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AN EVALUATION OF BI-DIRECTIONAL EARTHQUAKE SHAKING ON THE PROVISIONS OF THE AASHTO GUIDE SPECIFICATIONS FOR SEISMIC ISOLATION DESIGN

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SUMMARY

The *AASHTO Guide Specifications for Seismic Isolation Design (a.k.a., Guide Spec)* contain simplified procedures for estimating the displacement and force demand imposed on a bridge designed to be seismically isolated. The *Uniform Load Method* in this document is a linearized method for estimating uni-directional displacement response for purposes of design. It is understood that real ground motion time histories represent bi-directional shaking along two orthogonal axes at a given site. The *Guide Spec* stipulates that peak bi-directional force demand may be estimated by combining uni-directional maxima in a combination of 100 to 30% (or visa-versa). These procedures were established from the evaluation of elastic systems, and therefore may not adequately capture the nonlinear complexities of the bi-directional response of isolated bridges. Due to these underlying difficulties with current code procedures, a systematic evaluation of the effects of directivity and bi-directional input on the response of seismically isolated bridge systems was undertaken. It is evident from these results that the effect of bi-directional input on seismically isolated bridge systems is significant. It was found for all cases considered that on average peak displacement response due to bi-directional input is considerably larger than peak response due to uni-directional input applied separately. Further, current *Guide Spec* procedures due not adequately account for this coupling effect. This disparity is most significant for more rigid structures, employing stronger isolation systems, subjected to larger magnitude earthquakes, nearer the active fault. For these cases, softer site specific soils tend to increase the bi-directional effect. Coefficients to account for the effect of bi-directional input on systems designed by the *Guide Spec* procedures are suggested.

INTRODUCTION

Background

The AASHTO *Uniform Load Method* is a linearized procedure for estimating the mean peak displacement response of seismically isolated bridge systems subjected to earthquake motions compatible with a design spectrum (see Equation 5). The AASHTO design spectrum represents a uniform earthquake hazard defined by those events having a probability of exceedence of 10% in 50 years in areas defined regionally across the nation. The AASHTO pseudo-acceleration spectrum has a constant plateau in the acceleration sensitive “short period” region followed by a downward trending leg which varies proportionally to $1/T$, characteristic of the constant velocity region of the spectrum.

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It is understood that real ground motions are characterized by three-dimensional earth shaking. This may be represented by bi-directional shaking along two orthogonal axes in the horizontal plane of the earth plus a third component representing vertical motion. The AASHTO design spectrum is intended to represent the mean uniform hazard of all spectrum compatible ground motion records, taken from bi-directional time-history pairs, and therefore represents random or "average" uni-directional directivity with regard to any given site specific ground motion. Neglecting the effects of the vertical component as a simplification, this paper focuses on the difficulty posed in accounting for the effects of bi-directional input using a spectrum representing random uni-directional directivity. Two distinct difficulties are posed by this approach.

First of all, it has been illustrated that the difference between the mean spectrum representing fault normal or the "larger" orthogonal component of bi-directional ground motion history pairs and the mean spectrum of all ground motion history pairs (representing "average" directivity) increases with earthquake magnitude and for sites located more closely to the active fault (Somerville [7], see Figure 6). Consequently, it follows that design displacement estimates based upon a spectrum representing random directivity would underestimate mean displacement demands represented by the mean spectrum of the "larger" (fault normal) orthogonal component of the earthquake record. This underestimation would be most severe for larger magnitude earthquakes and sites located near fault.

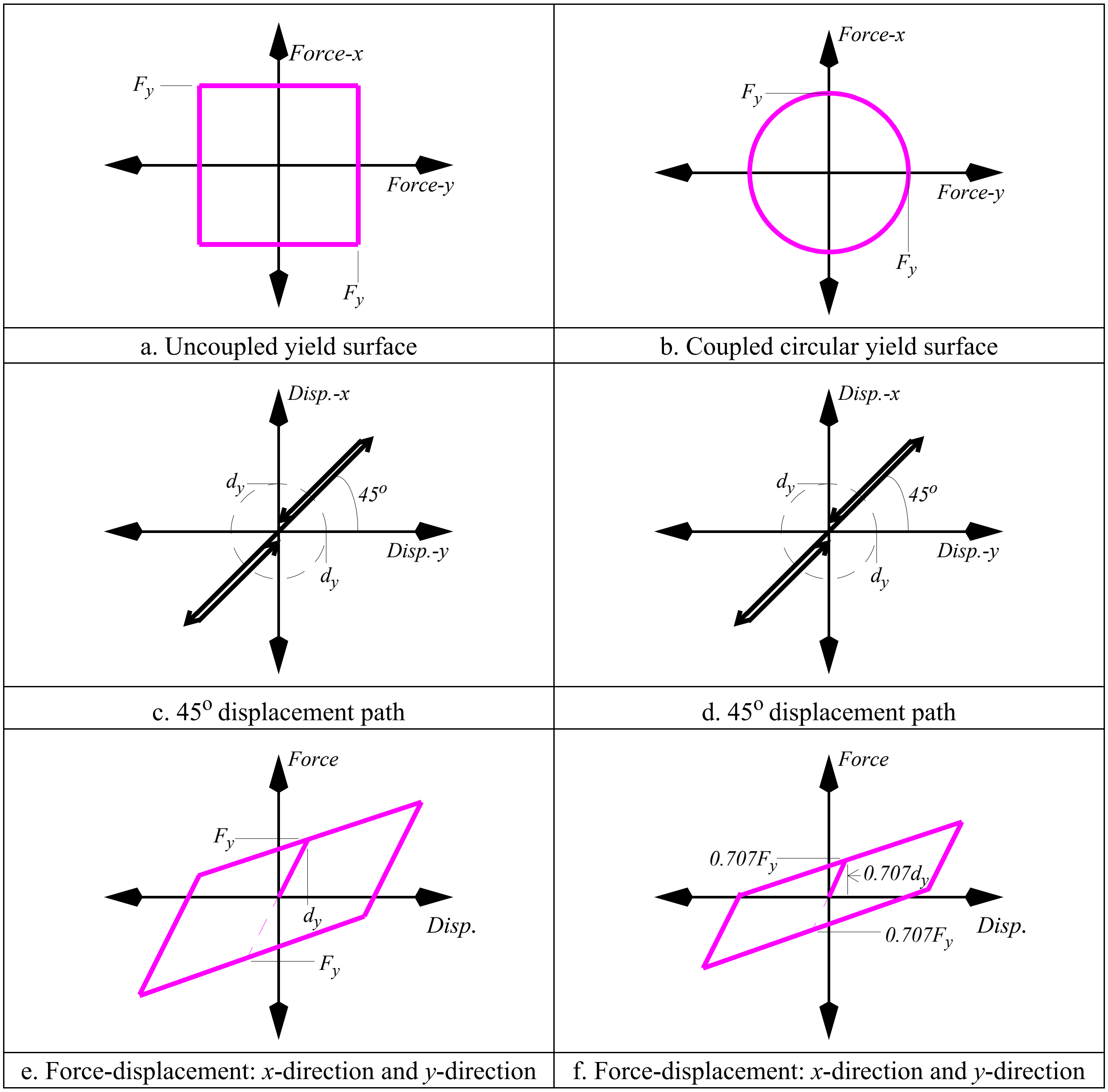
Secondly, it is not apparent that the peak response of a seismically isolated bridge system subjected to bi-directional input can be estimated with reasonable accuracy from the response of the same system subjected to each of the bi-directional components applied uni-directionally. The reason for this is twofold. Firstly, phasing within each of the ground motion components may dictate bi-directional response with peaks occurring more or less simultaneously producing a maximum vectored displacement much larger than either of the uni-directional maxima. Secondly, coupling which occurs in the bi-directional yield surface of typical seismic isolation systems causes a reduction in resisting force orthogonal to the direction of initial displacement (assuming it is larger than the yield displacement). Figure 1 compares the force-displacement response of two isolation systems with and without coupling for the same bi-directional displacement path. This coupling effect would presumably cause increases in displacement demand for systems subjected to bi-directional motions, since displacement along one axes will reduce the isolation system's resistance to motion in the orthogonal direction (compare uncoupled and coupled force-displacement response, Figure 1 (e) and (f), respectively).

