Reduction of Seismic Acceleration Parameters for Temporary Bridge Design

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Abstract: No prevailing method is currently available for reducing the seismic response acceleration parameters PGA, S_S, and S_1 from the probabilistic seismic hazard values used for permanent bridge design to levels suitable for temporary bridge design. A method of spectral reduction using spectral reduction factors was proposed to reduce the previously published spectral response acceleration parameters, the peak ground acceleration (PGA), the short-period response acceleration coefficient (S_s), and the long-period response acceleration coefficient (S_1), from the 1,000-year return period used for permanent bridge design to a return period suitable for temporary bridge design. The proposed spectral reduction factors are the ratios of the return period used for the seismic design of a permanent bridge to the return period used for the seismic design of a temporary bridge. Spectral ratios were obtained for each of the three seismic response acceleration coefficients for 100 locations around the United States. The examination of the short- and long-period response acceleration coefficients are presented in this paper. As a result of this examination, two spectral reduction factors for the seismic design of temporary bridges were proposed: one spectral reduction factor, of 2.5, to reduce each PGA, S_S, and S_1 parameter for the western United States, and one spectral reduction factor, of 3.75, to reduce each PGA, S_S, and S_1 parameter for the central and eastern United States. **DOI: 10.1061/(ASCE)BE.1943-5592.0001292.**

Introduction

No national consensus has been reached on what method should be used in design practice to reduce the values of the seismic design criteria used for permanent bridges to levels suitable for the design of temporary bridges. While AASHTO provides maps containing the spectral response coefficients corresponding to the return period used in the design of new bridges, some engineers may find these values too conservative because they do not reflect the reduced design life span of a temporary bridge; therefore, they are not as cost effective as using spectral response coefficients that incorporate the reduced time of exposure (Mohammadi and Heydari 2008).

The AASHTO *LRFD Bridge Design Specifications* (LRFD-BDS) specifies a probabilistic approach for the seismic design of new bridges in Article 3.10.1 (AASHTO 2015b, pp. 3–55); in this approach, bridge acceleration response spectra, based on a uniform risk of a 7% probability of exceedance in 75 years, were used to define the acceptable seismic hazard level in which the bridge "may suffer significant damage" but "have a low probability of collapse." The 7% probability of exceedance in 75 years corresponded to what was an approximately 1,000-year return period. However, AASHTO did not provide an alternate return period to be used for temporary bridge design that reflects the reduced design life span of a temporary bridge; however, it did provide restrictions governing the use of alternate response spectra for temporary bridges. In the AASHTO LRFD-BDS, Article 3.10.10 restricted the reduction of the response spectra for temporary bridges by a factor no greater than 2. For comparison, the *AASHTO Guide Specifications for LRFD Seismic Bridge Design* (LRFD-SBD) restricted the reduction of the response spectra for temporary bridges by a factor of no greater than 2.5, as specified in Article 3.6 (AASHTO 2015a).

In one practice currently used by some state transportation departments, a return period that was reduced from the 1,000-year return period given by AASHTO was specified to be used for temporary bridge design (Caltrans 2011; IDOT 2012; SCDOT 2008). In May 2011, Caltrans issued a memo to state bridge engineers setting a standard for the response spectra to be used in temporary bridge design (defined as bridges with a design life span of 5 or fewer years). It specified that temporary bridges "that carry or cross over public vehicular traffic" should be designed, per a response spectra corresponding to a 10% probability of exceedance in 10 years, corresponding to a return period of roughly 100 years (Caltrans 2011, pp. 20–21). If one assumes that this approach is to be adopted nationally, which is possible when recognizing influence has had on AASHTO design procedures over the years (Marsh et al. 2014), then questions arise about how the design parameters corresponding to a 10% probability of exceedance in 10 years could be obtained. According to the Caltrans definition of temporary bridges, in this paper, the term *permanent bridge* refers to a bridge with a design life span longer than 5 years.

