

Displacement Estimates in Isolated Bridge Structures

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Summary

The AASHTO equation for calculating displacements in seismically isolated bridges is based on the work of Kelly at UC Berkeley in the 1980s, whose focus was building structures. The equation assumes linearly increasing displacements in the constant-velocity region of the design spectrum and accounts for the effects of energy dissipation (hysteretic or viscous) by using properties of the equivalent viscoelastic system. The seismic input is assumed unidirectional for the AASHTO calculation. Recent work done under the direction of Whittaker while at UC Berkeley indicates that simultaneous seismic excitation along each horizontal axis of a bridge can substantially increase the maximum isolator displacement over that calculated assuming unidirectional excitation, especially if the isolators are (correctly) modeled using coupled plasticity or Bouc-Wen models.

Introduction

The objective of this research is to revise the AASHTO equation for displacements in seismically isolated bridges (AASHTO 1999, Section 7, Equation 3a) to account for bi-directional seismic input and for improved estimates of damping displacement-reduction factor B as proposed by Ramirez et al., (2000).

Five bins of earthquake ground motions have been selected and organized to perform linear and nonlinear response-history analysis. The mean spectrum for each of the bins matches well the assumed shape of the AASHTO design spectrum for isolated bridges. Results of analyses performed using binned ground motions, on average, will be assumed to represent well the response of an isolated bridge structure subjected to earthquake excitation.

The assumption of linearly increasing displacements in the constant-velocity region of the design spectrum is addressed. A relationship that better estimates unidirectional displacement demands based on the 5% damped, 1.0 sec spectral displacement is proposed.

Currently, recommendations to better estimate displacements in linear and nonlinear systems subjected to simultaneous bi-directional excitation based on unidirectional excitation are being developed. Likely, the result of this work will be a coefficient in the form of a unidirectional displacement multiplier. This multiplier is likely to be a function of magnitude, distance to fault, as well as of isolator properties. Preliminary results of linear and nonlinear response-history analyses are presented herein.

Ground Motion Components

A total of 52 recorded earthquake ground motions were utilized for this study. Ground motions have been organized into five bins based on magnitude and distance to fault. Earthquake time histories were extracted from two sources: the Pacific Earthquake Engineering Research (PEER) database (<http://peer.berkeley.edu/smcat/>) and the SAC steel project database (http://quiver.eerc.berkeley.edu:8080/studies/system/ground_motions.html).

Ground motions have been grouped into 5 bins based on magnitude and distance to fault: (1) Near-Field, (2) Large Magnitude Small Distance, (3) Large Magnitude Large Distance, (4) Small Magnitude Small Distance, and (5) Small Magnitude Large Distance (Krawinkler 2001). Each bin contains 20 acceleration time histories corresponding to 10 earthquake events with the exception of Bin 1, which contains 24 acceleration time histories. Each earthquake event consists of two perpendicular horizontal components. Table 1 is a summary of the ground motions bins and ground motion information including event magnitude and distance to fault.

Table 1. Ground motion bins

Bin	Name	Event Magnitude	Distance to Fault (km)	Soil Type	Soil Classification
1	NF	6.7 – 7.4	< 10	D	NEHRP
2	LMSR	6.7 – 7.3	10 – 30	A,C	USGS
3	LMLR	6.7 – 7.3	30 – 60	A,C	USGS
4	SMSR	5.8 – 6.5	10 – 30	A,C	USGS
5	SMLR	5.8 – 6.5	30 – 60	A,C	USGS

Elastic Response Spectrum

Binned ground motions used in this study produce, on average, a response spectrum that matches well the assumed shape of the AASHTO design spectrum. Short period mean spectral accelerations range from 1.0 g for near-field (Bin 1) to 0.2 g for small-magnitude, small-distance (Bin 5). This range of spectral demand is representative of seismic hazard levels throughout the United States.

Mean and mean $\pm 1\sigma$ (σ = sample standard deviation assuming a normal distribution) spectral information has been generated for all five bins. Figure 1 shows acceleration response spectra for all ground motion components in Bin 2 as well as the mean spectrum (shown by the heavy black line). Bin 2 spectra have been plotted to show scatter about the mean. Information for the remaining bins is not presented for brevity. Results of analyses performed using binned ground motions, on average, will be assumed to represent well the response of an isolated bridge structure subjected to earthquake excitation.