Current code procedures provide a method of estimating peak bi-directional force demand in isolated bridges by combining uni-directional maxima in a combination of 100 to 30% (or conversely 30 to 100%) (AASHTO [2]). However, these procedures were established from the evaluation of elastic systems (Park [5]), and therefore may not adequately capture the nonlinear complexities of bi-directional response.

Due to these underlying difficulties with current code procedures, a systematic evaluation of the effects of directivity and bi-directional input on the response of seismically isolated bridge systems was undertaken in these studies. The results of this evaluation are useful in establishing the efficacy of current code design procedures to account for these effects.

Isolated Bridge Systems

Isolated bridge systems with symmetric configurations of isolation bearing and substructure components were considered for this study (see Figure 2). Deck flexibility was assumed to be rigid. Longitudinal and transverse bridge axes were the *x*- and *y*-axis for purposes of modeling. 5% of the total mass was assumed as lumped at the substructure degree-of-freedom. A damping ratio of 5% was assumed for substructure components considering to total mass to be comprised of the deck and effective substructure mass



a. Uncoupled yield surface

b. Coupled circular yield surface

c. 45^o displacement path

d. 45^o displacement path

e. Force-displacement: *x*-direction and *y*-direction

f. Force-displacement: *x*-direction and *y*-direction

Figure 1 Bi-directional coupling in isolation bearing force-deformation response

oscillating at the non-isolated frequency of the bridge. System properties were defined as prescribed in AASHTO provisions as shown in Figure 5. For the range of isolated bridge system properties considered in this study, see Table 1. Isolation systems were considered rigid-plastic in all cases.

Modeling

Parametric analysis of these bridge configurations was performed utilizing a generalized multi-degree-of-freedom, bi-directional bridge model with dynamic degrees-of-freedom representing deck and substructure displacements in the *x*- and *y*-plane (see Figure 4). Isolation bearings were modeled as rigid-plastic using a bilinear coupled plasticity model with circular yield surface (see Figure 1 (b)). System degrees-of-freedom were reduced utilizing symmetry to four, two along each of the *x*- and *y*- axes of the deck and substructure

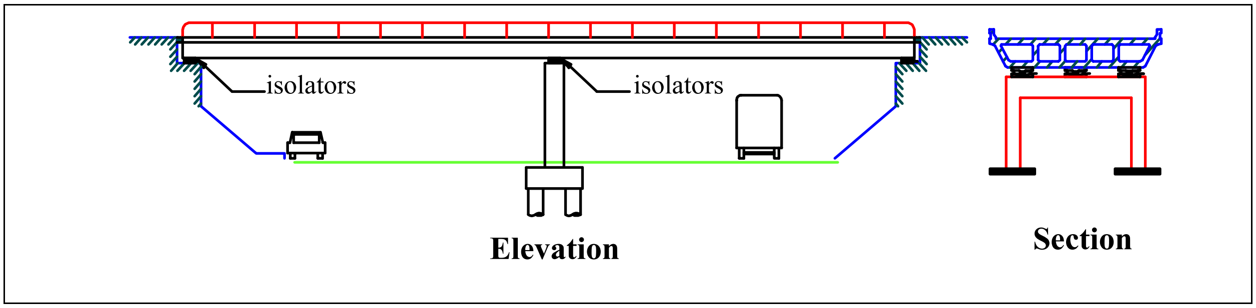


Figure 2 Typical elevation and section for symmetric isolated bridge system

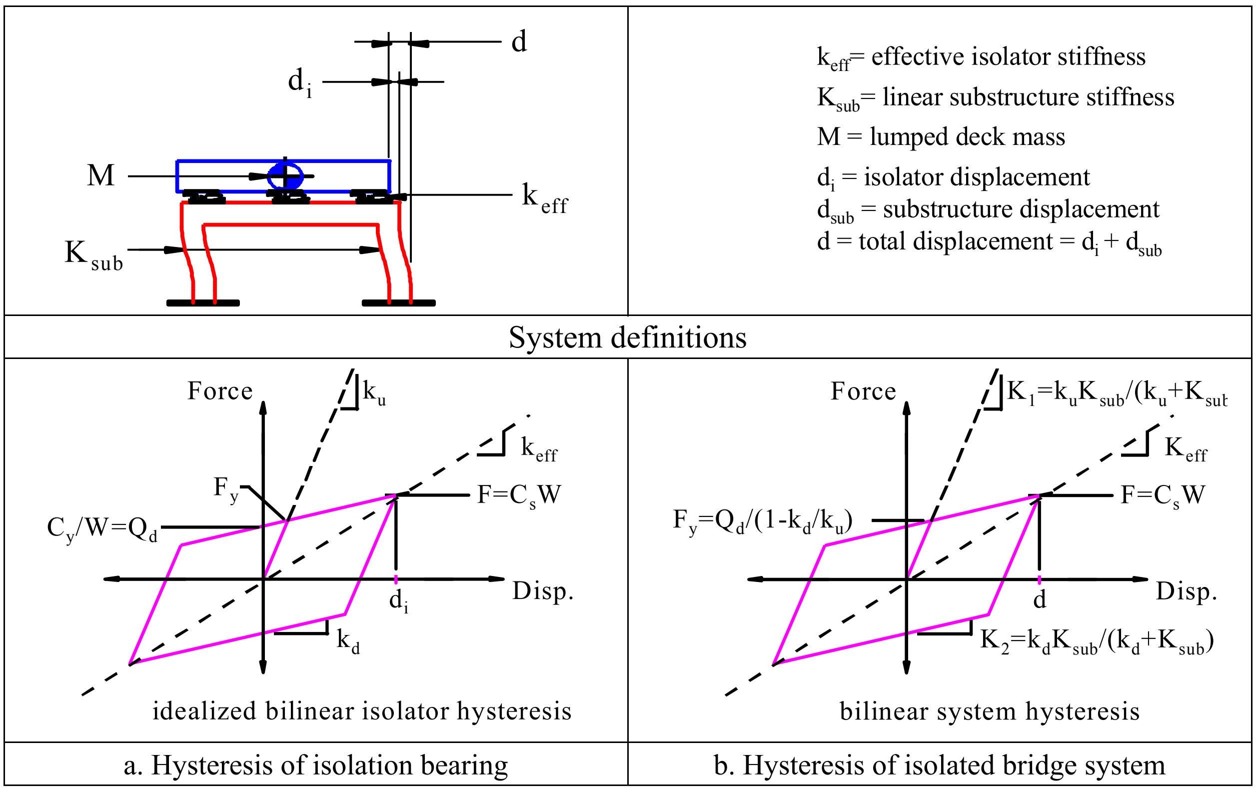


Figure 3 AASHTO structural idealization of an isolated bridge

component, respectively. Time-history analysis was performed utilizing standard numerical procedures (Newmark [3]).