Currently, for temporary bridge design with a reduced return period, the engineer must search the USGS website for the set of response parameters corresponding to that return period. In other words, because only one set of design maps has been presented by AASHTO, and it is based on a 1,000-year return period, the use of the USGS website has been necessary when designing for a reduced return period. However, not all engineers were familiar with the complexities of extracting such design values using tools (that may or not be provided at any point in time on the USGS website) operating on earthquake hazard parameters. In particular, this has been the complicated case affecting temporary bridge projects located in states less seismically active than California; for these instances, a simpler approach is desirable. One such approach, investigated

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herein, proposed using predetermined factors, to reduce the spectral acceleration coefficients used for the design of permanent bridges and given in the maps in Article 3.10.4.2, to obtain new values to be used for the design of temporary bridges with a shorter target return period. Using the proposed method, an engineer designing a temporary bridge could obtain values for the response parameters, PGA, S_S, and S_1, from the AASHTO maps corresponding to a 1,000-year return period, using the same procedure used for a permanent bridge design, and reduce these values to those corresponding to a 10% probability of exceedance in 10 years by using a spectral reduction factor, without the need to use the USGS website. This simplified method of producing seismic response spectra was aimed at temporary bridges that corresponded with the AASHTO definition of a *regular* bridge given in Article 4.7.4.3 of the LRFD-BDS (AASHTO 2015b) and for areas that typically did not require intensive seismic analysis; for these areas, the resulting designs were considered to be conservative if the spectral response accelerations calculated by the proposed method were greater in magnitude than the spectral response accelerations obtained from the USGS website. It is noteworthy that, because of the simplicity of the method used to develop the spectral reduction factors, a state, or any other such governing body, could apply the methodology to develop a unique set of spectral reduction factors for other specified return periods and areas.

Seismic Spectral Reduction Factors

The method proposed herein for the reduction of the seismic design spectra was based on the idea that any location on the map of the United States could be identified as belonging to a preidentified seismic group. Furthermore, each seismic group could be defined such that all locations within that group share identical values for the three separate spectral reduction factors that must be used to reduce the design spectra defined in Article 3.10.4.1 from a 7% probability of exceedance in 75 years to a 10% probability of exceedance in 10 years. Therefore, for each group, three spectral reduction factors were calculated, one for each of the spectral acceleration coefficients used in creating the design spectra defined in Article 3.10.4.1 of the LRFD-BDS; that is, one spectral reduction factor was for reducing the peak ground acceleration coefficient, one for the short-period spectral response coefficient, and one for the long-period spectral response coefficient. These spectral reduction factors are referenced herein as the *peak ground acceleration spectral reduction factor*, K_{PGA}, the *short-period spectral reduction factor*, K_{SD}, and the *long-period spectral reduction factor*, K_{1D}. For brevity herein, the results are presented only for the K_{SD} and K_{1D} factors, but similarities and differences in the findings obtained for the K_{PGA} are also described. Complete data and the results for the peak ground acceleration can be found in the report by Stucki and Bruneau (2018).

Site Locations Obtained for Analysis

One hundred locations were selected to provide adequate geographic coverage of the continental United States. Preference was given to areas of the country perceived as seismically active and large population centers. Additional locations were selected to ensure that each of the proposed seismic groups had at least 10 locations. The GPS coordinates for each location were retrieved using Google Earth.

For each location, the peak ground acceleration and the short- and long-period spectral response acceleration coefficients corresponding to a 10% probability of exceedance in 10 years and a 7% probability of exceedance in 75 years were obtained from the seismic hazard data available on the USGS website. The values obtained for the 2002 USGS seismic hazard data had been used in the development of the 2009 AASHTO seismic maps (USGS 2002). In addition to the 2002 seismic hazard data, the same three spectral response coefficients were also obtained using the 2014 seismic hazard data under the assuming that future editions of AASHTO would refer to the most recent seismic maps (USGS 2014). Some of the obtained values were also used for direct comparisons of how seismic demands have changed over time at the locations considered and how the coefficients calculated by the present methodology were affected by recent changes in the seismic hazard data maps. The seismic data were obtained from the USGS website and interpolated as described by Stucki and Bruneau (2018) to obtain the spectral values for the target probability of exceedance.

Two separate methods were used to regroup the 100 site locations into seismic groups. For one method, the 100 site locations were divided into seven seismic groups that were defined as a function of geographic location. For the other method, the 100 site locations were divided into four separate seismic groups that corresponded to the AASHTO seismic performance zones (defined in Article 3.10.6 of the LRFD-BDS). This paper presents only the results for the method by which the locations were divided into seismic groups according to geographic location because it was found to provide less scatter in the results (and was consistent with the defining characteristics of the seismological hazards throughout the continent, as briefly described in the Appendix).

