scale factors range from 2 to 4 (Bommer and Acevedo, 2004) who identify the basis for these values as the proposals of both Krinitzsky and Chang (1977) and Vanmarcke (1979). Krinitzsky and Chang (1977) asserted that 4 should be the upper limit for a scale factor while Vanmarcke (1979) defines a range for the limit of scale factor from 2 to 4 based on the characteristics of analysis. Although there is no rationale for such limitations, proposals contained in these two papers are generally used as a rule-of-thumb (Bommer and Acevedo, 2004).

Limitation for the maximum scale factor that can be applied to an acceleration time series in order not to introduce any bias on results has been studied by other researchers. However, concerns regarding the limitation for scale factors are mostly based on variation in ground motion characteristics and much less on their effects on structures. Moreover, most of the time, discussions are limited to elastic systems or inelastic systems with low or moderate ductility. Also, the hysteretic models considered in inelastic systems are non-deteriorating. The periods of the idealized structures are mostly less than 2 s., a lower threshold for seismic isolated structures (SIS).

This study aims to obtain a limitation (if any) for scale factors that can be applied to acceleration time series in NRHA of SIS, equipped with lead rubber bearings (LRBs). To achieve this goal, an idealized seismic isolated bridge (SIB), where the isolation system is composed of LRBs, is subjected to uni-directional excitations of several ground motion records. In the analyses, LRBs are represented by both deteriorating and non-deteriorating hysteretic behaviors. Results obtained from NRHA are discussed through the concept of bounding analysis. The objective of performing bounding analysis is to define a design envelope for the response of isolation systems. In bounding analysis, using the upper bound properties gives the maximum isolator force and using lower bound properties results in maximum isolator displacement (MID). Since generally the most important response quantity in a SIB is the MID, discussions related to bounding analysis are limited to results of analyses in which lower bound properties are considered. It is to be noted that most of the discussions related to isolator displacements are based on non-deteriorating hysteretic representations, and researchers do not consider the geometrical features of the isolator by neglecting any conceivable instabilities due to excessive displacements. Such instability issues are also addressed in the present study with isolators designed in accordance with the requirements for stability and strength. Moreover, MIDs obtained from the analyses are considered to be valid if and only if they are less than the design displacements calculated by using the requirements for stability and strength.

2 ANALYTICAL MODEL OF THE BRIDGE

The structure considered is a typical seismic isolated bridge isolated by an LRB that supports a tributary bridge superstructure and mounted on top of the bridge substructure (Figure 1). The mass of the tributary weight, W, acting on the isolation units in the present study is 300 t.

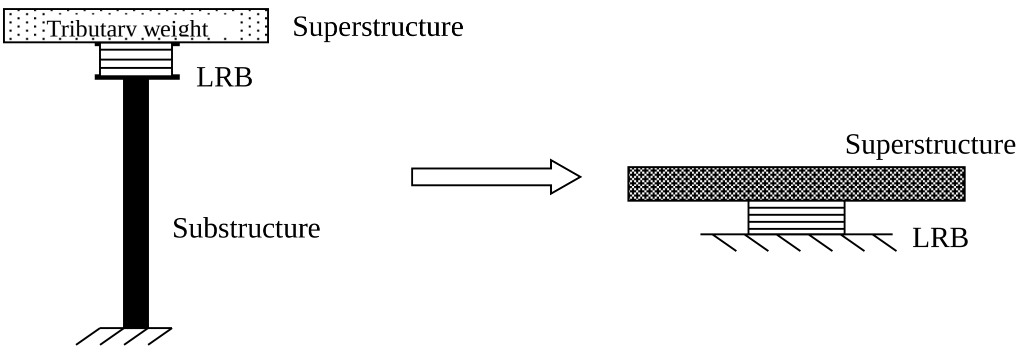

Figure 1. Idealization for seismic isolated bridge model.

In an attempt to focus solely on the response of isolators, the superstructure + LRB + substructure form is further simplified into a single-degree-of-freedom system in which the only nonlinearity takes place at the isolation level (Figure 1). Hence, the nonlinear response of the isolation unit can be tracked clearly.

3 HYSTERETIC BEHAVIORS OF LRBS USED IN ANALYSES

For LRBs, shape of the hysteresis loops used in bounding analyses is directly related to effective yield stress of the lead. In lower bound analysis, yield strength of an LRB is determined by considering the effective yield stress of lead which is the average of effective yield stresses of lead during the first three successive cycles of loading. On the other hand, the effective yield stress of lead used to calculate the yield strength of LRB for upper bound analysis is obtained by considering the very first cycle of loading.