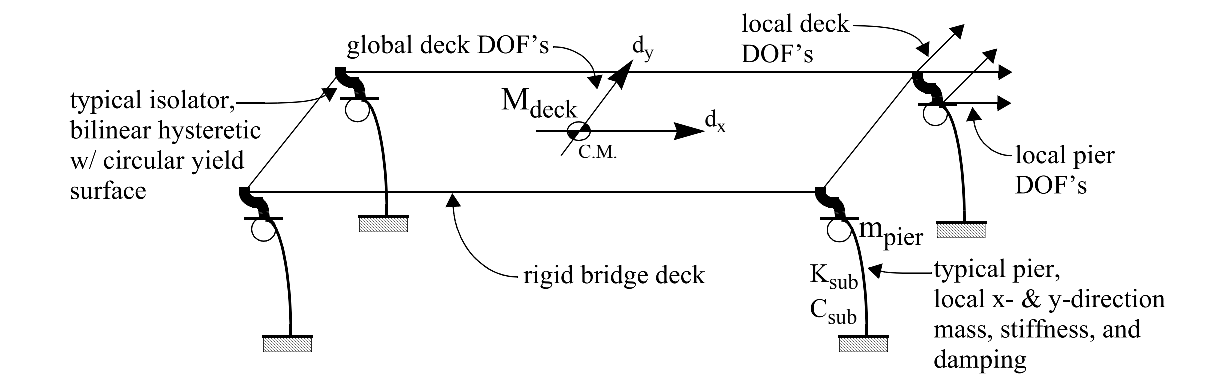
Ground motion time-history suites

The evaluation was performed using fifty bi-directional pairs of ground motion time-history records (*x*-and *y*-direction orthogonal components), entitled Suite A. These one-hundred motions were classified into five bins of twenty motions each (i.e., ten pairs per bin) grouped by magnitude, distance to active fault, and soil type, outlined in Table 2 below. Bin 1 motions were selected from the ground motion database developed for the SAC Joint Venture project (SAC [6]). Bin 2 through 5 motions were selected from the PEER Strong Motion Database (PEER [4]).

Figure 5 (a) and (b) show the mean psuedo-acceleration spectrum computed for the set of twenty histories for each of the Bin 1 and 2 ground motion suites, respectively (for a damping ratio of 5%). Maxima,

Table 1 Range of isolated bridge system properties

Parameter	*Definition*[1]	*Range*
T_{sub} (sec)	$T_{sub} = 2\pi\sqrt{\frac{M}{K_{sub}}}$	0.05, 0.5, 1.0, 1.5, 2.0
Cy_{iso}	$Cy_{iso} = \frac{Fy}{Mg}$	.03, .06, .09, .12
T_{iso} (sec)	$T_{iso} = 2\pi\sqrt{\frac{M}{k_d}}$	2, 3, 4, 5
1. See Figure 3 above for definition of standard parameters		



c. MDOF bi-directional bridge model

Figure 4 Idealized analytical bridge model

minima, and $\pm 1\sigma$ statistics are shown to illustrate the distribution in the sets of ground motion data. Also shown is a comparison of the mean psuedo-acceleration spectra of the five bi-directional bin motions to the spectral shape represented by the AASHTO design spectrum for three selected values of A and S_i (see Figure 5 (c)). Note the increase in average amplitude and preponderance of long period content for motions of increasing magnitude and/or decreasing distance to the active fault. It is also seen in this figure that the mean spectra represented by the Bin 1 through 5 motions fit well to the AASHTO spectral shape, particularly on the descending branch, or velocity sensitive region. This similarity is important. The design procedures contained in the AASHTO *Guide Specifications* are intended to produce an estimate of the mean response of systems to motions compatible with this spectral shape (i.e., motions which represent the design basis hazard level and "match" the spectrum closely on average). In this respect, it follows that mean response characteristics computed for isolated bridge systems subjected to each of these motion bins may be interpreted to apply generally to the *Guide Spec* procedures.

Figure 6 shows a comparison, for the Bin 1 and Bin 2 records of this suite, of the mean pseudo-acceleration spectrum computed for the first *(x*-direction) and second (*y*-direction) component histories in the bin to that computed for all ground motion histories in the same bin. Figure 6 (a) shows these results for the Bin 1 near-fault motions, where the first- and second- component histories represent fault-normal and fault-parallel components, respectively. For this plot the effect of directivity on the spectra is readily apparent. The difference between the "larger", or fault normal, component and the mean spectrum representing "average" directivity is very pronounced, consistent with trends for near-fault motions presented by

Somerville [7]. Analyses performed utilizing the Bin 1 motions may therefore be interpreted as accounting explicitly for the effect of fault directivity. This same comparison is shown in Figure 3 (b) for Bin 2 motions. For this bin, ground motion pairs are oriented with random directivity, and the difference between the mean spectra of the first- and second- orthogonal component and the mean spectrum of all motions in the bin is nearly negligible, as expected. This trend was similar for Bin 3 through Bin 5 motions. For these motions, results will be interpreted to apply generally to the spectrum representing "average" or random directivity only.

Table 2 Ground motion bin classification for Suite A

BIN	*Name*	*Magnitude*	*R(km)*	*Soil Type*	*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

Analytical Procedure

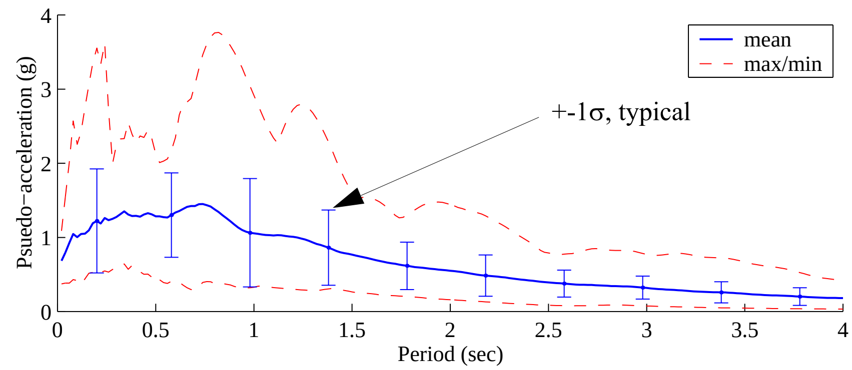
Bi-directional analyses of simple isolated bridge systems were performed utilizing each pair of ground motion histories in Suite A and utilizing each orthogonal uni-directional component separately. For each time-history analysis peak displacement response was determined, where D_{xy}, D_x, and D_y represent the peak displacement response from the bi-directional, first-component, and second-component analysis for each ground motion pair, respectively. Statistical variation in the ratios D_{xy}/D_x, D_{xy}/D_y, and $D_{xy}/\mathrm{mean}(D_x,D_y)$, and the coefficient C_{xy} for each bin of ground motion records were also computed to evaluate the effect of bi-directional input on response. Results for the ratios D_{xy}/D_x and D_{xy}/D_y represent the increase in maximum displacement due to bi-directional input over the peak response due to the uni-directional inputs applied separately. Results for the ratio $D_{xy}/\mathrm{mean}(D_x,D_y)$ represent the increase in maximum displacement due to bi-directional input over the average response due to the uni-directional inputs applied separately. Mean values of these ratios provide a measure of the effect of the bi-directional input on system response.