Spectral Reduction Factors

The methodology used for calculating the spectral reduction factors proceeded through steps using the various parameters as defined in this section. First, a short-period spectral reduction factor is used to reduce the response spectral acceleration coefficient pertaining to the short-period as follows:

$$S_{SD} = \frac{S_{S-75}}{K_{SD}} \tag{1}$$

where S_{SD} = design short-period response spectral acceleration coefficient for temporary bridges; S_{S-75} = short-period response acceleration coefficient corresponding to a 7% exceedance in 75 years; and K_{SD} = short-period spectral reduction factor.

A similar long-period spectral reduction factor is used to reduce the response spectral acceleration coefficient pertaining to long-period, as follows:

$$S_{1D} = \frac{S_{1-75}}{K_{1D}} \tag{2}$$

where S_{1D} = design long-period response spectral acceleration for temporary bridges; S_{1-75} = long-period response acceleration coefficient corresponding to a 7% exceedance in 75 years; and K_{1D} = long-period spectral reduction factor.

It is noteworthy that when using a reduced spectrum, the specification given in Article 3.6 of the LRFD-SBD was assumed to still apply; that is, the seismic design category of the bridge was determined from the reduced spectrum used for the temporary bridge design, with the one exception that "a temporary bridge classified in SDC B, C, or D based on the unreduced spectrum cannot be reclassified to SDC A based on the reduced/modified response spectrum" (pp. 3–56). It was assumed that this provision similarly applies to the seismic performance zones, defined in Article 3.10.6 of the AASHTO LRFD-BDS, given that the seismic performance zones

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had almost identical defining criteria as the seismic design categories defined in Article 3.5 of the AASHTO LRFD-SBD. Hence, it was assumed that a temporary bridge meeting the criteria for seismic performance Zone 2, 3, or 4 using the 1,000-year return period cannot be reclassified as belonging to seismic performance Zone 1 using the reduced response spectrum. This restriction was not explicitly specified in Article 3.10.10 of the AASHTO LRFD-BDS, the article governing seismic requirements for temporary bridges, but was assumed for the proposed method to provide continuity between the LRFD-SBD and the LRFD-BDS from AASHTO.

Soil site Class B, defined in Article 3.10.3.2 of the LRFD-BDS, was assumed for every location considered. It ensured that the site factor at the zero period on the acceleration spectrum, F_{pga}, the site factor for the short-period range, F_a, and the site factor for the long-period range, F_v, each had a value of 1.0.

For soil site classes, two possible approaches could have been taken. The first could have been applied to the site factors before performing the spectral reduction. Because site factors vary with the magnitude of ground motion, for most cases (except soil site Class A), this is the more conservative approach and the one recommended herein given that significant ground motions reductions had already been applied. The second approach used the site factors determined after the spectral reduction; it is arguably more consistent, but could result in site factors of lesser magnitude, and thus, a design spectrum of an even lesser magnitude.

Method of Calculating K_{SD} and K_{1D}

Using the response spectral acceleration parameters retrieved from the USGS website, two separate spectral reduction ratios were calculated for each location. The spectral reduction ratios corresponded to the coefficients S_S and S_1, and they were used to derive the spectral reduction factors for the seismic groups. The first of these is the short-period spectral reduction ratio, K_S, calculated as follows:

$$K_S = \frac{S_{S-75}}{S_{S-10}} \tag{3}$$

where S_{S-75} = short-period acceleration coefficient corresponding to a 7% probability of exceedance in 75 years; and S_{S-10} = short-period acceleration coefficient corresponding to a 10% probability of exceedance in 10 years.

The second ratio is the long-period spectral reduction ratio, K_1, calculated as follows:

$$K_1 = \frac{S_{1-75}}{S_{1-10}} \tag{4}$$

where S_{1-75} = long-period acceleration coefficient corresponding to a 7% probability of exceedance in 75 years; and S_{1-10} = long-period acceleration coefficient corresponding to a 10% probability of exceedance in 10 years.

For each seismic group, the mean value of the short-period spectral reduction ratio, $K_{S\mu}$, and the mean value of the long-period spectral reduction ratio, $K_{1\mu}$, were used in this study to establish a preliminary value for the respective reduction factors corresponding to each group. To ensure conservatism, one standard deviation is subtracted from the mean value to obtain a design value for the group as follows:

$$K_{SD} = K_{S\mu} - \sigma_S \tag{5}$$

where K_{SD} = design short-period spectral reduction factor; and σ_S = standard deviation from $K_{S\mu}$. The value of K_{SD} is to be used in Eq. (1) to reduce the short-period response spectral acceleration coefficient.