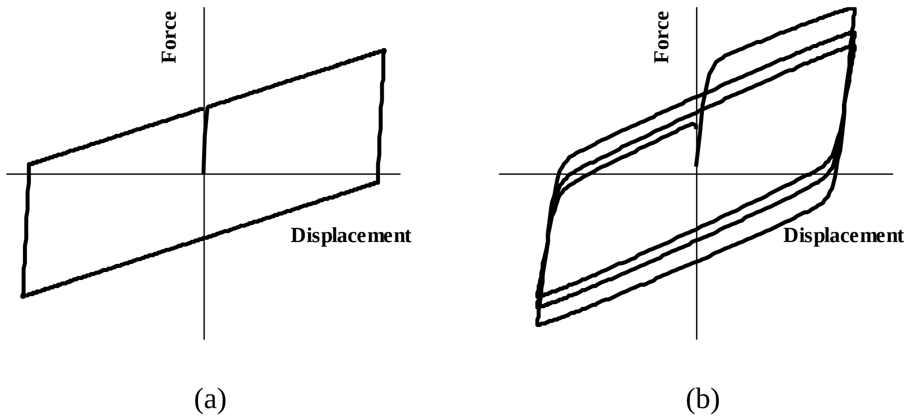

Figure 2. (a) Non-deteriorating and (b) deteriorating hysteretic force-deformation relationship for LRB.

In assessing the success of bounding analyses in fulfilling their intended purpose, which is to provide conservative estimates for MID, results of lower bound analyses are compared with the results of analyses where LRBs are modeled as deteriorating hysteretic systems. In this sense, two distinct representations are used to idealize hysteretic force-deformation relationship of LRBs. The first is a generic non-deteriorating hysteresis loop that does not take into account the effect of lead core heating (Fig. 2(a)), an effect that causes deteriorating strength in the element. The second representation is a deteriorating hysteresis loop in which the strength of the LRB degrades gradually as a function of the instantaneous lead core temperature (Fig. 2(b)). In this case, the initial strength of LRB is identical to the case where effective yield stress of lead is obtained in accordance with the upper bound characteristic. With the initiation of motion, the strength is updated at each time increment during the analyses according to the deteriorating model developed by Kalpakidis and Constantinou (2009a), which is described in the following section.

4 EFFECT OF LEAD CORE HEATING IN LRBS

Experiments conducted with LRBs have revealed that hysteretic force-deformation relationship of LRBs deteriorates when subjected to cyclic loading (Robinson, 1982). Recently, Kalpakidis and Constantinou (2009a,b) have focused on modeling deterioration in strength. They have developed a model that associates the reduction in the strength of the bearing to a reduction in the yield stress of lead core as a function of the temperature increment that occurs due to cyclic motion. According to the model, the relation between the yield strength of lead, σ_{YL} and the instantaneous temperature rise, T_L, is given by the following equation:

$$\sigma YL(TL) = \sigma YL0.\, e^{-E2TL} \quad (1)$$

here, σ_{YL0} is the initial yield strength of lead and equals to 13.5 MPa, E_2 is a constant that relates the temperature and yield stress, and equals 0.0069 (Kalpakidis and Constantinou, (2009a)).

5 CHARACTERISTICS OF THE LRBS USED IN THE ANALYSES

To achieve the objectives of the present study, a parametric investigation is conducted by considering not only the variation in ground motion characteristics but also the variation in isolator characteristics. Thus, the isolation period T is also considered as a parameter in NRHA. Accordingly, four different LRBs are designed so that the isolation periods are 2.25, 2.50, 2.75, and 3.0 s. Ratio of the characteristic strength, Q, (zero-displacement force-intercept in bilinear force-deformation relationship of LRB) to weight, W, acting on the isolators is taken as 0.12. Properties of the LRBs considered in this study are given in Table 1 where r is the radius of lead core, D is the bonded diameter of the bearing, F_{lower} is the yield strength of the non-deteriorating hysteretic representation, F_{heat} is the yield strength of the deteriorating hysteretic representation in which lead core heating effect is considered, and U is the design displacement capacity of the bearing. Properties of the LRBs in Table 1 are determined by performing an iterative procedure in accordance with the requirements for stability and strength.