The coefficient, C_{xy}, was computed as follows,

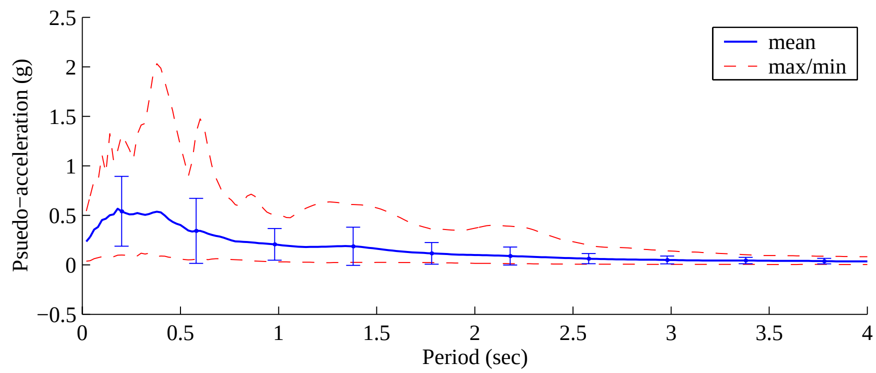
$$C_{xy} = \frac{\left(\sum_i D_{xy}^i\right)/N}{\left(\sum D_x^i + \sum D_y^i\right)/(2N)} = \left(2\sum_i D_{xy}^i\right)\Big/\left(\sum_i D_x^i + \sum_i D_y^i\right) \tag{1}$$

where the bi-directional peak response D_{xy} and uni-directional responses D_x and D_y for each ground motion record pair is denoted by the index i, and all summations are computed over the range $(1,N)$, where N is the number of ground motion pairs in the bin. First, define D as the average peak response due to uni-directional inputs for a suite of records representing N ground motion pairs, where

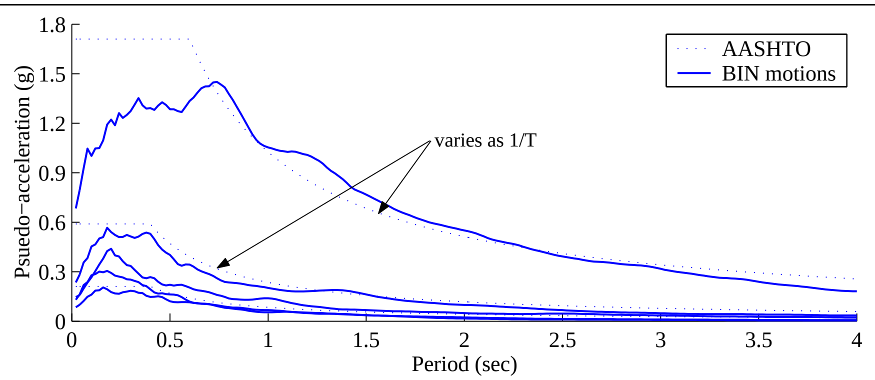
$$D = \left(\sum_i D_x^i + \sum_i D_y^i\right)/2N \tag{2}$$



a. Bin 1 - NF



b. Bin 2- LMSR



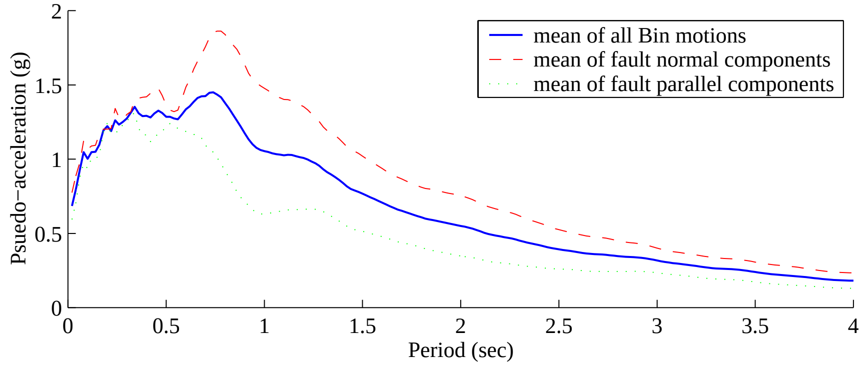
c. Mean spectra vs. AASHTO spectral shape

Figure 5 Mean psuedo-acceleration spectra: Suite A, 5% damping

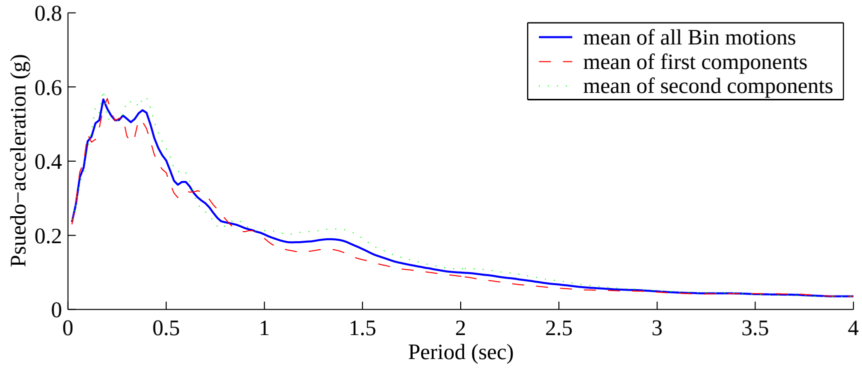
with indices and the range of summations defined as before. Second, define D_{bi} as the average peak response due to bi-directional inputs for the same suite of records, where

$$D_{bi} = \left(\sum_{i} D_{xy}^{i} \right) / N \tag{3}$$

with indices and the range of summations as previously defined. The coefficient C_{xy} is then redefined as follows



a. Bin 1 - NF



b. Bin 2- LMSR

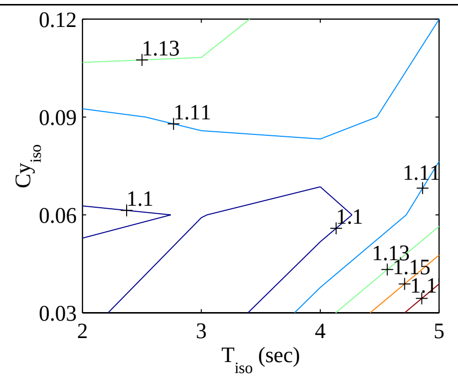
Figure 6 Mean psuedo-acceleration spectrum of Suite A ground motion bins vs. mean spectrum of first (x-direction) and second (y-direction) component histories, 5% damping

$$C_{xy} = \frac{\left(\sum_i D^i_{xy}\right)/N}{\left(\sum D^i_x + \sum D^i_y\right)/(2N)} = \frac{D_{bi}}{D} \Rightarrow D_{bi} = C_{xy} D \tag{4}$$

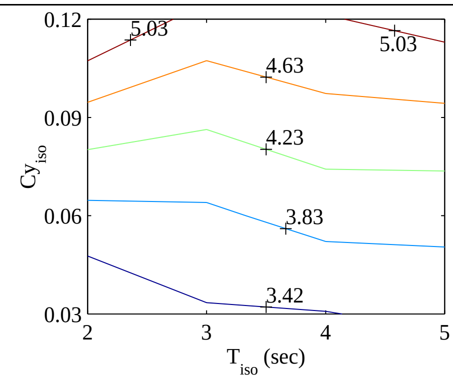
Thus, the coefficient C_{xy} provides a useful factor for computing the average peak bi-directional response for a given suite of ground motion pairs directly given the average uni-directional response for all records from the same suite of motions.