Spectral Displacements

The equation for calculating design displacements in isolated bridge structures is given by Equation 3a of the *Guide Specification for Seismic Isolation Design* (AASHTO 1999). This equation assumes linearly increasing displacements in the constant-velocity region of the design spectrum.

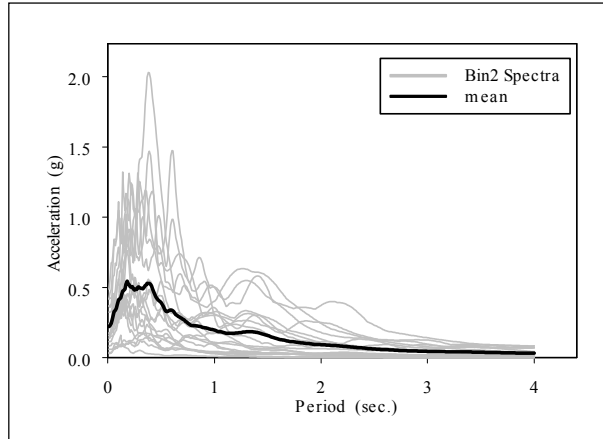


Figure 1. Acceleration response spectra for Bin 2 ground motions

Displacements obtained using the AASHTO formula, although conservative, tend to be inaccurate and significantly overestimate displacement demands. A relationship is proposed to better estimate the displacement demand in the constant-velocity region of the design spectrum based on the 5% damped, 1.0 sec displacement. The proposed relationship is given by:

$$d(T) = d(T = 1.0) T^\alpha \quad (1)$$

where $d(T)$ is the displacement demand for the period of interest, $d(T = 1.0)$ is the 5% damped, 1.0 sec displacement, T is the period of interest and α is an exponent of the period, which is less than or equal to unity for all bins. Regression analysis was performed on the constant-velocity portion of the mean acceleration spectrum for each of the five bins to determine the value of the exponent α . Results of the regression analysis confirm Equation 3a to be conservative. Values of α ranged from 0.75 for near-field to 0.08 for small-magnitude, small-distance. Note that smaller values of α represent larger deviation (smaller demand) from those obtained assuming linearly increasing displacement. Shown below in Figure 2 are results of regression analysis performed on Bin 2. The dashed line represents a value of $\alpha = 1.0$ (i.e., linearly increasing displacements), which corresponds to the displacements obtained using Equation 3a with 5% damping. The solid line represents displacements that would be obtained using the relationship presented in Eq. 1 above with $\alpha = 0.74$.

Linear Response-History Analysis

Response-history analysis of linear systems with 5% damping was undertaken utilizing horizontal ground motion pairs from the five bins mentioned previously. Displacements in each of the two horizontal orthogonal directions were combined using linear superposition theory to determine the maximum horizontal displacement. Maximum horizontal displacements were then statistically sorted to determine, on average, the increase in displacement due to consideration of bi-directional excitation for a linear system. Currently, regression analysis is being utilized to determine a coefficient that will serve as a multiplier to calculated unidirectional displacement to account for bi-directional earthquake loading for linear systems. This multiplier is expected to be a function of earthquake magnitude, distance and natural period of the linear system.

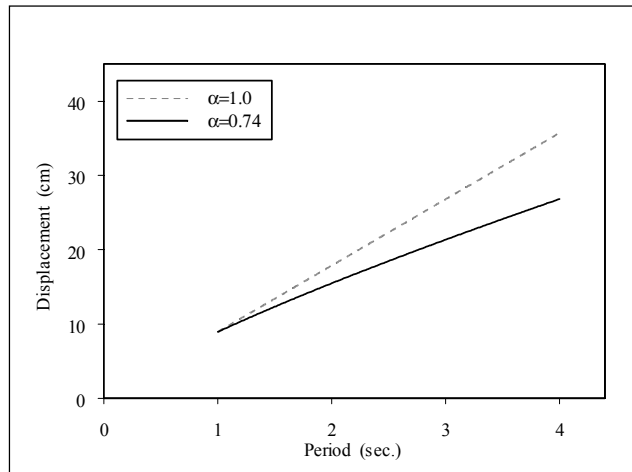


Figure 2. Design displacements for 5% critical damping based on Bin 2 mean spectrum

Preliminary results of the response history data suggest that consideration of simultaneous bi-direction excitation results in horizontal displacements that are significantly larger than those obtained from unidirectional considerations only. For example, preliminary analysis of data suggests a unidirectional multiplier of approximately 1.4 for Bin 2 (LMSR) assuming a constant linear best fit. Although results are preliminary, a multiplier of 1.4 suggest that bi-directional excitation has a significant effect on the maximum displacement.