Table 1 Properties of LRBs considered in this study

k (kN/m)	T (s)	F_{lower} (kN)	F_{heat} (kN)	U (mm)
Q/W=0.12; r = 106 mm; D = 1270 mm; Y = 25 mm				
2364	2.25	411.2	534.7	780
1891	2.50	400.3	523.9	882
1567	2.75	392.1	515.6	988
1315	3.00	385.9	509.4	1092

6 EMPLOYED GROUND MOTION RECORDS

All of the ground motion records used here were selected to be representative of near-field earthquakes for which the closest distance to the fault rupture (R) is less than 20 km (Somerville et al., 1997)). The corresponding moment magnitudes (M_w) of the selected records lie between 6.0 and 7.5. Figure 3 shows the variation of R versus M_w for the selected ground motions. In Figure 3, ground motions are grouped according to their peak ground velocity (PGV) values based on the results of Avsar and Ozdemir (2013). In that study, Avsar and Ozdemir (2013) investigated the efficiency of several ground motion intensity measures (IMs) to be used in estimating the response of SIBs. They investigated the suitability of IMs through their correlation with MID obtained from NRHA. Although Avsar and Ozdemir (2013) proposed new IMs that have better correlation with MID compared to commonly used IMs, correlations of these proposed IMs depend on isolator characteristics (it becomes poorer with increasing isolation period). On the other hand, they found that PGV, which has the second best correlation with MIDs, is not sensitive to any change in isolator characteristics. To avoid any inconsistency in the discussions presented in the following sections due to change in isolation period, three ground motion groups are defined according to PGV ranges: 30cm/s<PGV<50cm/s, 50cm/s<PGV<70cm/s, and PGV>70cm/s. Each ground motion group consists of 20 near field records (10 records for soil class B and 10 records for soil class C).

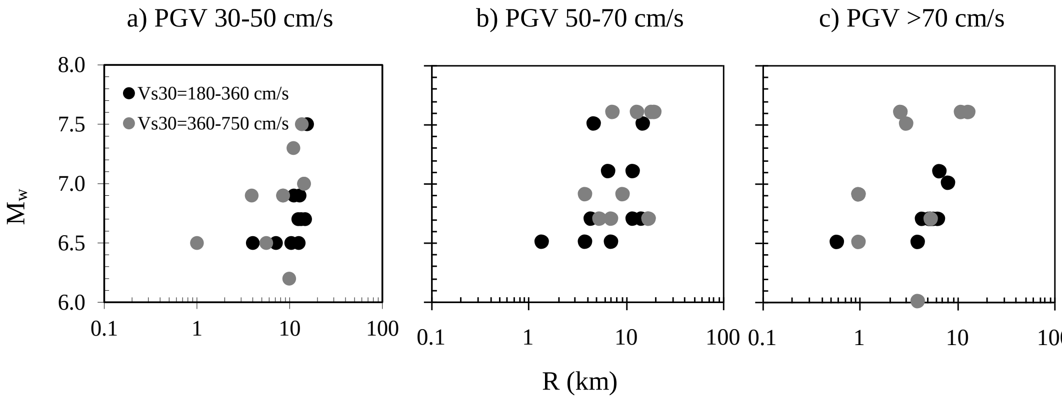

Figure 3. Closest distance to fault rupture (R) versus magnitude (M_w) for selected ground motions as a function of both site classification and PGV.

7 ANALYSES RESULTS

In this section, the validity of lower bound analysis performed during the design of LRBs in estimating conservative isolator displacements is tested under increasing scale factors (from 1.0 to 4.0 at intervals of 0.5). For this purpose, MIDs obtained from bounding analysis (MID_{Low}) are normalized by those obtained from analyses in which lead core heating is of concern (MID_{Heat}). In the comparisons, for values of MID_{Low}/MID_{Heat} ratios greater than or equal to 1.0, bounding analysis is conservative. It is recalled that MID is defined as the maximum absolute displacement of the isolator. The variation of MID_{Low}/MID_{Heat} ratios with increasing scale factor for each ground motion under consideration are presented in Figure 4 for different PGV values and isolation periods. In Figure 4, mean of the all data is presented by indicating maximum and minimum values for MID_{Low}/MID_{Heat} ratios without any distinction between representative soil properties of the ground motion records.