RESULTS

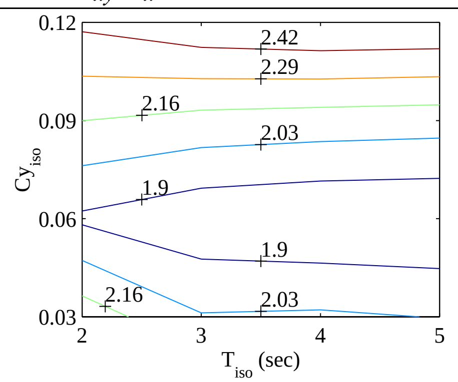
Selected results from these studies are shown in the figures below. Mean contour results for the ratios D_{xy}/D_x and D_{xy}/D_y for ground motions Bins 1 and 2 are shown in Figure 7 for systems with the most rigid initial stiffness properties considered (i.e., T_{sub} = .05 sec) over the entire range of parameters considered for isolation system period and strength (see Table 1). For Bin 1 motions, which are oriented orthogonal to the active fault, the trend is for D_{xy}/D_x ratios to be much smaller than D_{xy}/D_y. This is to be expected since D_x represents the peak displacement due to fault-normal motions, which generally possess larger spectral response (Somerville [7], see Figure 6 (a)). For Bin 2 motions, which are oriented somewhat randomly, the trend is for D_{xy}/D_x and D_{xy}/D_y ratios to be generally similar. This was likewise the case for Bin 3 through Bin 5 motions which were also randomly oriented.



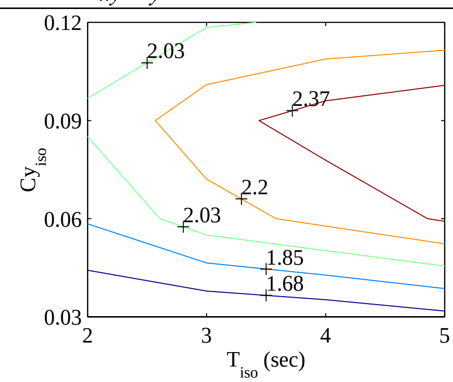
a. D_{xy}/D_x mean contours: Bin 1



b. D_{xy}/D_y mean contours: Bin 1



c. D_{xy}/D_x mean contours: Bin 2

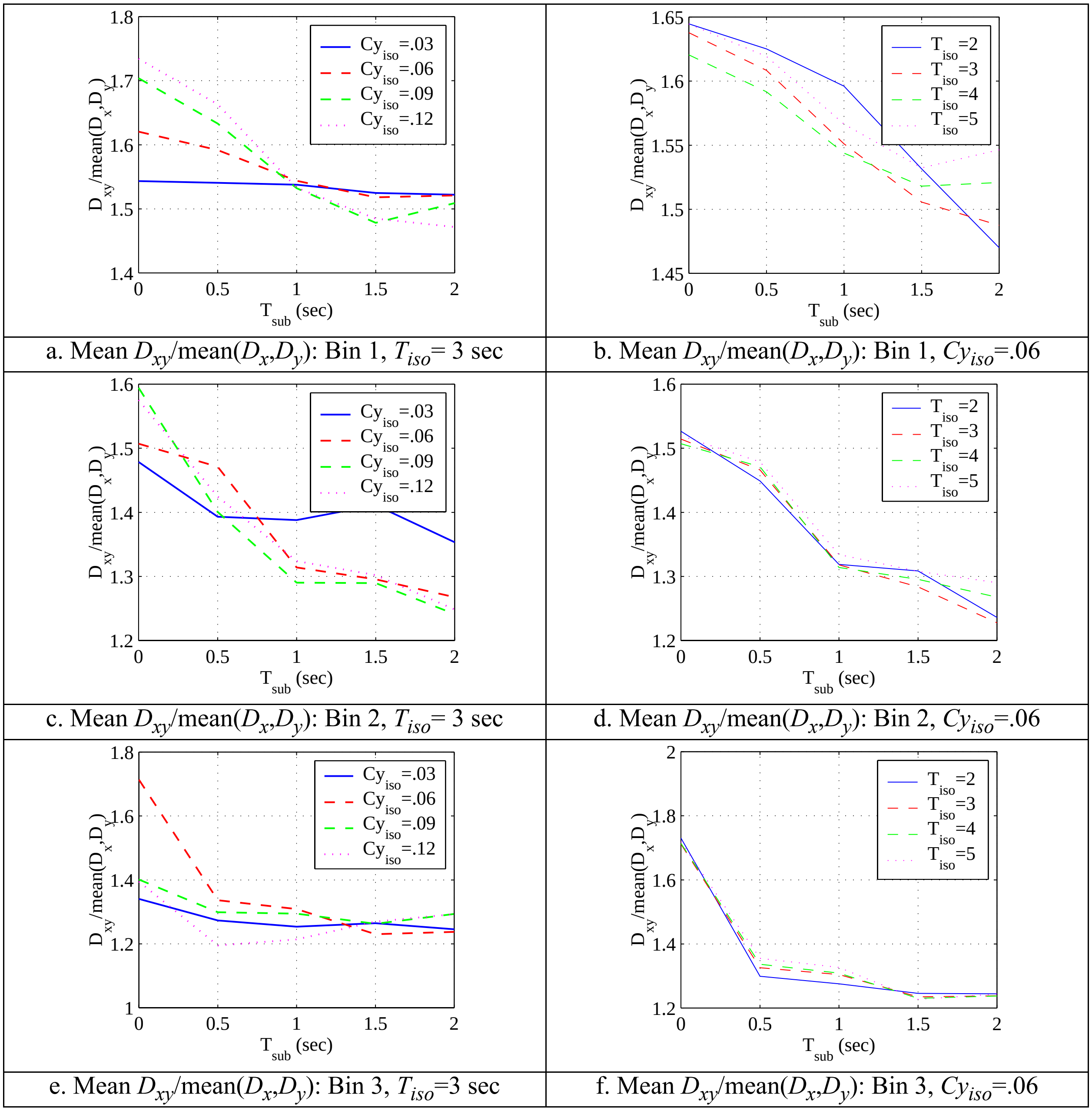


d. D_{xy}/D_y mean contours: Bin 2

Figure 7 Mean D_{xy}/D_x and D_{xy}/D_y contours for Bin 1 and 2 ground motion histories, T_{sub} = 0.05 sec

Figure 8 shows mean results for the ratio D_{xy}/mean(D_x,D_y) for ground motion Bins 1 through 3 (larger magnitude earthquakes, see Table 2). These plots illustrate how variations in substructure (or first-slope stiffness properties) and isolation properties effect bi-directional response. Generally, mean D_{xy}/ mean(D_x,D_y) ratios decreased with decreasing system initial (i.e., first-slope) stiffness (i.e., increasing T_{sub}), implying that bi-directional motions had more effect on systems which were more initially rigid (i.e., prior to bearing yield). Strength had a significant effect on systems with more rigid first-slope stiffness and a minor or negligible effect on systems which were more initially flexible. This trend is illustrated by the larger dispersion in D_{xy}/mean(D_x,D_y) contours at different strength values for systems with

T_{sub} < 0.5 seconds (see Figure 8 (a), (c), and (e)). For these systems (i.e., T_{sub} < 0.5 second), the D_{xy}/ mean(D_x,D_y) ratio generally increased systematically with increasing strength for Bin 1 and Bin 2 motions. For Bin 3 motions, however, the D_{xy}/mean(D_x,D_y) ratio increased then decreased with increasing strength for these cases (i.e., T_{sub} < 0.5 second). On the other hand, strength had a minor or negligible effect (i.e., less than 10% difference in response over the range of strength considered) for systems which were more initally flexible (i.e., T_{sub} > 0.5 sec). Variations in characteristic isolator period over the range considered generally had little effect on the D_{xy}/mean(D_x,D_y) ratio for Bin 1 through 3 motions (see Figure 8 (b), (d), and (f)). In an effort toward brevity, only the selected results in Figure 8 are presented. However, results were consistent over the entire range of parameters.