Likewise, the long-period reduction factor is calculated as

$$K_{1D} = K_{1\mu} - \sigma_1 \tag{6}$$

where K_{1D} = design long-period spectral reduction factor; and σ_1 = sample standard deviation from $K_{1\mu}$. The value of K_{1D} is to be used in Eq. (2) to reduce the long-period spectral response acceleration coefficient to values corresponding to a 10% probability of exceedance in 10 years.

Design Reduction Factors by Geographic Location

The 100 locations considered were divided into seven seismic groups. The boundaries for Groups 1, 2, 3, and 4 were taken from seismic Regions 1, 2, 3, and 4 defined in Article 3.10.2.1 of the LRFD-BDS, and the GPS coordinates of these bounds were taken from the seismic design maps found in Article 3.10.2.1 of the same document (AASHTO 2015b) with a minor alteration made to remove the area of overlap between Regions 1 and 2. The bounds are listed in Table 1. These geographic regions were given special consideration for this study because they were seismically active regions relative to the rest of the country.

The resulting division of the conterminous United States into seismic groups can be seen in Fig. 1. For the remainder of the country outside of the defined seismic performance zones, a western, central group, and eastern group were defined.

General Procedure for Each Group

The results for each seismic group were determined using the same general procedure and are presented in the following section for both the 2002 and 2014 USGS seismic hazard data sets. For comparison, the data sets are presented graphically in a side-by-side format in Fig. 2.

For each seismic group, the values of K_S and K_1 were calculated for each location, respectively, using Eqs. (3) and (4). Fig. 2 presents plots with trend lines corresponding to the mean values for K_S and K_1 of each group. For simplicity, the trend lines were produced using the mean values as opposed to values obtained through more sophisticated methods such as linear regression. The left-hand plot, Fig. 2(a), of each location for each seismic group shows the short-period response acceleration value corresponding to a 7% probability of exceedance in 75 years on the y-axis and the short-period response acceleration value corresponding to a 10% probability of exceedance in 10 years on the x-axis, and the right-hand plot, Fig. 2(b), of each location for each group shows the long-period response acceleration value corresponding to a 7% probability of exceedance in 75 years on the y-axis and the long-period response acceleration value corresponding to a 10% probability of exceedance in 10 years on the x-axis. Tables 2 and 3 present the mean value and standard deviation for K_S and K_1 for each group. As defined in Eqs. (5) and (6), a subtraction of one standard deviation

Table 1. Bounds for seismic Groups 1–4 by degrees of latitude and longitude

Group	Latitude (°N)	Longitude (°W)
1	32 to 39	115 to 125
	39 to 43	116 to 125
2	39 to 44	109 to 116
3	34 to 39	87 to 92
4	31 to 35	77 to 83