The data given in Figure 4 is limited to cases where the MIDs from NRHA are less than the design displacements of the considered LRBs (see Table 1) so that “realistic” outputs are obtained. If the number of “realistic” results is less than 10 (out of 20) for any group of analyses, the data in that group was excluded from discussions for the purpose of working with mean values. This is why there is no data for some of the scale factors in Figure 4 (i.e. for scale factors greater than 2.0 when 70<PGV and T=2.25s.).

Based on the mean values presented in Figure 4, it can be said that the general tendency for MID_{Low}/MID_{Heat} ratios is to decrease with increasing PGV values for all of the isolation periods under consideration. This is especially more pronounced for the data that corresponds to ground motions with PGV values greater than 70 cm/s. For instance, when scale factor is 1.0 and isolation period T is equal to 2.75 s., the mean of MID_{Low}/MID_{Heat} ratios are 1.28, 1.18, and 1.14 for PGV values of 30<PGV<50, 50<PGV<70, and PGV>70, respectively. However, these values are obtained as 1.05 and 1.02 for ground motions with 30<PGV<50, and 50<PGV<70 when scale factor is 4.0. For ground motions having PGV values greater than 70cm/s, there is not enough data to be able to discuss in terms of mean values when scale factor is 4.0. Corresponding data indicates that success of bounding analysis in providing conservative estimates for MIDs depends highly on the PGV value of the accelerogram and decreases with increasing scale factor.