Nonlinear Response-History Analysis

Nonlinear response-history analysis was performed using a mathematical model of an isolated bridge structure. Response-history analysis was performed for each of the ground motion pairs mentioned previously. Properties for the bridge model (i.e., mass, length, width) are based on a single span of a multi-span bridge that was proposed in an Applied Technology Council report (ATC 1981). Isolator parameters (i.e., normalized characteristic strength and second slope period) were varied to ensure broad applicability of results for isolated bridges in the United States. Four values of the characteristic strength Q_d/W (normalized by the weight acting on the isolator) were chosen and range from 0.03 to 0.12. Similarly, five values of the second slope period, T_d , were chosen and range from 1.5 sec to 4.0 sec resulting in 20 combinations of isolation parameters.

A Matlab model of a rigid superstructure supported by four seismic isolators was used to study the response of the isolation system subjected to unidirectional and bi-directional seismic input (Mosqueda 2001). This model represents the simplest of isolation systems so that a clear understanding of the response of the isolators subjected to bi-directional excitation is possible. The isolators were explicitly modeled using a rate-independent coupled plasticity model also implemented in Matlab (Huang 2000).

Shown in Figure 3 are some preliminary results of the nonlinear response history analysis for unidirectional and bi-directional excitation with isolator parameters $Q_d/W = 0.09$ and $T_d = 4.0$ sec. The ground motions used for the analyses shown in Figure 3 are from the Northridge earthquake, Canoga Park station. These ground motions were extracted from PEER's database and have been included in Bin2. Two important results of bi-directional excitation are shown in Figure 3. The first

one is the effect on unidirectional isolator properties (i.e., Q_d) and the second one is the increase in displacement along the x-direction horizontal axis. Due to the coupled behavior of the isolator, the contribution of yield force along the x-direction horizontal axis varies (always less than or equal to the unidirectional yield force) corresponding to the phasing of the horizontal ground motion in the perpendicular direction. The result of the bi-directional analysis is shown below by the solid black line. The result of this reduction in yield force along a single axis is an increase in isolator displacement along that axis.

Although the results shown in Figure 3 are preliminary, they suggest that bi-directional loading has a significant effect on maximum isolator displacement. Currently, nonlinear response history analysis is being performed for the remaining bins of ground motions. Likely, a displacement multiplier will be proposed to account for this increase in displacement due to bi-directional excitation in yielding systems. This multiplier is expected to be a function of earthquake magnitude, distance to fault and isolator parameters, namely, Q_d and T_d .

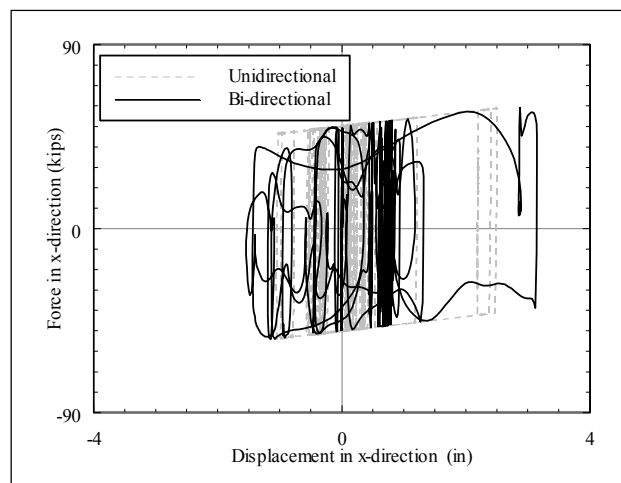


Figure 3. Results of nonlinear response-history analysis for unidirectional and bi-directional excitation

Concluding Remarks

Although this research is still in progress, preliminary results are in agreement with its objectives. The assumption of linearly increasing displacement in the constant-velocity region of the design spectrum is conservative, however, displacement demand is significantly overestimated. Both linear and nonlinear response history analysis indicate that bi-directional earthquake excitation significantly increases maximum horizontal isolator displacements. Finally, recommendations to improve the AASHTO equation for displacements in seismically isolated bridges to account for bi-directional excitation will be presented upon completion of this research.

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