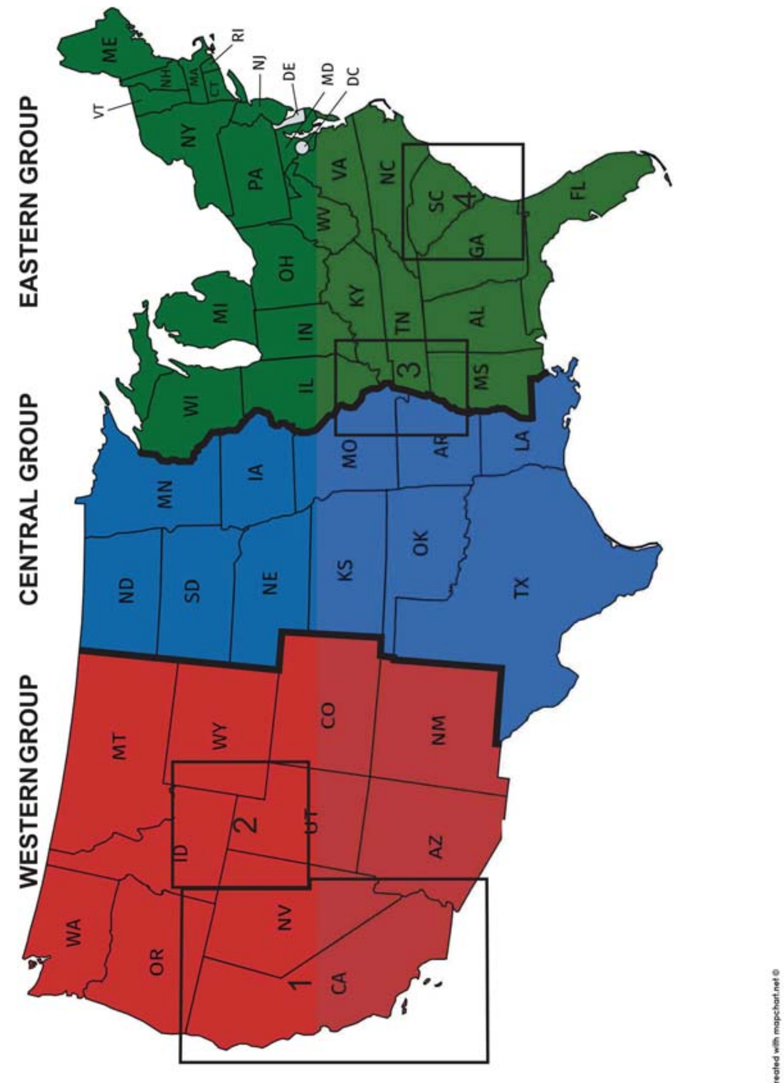

Fig. 1. Seismic groups divided by geographic location. (Map data from http://mapchart.net.)

from the mean gives the spectral reduction factors for each seismic group. The two spectral reduction factors were the proposed alternatives to using the USGS website for spectral response coefficient values corresponding to temporary bridge design.

For each location, the two spectral response coefficients from AASHTO were calculated using the proposed spectral reduction factors. To compare the values of the spectral response coefficients calculated using the proposed spectral reduction factors with the values obtained directly from the USGS seismic hazard data, the following ratios are used

$$\frac{S_{SD}}{S_{S-10}} \tag{7}$$

and

$$\frac{S_{1D}}{S_{1-10}} \tag{8}$$

The spectral response coefficients in the numerator of each ratio were calculated using the proposed spectral reduction factors, and the denominators were the obtained values from the USGS seismic hazard data. Hence, a value greater than 1 in either Eq. (7) or Eq. (8) indicated a conservative response coefficient relative to the response coefficient obtained directly from the USGS website. Plots of the two ratios are shown in Fig. 3 for each seismic group. A horizontal bold line in each plot is shown at the value of one; points below the line indicate nonconservative calculated values relative to the obtained values; in other words, a point below the line indicates a calculated response spectrum smaller in magnitude than the obtained spectral response acceleration. The points above the horizontal bold line were conservative relative to obtained values; for each of these points, the calculated value was a spectral response coefficient greater than the obtained value. Also, Tables 2 and 3 present the design spectral reduction ratio for each coefficient.

It is noteworthy that, within each seismic group, only the spectral reduction factors remained the same for any two locations. The acceleration parameters that were being reduced were identical to the ones that could be used at a location for a permanent bridge design. Therefore, being in the same seismic group did not mean having an equivalent or similar probabilistic earthquake hazard.

It is also noteworthy that, when hazard curves were generated, both the 2002 and 2014 USGS seismic hazard data sets show