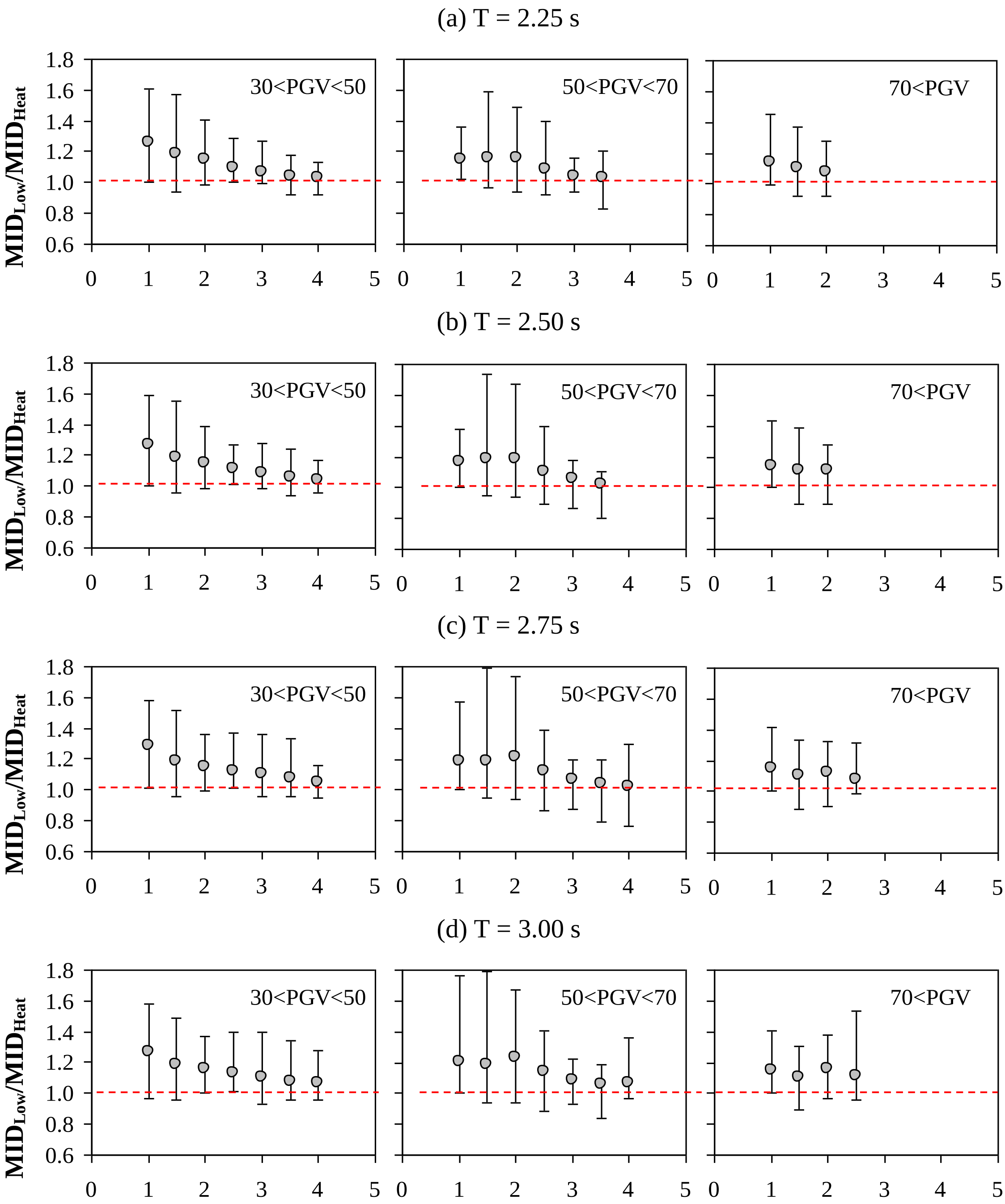

Figure 4. Variations of mean MID_{Low}/MID_{Heat} ratios for different PGV values and isolation periods.

Figure 4 also allows discussion of the effect of isolation period on the variation of MID_{Low}/MID_{Heat} ratio due to change in scale factor. Based on the mean values presented in Figure 4, it is evident that the variations in MID_{Low}/MID_{Heat} ratios for the considered isolation periods are very similar to each other. For instance, for ground motions with PGV values ranging from 30 cm/s to 50 cm/s, the mean values for MID_{Low}/MID_{Heat} ratios are almost identical for all isolation periods under consideration and equal to 1.27 when the scale factor is 1.0. Then, as the magnitude of scale factor increases the corresponding MID_{Low}/MID_{Heat} ratios decreases in very similar trends for all isolation periods within a very narrow band. This observation is also valid for the cases where PGVs are in between 50cm/s and 70cm/s or greater than 70cm/s and the band with for MID_{Low}/MID_{Heat} ratios is not more than 0.05. This indicates that effect of isolation period on variation of MID_{Low}/MID_{Heat} ratio as a function of the scale factor is negligible.

8 PROPOSED LIMITS FOR SCALE FACTORS

Based on the results presented, it is evident that there is a need to define a limitation for scale factors to be used in dynamic analyses of LRB isolated structures. In order to determine the parameters that should be considered in the process of stating the limitations for scale factors, effects of PGV, isolation period, and soil characteristics of the ground motions were investigated thoroughly. Comparative discussions of results that corresponds to cases where lead core heating effect is considered, with those of bounding analyses showed that the effect of isolation period is so small that it can be negligible and not considered in the proposed relations. The same comparisons done for the effect of soil characteristics of ground motions revealed that although there is differentiation in the safety level of bounding analyses in providing conservative estimations for MIDs due to soil classification, the general tendency for MID_{Low}/MID_{Heat} ratios are very similar. Thus, soil classification was also not considered as a parameter in the proposed relations. As a result, the proposed limits for scale factors are based only on the PGV values of the ground motions and given as follows:

$$\begin{aligned} &ScaleFactor \le 4 \quad when \quad 30cm/s < PGV < 50cm/s \\ &ScaleFactor \le 3 \quad when \quad 50cm/s < PGV < 70cm/s \\ &ScaleFactor \le 2 \quad when \quad 70cm/s < PGV \end{aligned}$$

9 CONCLUSIONS

In this study, the scaling of acceleration time series to be used in dynamic analysis of structures isolated with lead rubber bearings (LRBs) was studied to obtain a limit for scale factors. For this purpose, several uni-directional NRHA were conducted with the parameters namely, isolation period and peak ground velocity (PGV) of the ground motions. In the analyses, a recently proposed deteriorating hysteretic bilinear representation is used to model the behavior of LRBs where lead core heating effects can be adopted accordingly. Discussions for limitation of scale factors were done through the concept of bounding analyses that intends to provide design envelopes for response quantities of isolated structures. Maximum isolator displacement (MID) was the considered response quantity for the investigated idealized seismic isolated system. The validity of bounding analyses in terms of MIDs was investigated as a function of the scale factor. Evaluation of results obtained from bounding analyses is conducted by considering MID_{Low}/MID_{Heat} ratios for various scale factors and isolation periods. Here, MID_{Low} represents the MID obtained from lower bound analysis whereas MID_{Heat} stands for the MIDs when lead core heating is considered. Selected ground motions are clustered in three distinct groups according to their peak ground velocities. As a result, based on the findings of this study, upper limits for scale factors to be used in dynamic analysis of LRB isolated structures are proposed.

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