a. Mean D_{xy}/mean(D_x,D_y): Bin 1, T_{iso}= 3 sec

b. Mean D_{xy}/mean(D_x,D_y): Bin 1, Cy_{iso}=.06

c. Mean D_{xy}/mean(D_x,D_y): Bin 2, T_{iso}= 3 sec

d. Mean D_{xy}/mean(D_x,D_y): Bin 2, Cy_{iso}=.06

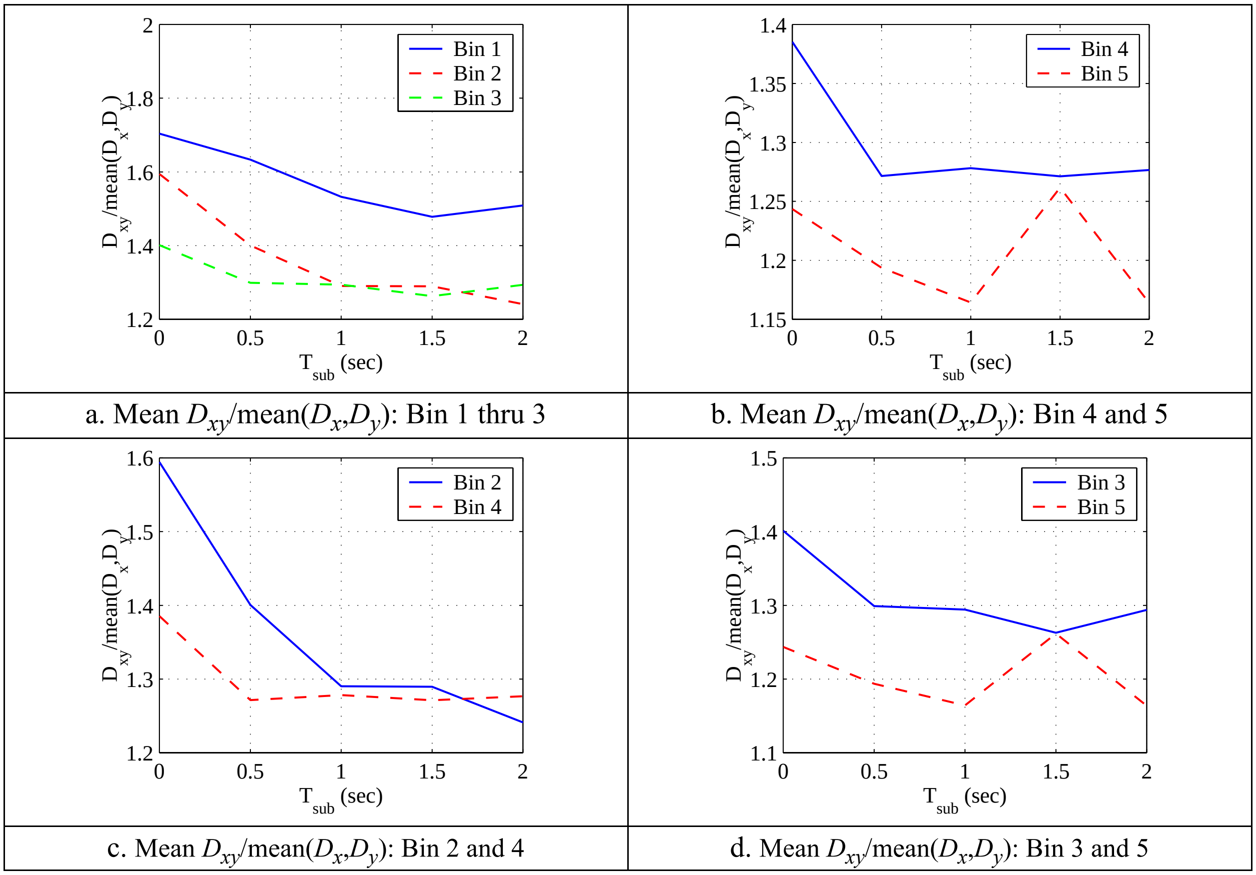
e. Mean D_{xy}/mean(D_x,D_y): Bin 3, T_{iso}=3 sec

f. Mean D_{xy}/mean(D_x,D_y): Bin 3, Cy_{iso}=.06

Figure 8 Influence of isolator Cy_{iso} and T_{iso} on mean D_{xy}/mean(D_x,D_y) results

Figure 9 shows mean results for the ratio D_{xy}/mean(D_x,D_y) for ground motion Bins 1 through 5. These plots illustrate the effect of earthquake magnitude and distance on bi-directional response. Figures 9 (a) and (b) illustrate that the D_{xy}/mean(D_x,D_y) ratio generally decreased for motions of increasing distance from the earthquake fault. Figures 9 (c) and (d) illustrate that D_{xy}/mean(D_x,D_y) ratios generally decreased for earthquakes of decreasing magnitude. These results were consistent over the range of parameters studied.

Figure 10 shows mean results for the D_{xy}/mean(D_x,D_y) ratio for Bin 2 through 5 sorted by ground motion bin and soil type. Figure 10 (a) shows the ratio D_{xy}/mean(D_x,D_y) was generally larger for softer soils (Type



a. Mean D_{xy}/mean(D_x,D_y): Bin 1 thru 3

b. Mean D_{xy}/mean(D_x,D_y): Bin 4 and 5

c. Mean D_{xy}/mean(D_x,D_y): Bin 2 and 4

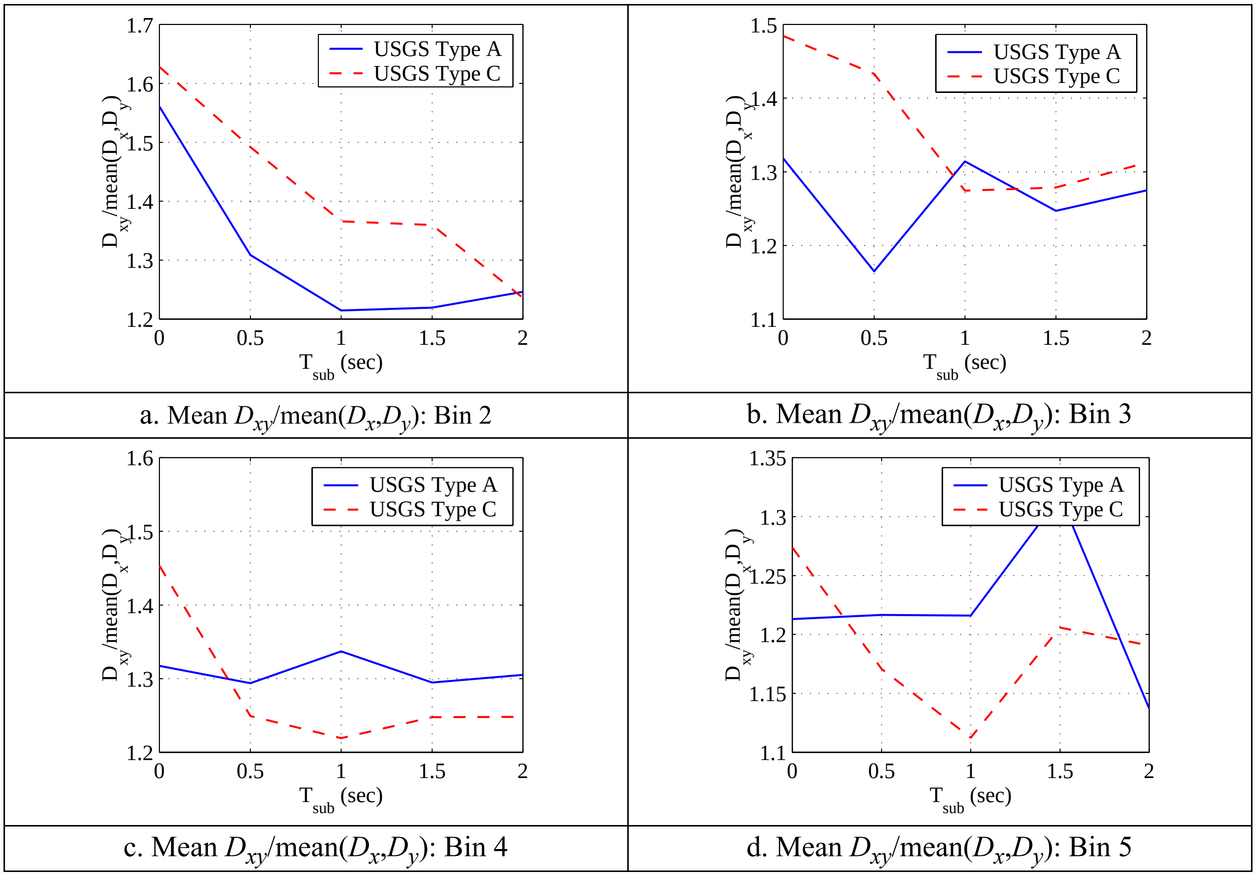
d. Mean D_{xy}/mean(D_x,D_y): Bin 3 and 5