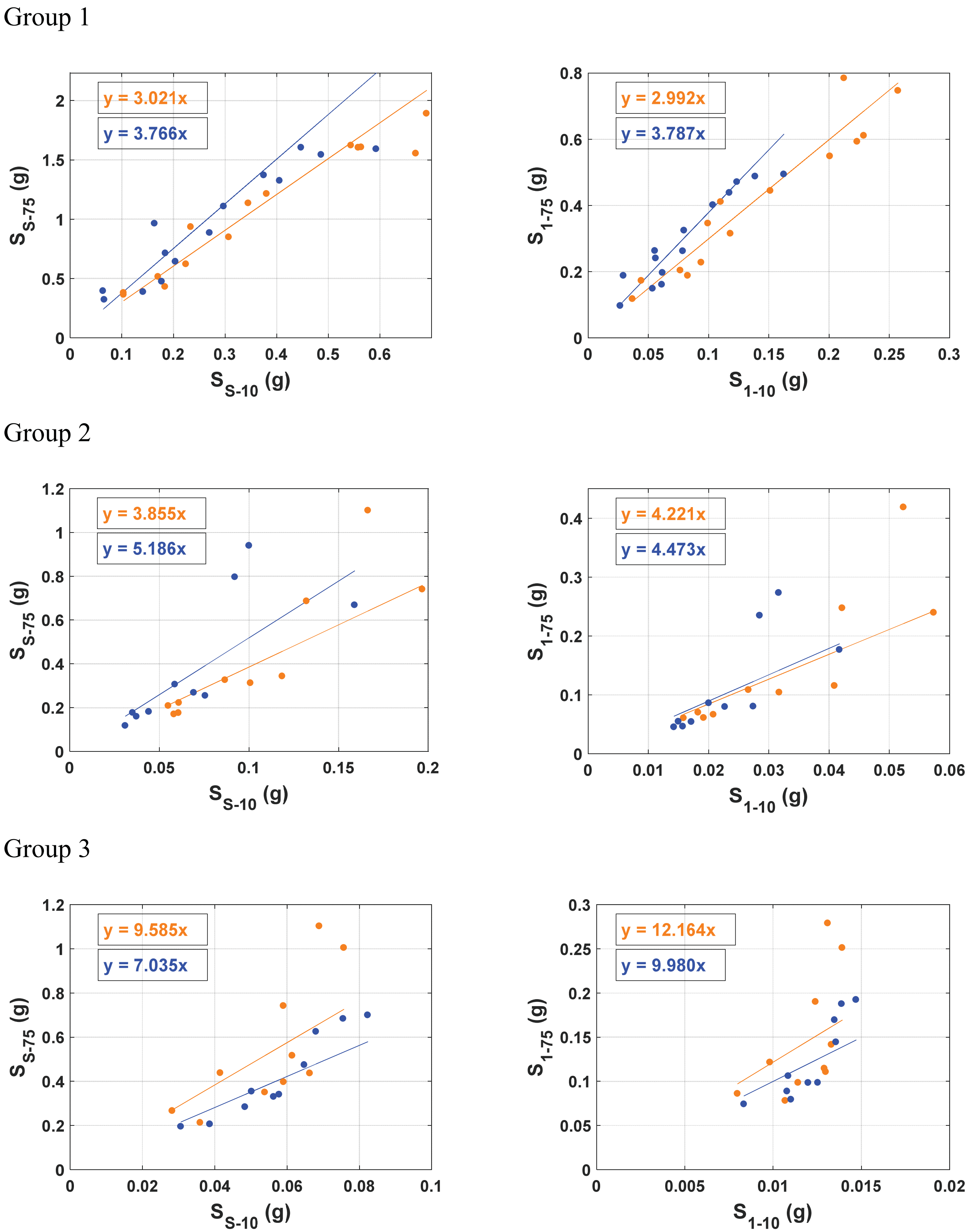

Fig. 2. Mean spectral ratios for seismic groups: (a) spectral ratio for mean short-period response acceleration, K_S; and (b) spectral ratio for mean long-period response acceleration, K_1.

truncated data at a minimum peak ground acceleration of 0.05 g, a minimum short-period response acceleration of 0.05 g, and a minimum long-period response acceleration of 0.025 g. A response acceleration less than the truncated values could not be obtained by interpolation. In this study, for locations where this truncation occurred, the spectral response acceleration coefficients failed to meet the minimum acceleration value corresponding to that coefficient; therefore, they were not considered in the analysis. It is noteworthy that not all spectral response coefficients at that location were ignored; only those that did not meet the minimum acceleration values were not used.