Figure 9 Effect of magnitude and distance on mean D_{xy}/mean(D_x,D_y) results: T_{iso}= 3sec, Cy_{iso}= .09

C) for Bin 2 motions in this study. For Bin 3, 4, and 5 motions, this effect was generally similar for systems which were more initially rigid (i.e., T_{sub} < approximately 0.5 seconds). However, for systems with more flexible first-slope properties, the effect of soil type appeared negligible for Bin 3 motions while D_{xy}/mean(D_x,D_y) tended to decrease for softer soils for Bin 4 and Bin 5 motions. These results were consistent over the range of parameters considered.

In Figure 11 results for D_{xy}/mean(D_x,D_y) and the C_{xy} coefficient for Bin 2 motions are shown alongside for comparison. Results are presented over the entire range of system parameters. Trends in D_{xy}/mean(D_x,D_y) due to variations in system parameters, earthquake magnitude and distance, and soil type are consistent with the previous discussion. In addition, it is apparent from these figures that the values for the average D_{xy}/mean(D_x,D_y) ratios and the C_{xy} coefficient in this study are similar over the range of parameters considered for the five ground motion bins. Values for both the C_{xy} coefficient and D_{xy}/mean(D_x,D_y) ratio are largest for isolated bridge systems with the most rigid first-slope properties (T_{sub} < 0.5 seconds).

Table 3 below summarizes these statistical results for each ground motion bin for isolated bridges with the most rigid first-slope stiffnesses considered. Ranges under each heading indicate results computed over the entire range of system parameters considered. The ratio of average peak bi-directional response to average peak uni-directional response, as represented by the C_{xy} coefficient, ranged between approximately 20-75%. On average, increases in peak displacement response due to bi-directional input of approximately 25-75% above the average response due to the same orthogonal pair of uni-directional motions applied separately (represented by the ratio D_{xy}/mean(D_x,D_y)) were realized in this study for the ranges of bridge



a. Mean D_{xy}/mean(D_x,D_y): Bin 2

b. Mean D_{xy}/mean(D_x,D_y): Bin 3

c. Mean D_{xy}/mean(D_x,D_y): Bin 4

d. Mean D_{xy}/mean(D_x,D_y): Bin 5

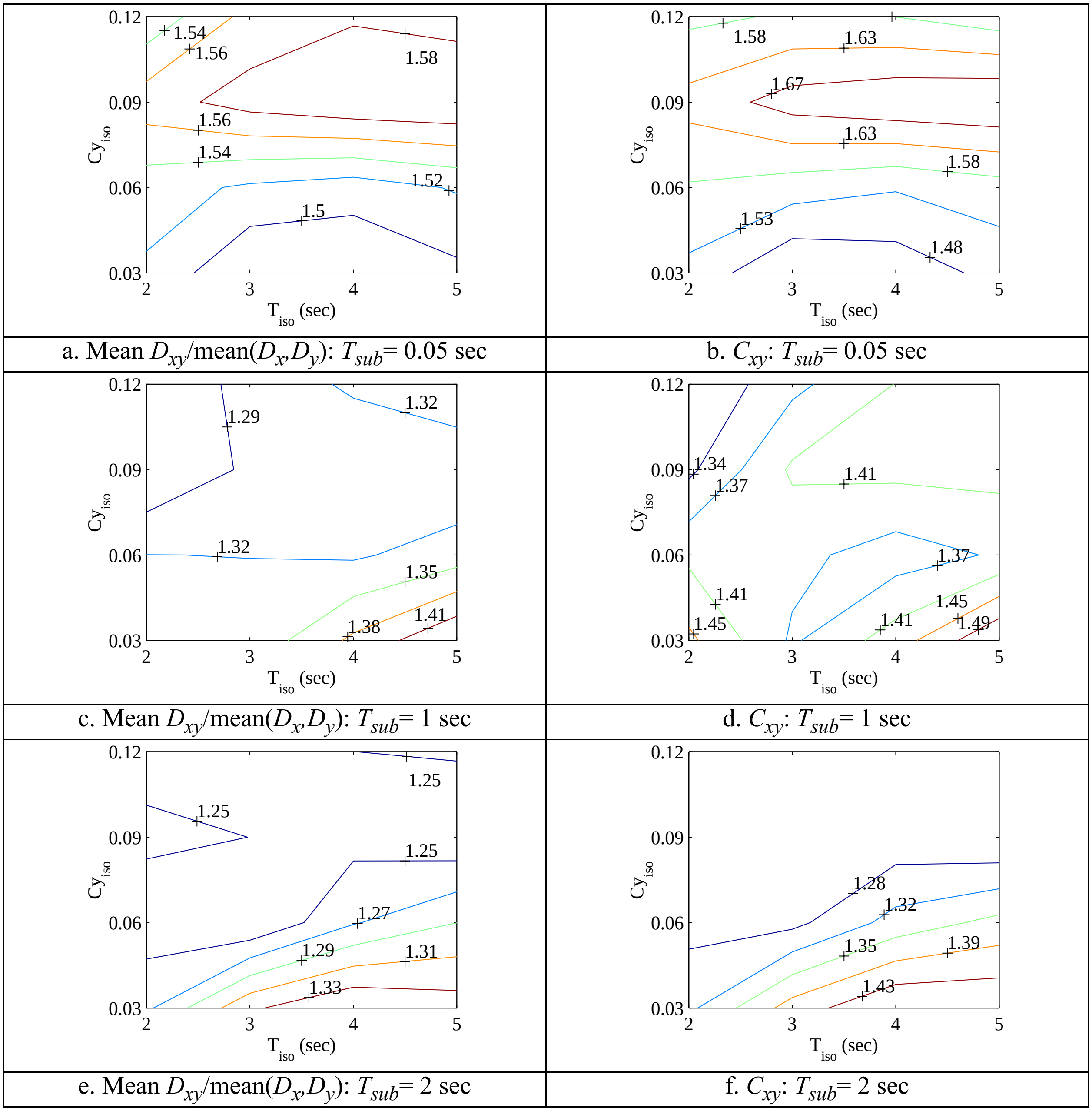
Figure 10 Effect of soil type on mean D_{xy}/mean(D_x,D_y) results: T_{iso}=3sec, Cy_{iso}=.09

system parameters, ground motion distance, magnitude, and site specific soil type considered. Mean+1σ and maximum ranges of this increase due to bi-directional input of approximately 50-100% and 75-140%, respectively, were realized over the parameter range.