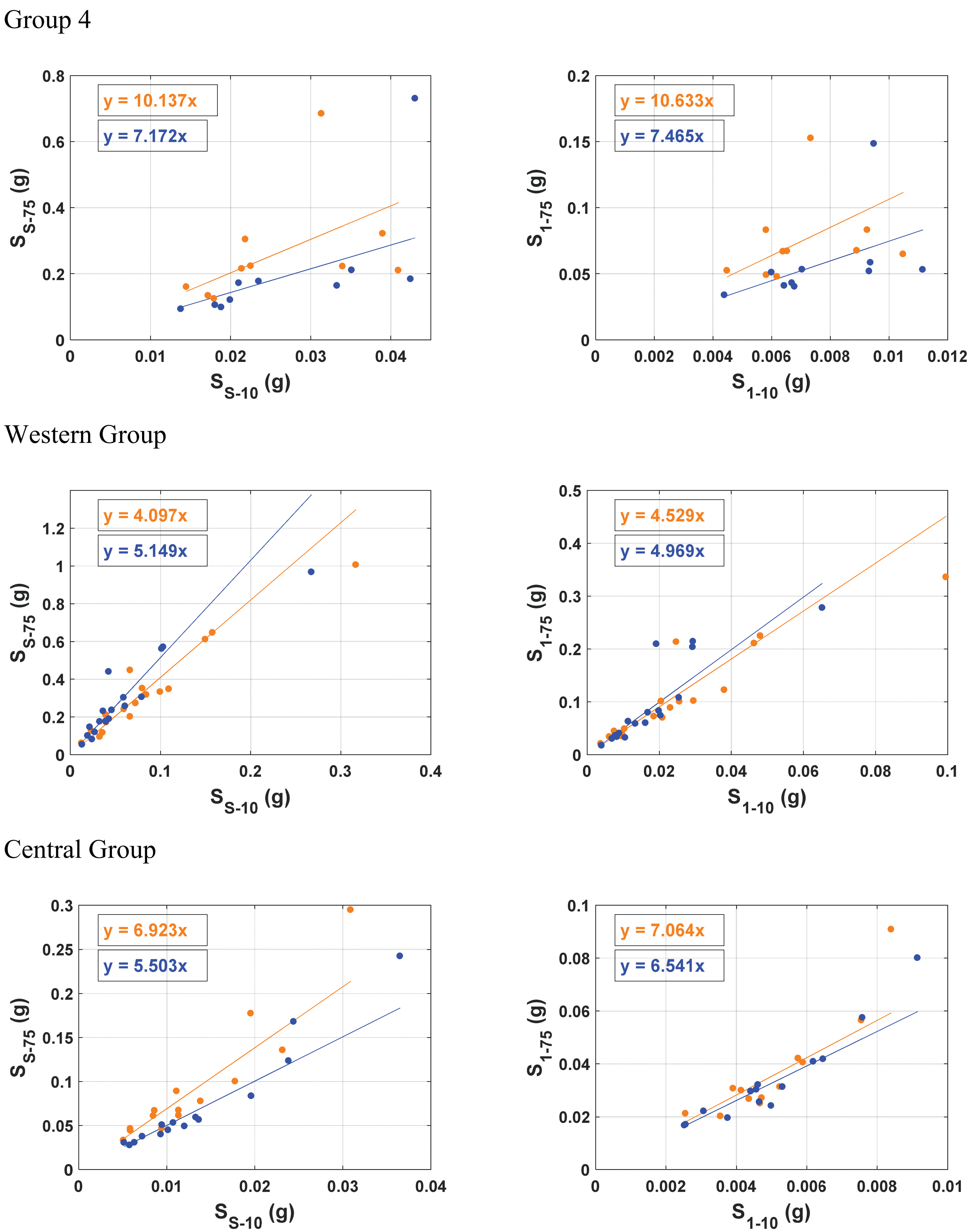

Fig. 2. (*Continued.*)

Observations

The spectral reduction factors for Group 1 derived from the 2002 USGS hazard data, given in Table 2, aligned closely with the spectral reduction limit of 2.5 for the temporary bridge design specified in Article 3.6 of the LRFD-SBD. This finding makes intuitive sense considering that the vast majority of California resides within the confines of Group 1, that Caltrans played a role in the development of the LRFD-SBD (Marsh et al. 2014), and that the 100-year return period for a temporary bridge design, as shown herein, was borrowed from Section 20-2 of the Caltrans memo to designers (Caltrans 2011). The spectral reduction factors derived from the