DISCUSSION

It is evident from these results that the effect of bi-directional input on seismically isolated bridge systems is significant. It was found for all cases considered in these studies that on average peak displacement response due to bi-directional input is considerably larger than peak response due to uni-directional input applied separately. This disparity is most significant for more rigid structures, employing stronger isolation systems, subjected to larger magnitude earthquakes, nearer the active fault. For these cases, softer site specific soils tend to increase the bi-directional effect.

As discussed earlier, the behavior of an isolated bridge system subjected to bi-directional input is effected by two factors which influence the coupling effect in the response. First, phasing within each of the ground motion components may dictate bi-directional response with uni-directional peaks occurring more or less simultaneously producing a maximum vectored displacement much larger than either of the uni-directional maxima. This coupling in the ground motion components has been shown to be most significant for near-fault motions (which contain a more coherent impulsive content than in the far-field) and for soft soils. The results of this study are consistent with this trend, where it is seen that the bi-directional effect is more pronounced for near fault events. Second, coupling which occurs in the circular force-displacement yield surface characteristic in the bi-directional response of typical seismic isolation bearings causes a reduction



a. Mean D_{xy}/mean(D_x,D_y): T_{sub}= 0.05 sec

b. C_{xy}: T_{sub}= 0.05 sec

c. Mean D_{xy}/mean(D_x,D_y): T_{sub}= 1 sec

d. C_{xy}: T_{sub}= 1 sec

e. Mean D_{xy}/mean(D_x,D_y): T_{sub}= 2 sec

f. C_{xy}: T_{sub}= 2 sec

Figure 11 Comparison of mean D_{xy}/mean(D_x,D_y) and C_{xy} contours: Bin 2

Table 3 Range of contour values for C_{xy} and D_{xy}/mean(D_x,D_y), T_{sub} = 0.05 sec

		D_{xy}/mean(D_x,D_y)		
Bin	C_{xy}	*mean*	*mean +1σ*	*maximum*
1	1.58-1.75	1.57-1.76	1.74-1.95	1.85-2.15
2	1.48-1.67	1.50-1.58	1.68-1.93	1.87-2.19
3	1.37-1.72	1.38-1.66	1.64-2.05	1.80-2.43
4	1.26-1.48	1.29-1.37	1.54-1.78	1.75-2.28
5	1.19-1.41	1.26-1.36	1.53-1.64	1.79-2.09

in resisting force orthogonal to the direction of initial displacement beyond yield (see Figure 1). This coupling effect would tend to be more pronounced for more rigid systems, where interaction with the yield surface would occur more readily (i.e., at smaller displacements). In addition, the greatest reduction in resisting force orthogonal to the direction of initial displacement would occur for the strongest isolation systems. This is also consistent with the results of these studies, where the bi-directional effect was most pronounced for more rigid substructures with stronger isolation systems.

As described previously, the AASHTO *Uniform Load Method* is a linearized procedure for estimating the mean peak displacement response of seismically isolated bridge systems subjected to a suite of uni-directional spectrum compatible motions. The method utilizes a design spectrum representing random or "average" directivity with regard to any given site specific ground motion record (AASHTO [2]). If it is assumed that this method provides a reliable estimate of the mean peak response of an isolated bridge system subjected to a sufficiently large sampling of spectrum compatible motion pairs, then the results of this study indicate that the method will significantly underestimate on average the peak displacement response of the system when subjected to the same ground motion pairs applied bi-directionally. In addition, since the difference between the mean spectrum of "larger" (fault-normal) ground motions and the mean spectrum of all ground motion pairs (representing "average" or random directivity) increases with closer proximity to the active fault, it may be construed based on the results presented herein that the AASHTO *Guide Spec* procedures will increasingly underestimate the increase in response due to bi-directional effects with closer fault proximities.

The AASHTO *Guide Spec* code procedures provide a method for estimating effects of bi-directional input by combining 100% plus 30% of orthogonal maxima (AASHTO [2]). If this procedure is applied a maximum factor of only approximately 1.04 would be applied to account for the increase in response due to bi-directional effects, assuming design response in a symmetric system to be equal in each orthogonal direction. The results of this study indicate that this factor is inadequate to capture average increases in displacement response due to bi-directional coupling in symmetric bridge systems.

If D is the mean response of an isolated bridge system subjected to a suite of N ground motion pairs whose mean spectrum is assumed compatible with the AASHTO design spectrum, then the *Guide Spec'*s *Uniform Load Method* would provide an estimate of this response as follows

$$d = \frac{10AS_iT_{eff}}{B} \approx D \tag{5}$$

Given this and C_{xy} as defined in Equation (1), a method for computing average peak response due to bi-directional input from the same suite of N ground motion pairs may be postulated using Equation (4) as

$$D_{bi} = C_{xy}D \approx C_{xy}d \tag{6}$$

Since the mean spectra of each of the bins of time-history pairs utilized in these studies fit closely to the shape of the AASHTO design spectrum (as shown in Figure 5 (c)), the coefficient C_{xy} may be considered broadly to account for bi-directional effects on response computed by AASHTO *Guide Spec* procedures. The values of the C_{xy} coefficient computed in this study ranged between approximately 1.20 to 1.75 (see Table 3 above).

CONCLUSIONS

An evaluation of the effects of directivity and bi-directional input on the response of simple seismically isolated bridge systems was undertaken. It is evident from these results that on average peak displacement response due to bi-directional input was considerably larger than the average of peak responses due to uni-directional input applied separately. This disparity was most significant for more rigid structures, employing stronger isolation systems, subjected to larger magnitude earthquakes, and located nearer to the active fault. For these cases, softer site-specific soils tend to further increase the bi-directional effect. The results of this study indicate that the *Guide Spec* procedure for estimating bi-directional effects using a combination of 100% plus 30% of orthogonal maxima (AASHTO [2]) is inadequate to capture average increases in displacement response due to bi-directional coupling. It is therefore recommended that a revision to code procedures be applied to account for the effects of bi-directional interactions. For simple bridge overcrossings, substructure stiffness is typically dictated by essentially rigid abutment conditions. Further, design basis earthquake demand is nearly equivalent to the Bin 2 motions considered in these studies (see Table 2). Given these general conditions, it is recommended that the effects of bi-directional input on simple bridge overcrossings be computed by weighting design displacements as follows

$$d_{bi} = C_{xy}\left(\frac{d_x + d_y}{2}\right) \qquad (7)$$

where d_{bi} is the peak bi-directional displacement in any vectored direction, C_{xy} is a bi-directional weighting factor, and d_x and d_y are the uni-directional design displacements computed by *Guide Spec* procedures in each orthogonal direction of the bridge, respectively. It is recommended that a factor of C_{xy} = 1.5 be used for the weakest and most initially flexible isolation systems (where bi-directional interactions would be least) and C_{xy} = 1.7 be used for the strongest and more initially rigid isolation systems (where bi-directional interactions would be greatest). For near-fault and softer site specific soil conditions these factors should be increased by an additional 5%.

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