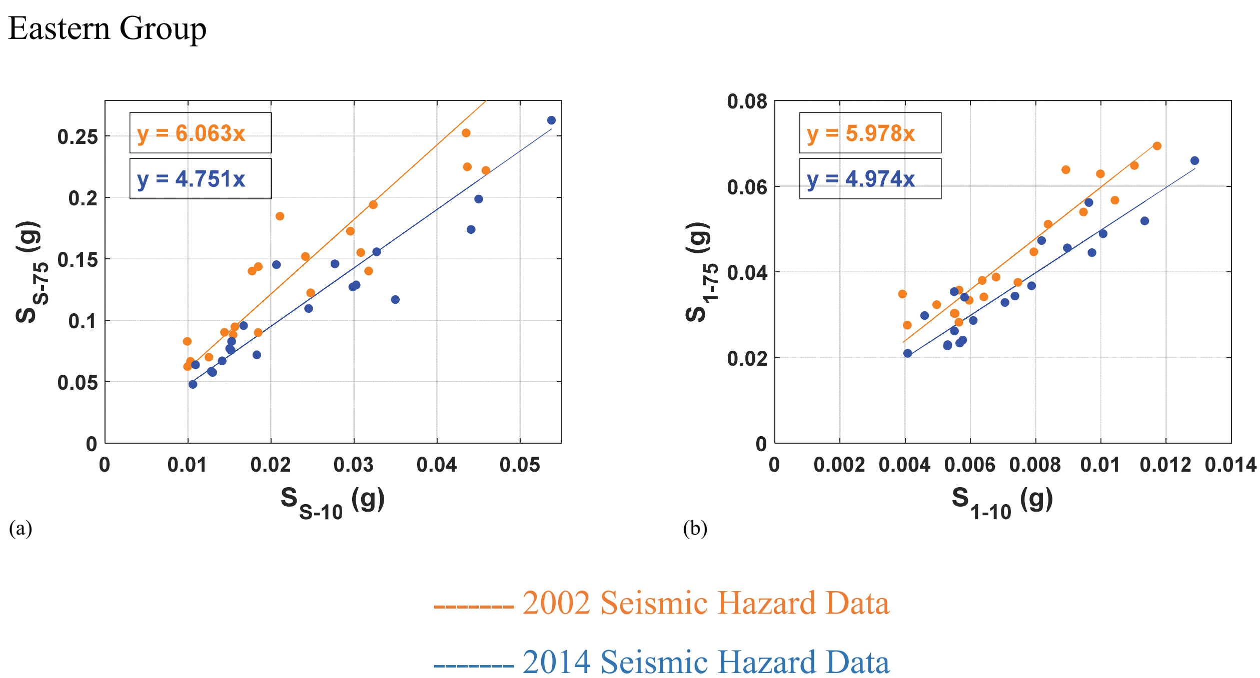

Fig. 2. (*Continued.*)

Table 2. Mean spectral ratios and spectral reduction factors for seismic groups from the 2002 USGS seismic hazard data

	Mean spectral ratios				Reduction factors	
Seismic group	$K_{S\mu}$	σ_S	$K_{1\mu}$	σ_1	K_{SD} $(K_{S\mu} - \sigma_S)$	K_{1D} $(K_{1\mu} - \sigma_1)$
1	3.021	0.475	2.992	0.519	2.546	2.473
2	3.855	1.190	4.221	1.573	2.665	2.648
3	9.585	3.436	12.164	4.624	6.149	7.648
4	10.137	4.825	10.633	4.257	5.312	6.376
Western	4.097	1.025	4.529	1.332	3.072	3.197
Central	6.923	1.434	7.064	1.510	5.489	5.553
Eastern	6.063	1.205	5.978	0.865	4.858	5.113

Table 3. Mean spectral ratios and spectral reduction factors for seismic groups from the 2014 USGS seismic hazard data

	Mean spectral ratios				Reduction factors	
Seismic group	$K_{S\mu}$	σ_S	$K_{1\mu}$	σ_1	K_{SD} $(K_{S\mu} - \sigma_S)$	K_{1D} $(K_{1\mu} - \sigma_1)$
1	3.766	1.121	3.787	0.948	2.645	2.839
2	5.186	2.097	4.473	2.144	3.089	2.329
3	7.035	1.429	9.980	2.332	5.606	7.648
4	7.172	3.632	7.465	3.075	3.540	4.389
Western	5.149	1.616	4.969	1.869	3.533	3.100
Central	5.026	0.870	6.541	0.994	4.156	5.547
Eastern	4.751	0.800	4.974	0.707	3.951	4.267

2014 USGS hazard data for Group 1, provided in Table 3, were slightly higher at 2.67, but suggested that conservative results were still obtained within the limit of 2.5.

The spectral reduction factors of 2.6 and 2.84 for the 2002 and 2014 USGS hazard data for Group 2, which borders Group 1, also roughly corresponded with the limit of 2.5. Table 4 lists the average spectral reduction factor values of the three seismic groups in the western half of the United States (Group 1, Group 2, and western group), along with the other four seismic groups. It is noteworthy that the values presented in Table 4 represent the mean of the spectral reduction factors corresponding to the short-period response acceleration and the long-period response acceleration; they also represent the peak ground acceleration that was not covered in previous sections of this paper. Although not all the results for the peak ground acceleration were covered in this paper, the results followed the same trend as that for the short- and long-period response acceleration values. For example, for Group 1, the K_{PGAD} value of 2.471 was approximately equivalent to the K_{SD} value of 2.546 and the K_{1D} value of 2.473. For Group 2, the result for K_{PGAD}, which was 2.488, was close to that for K_{SD}, which was

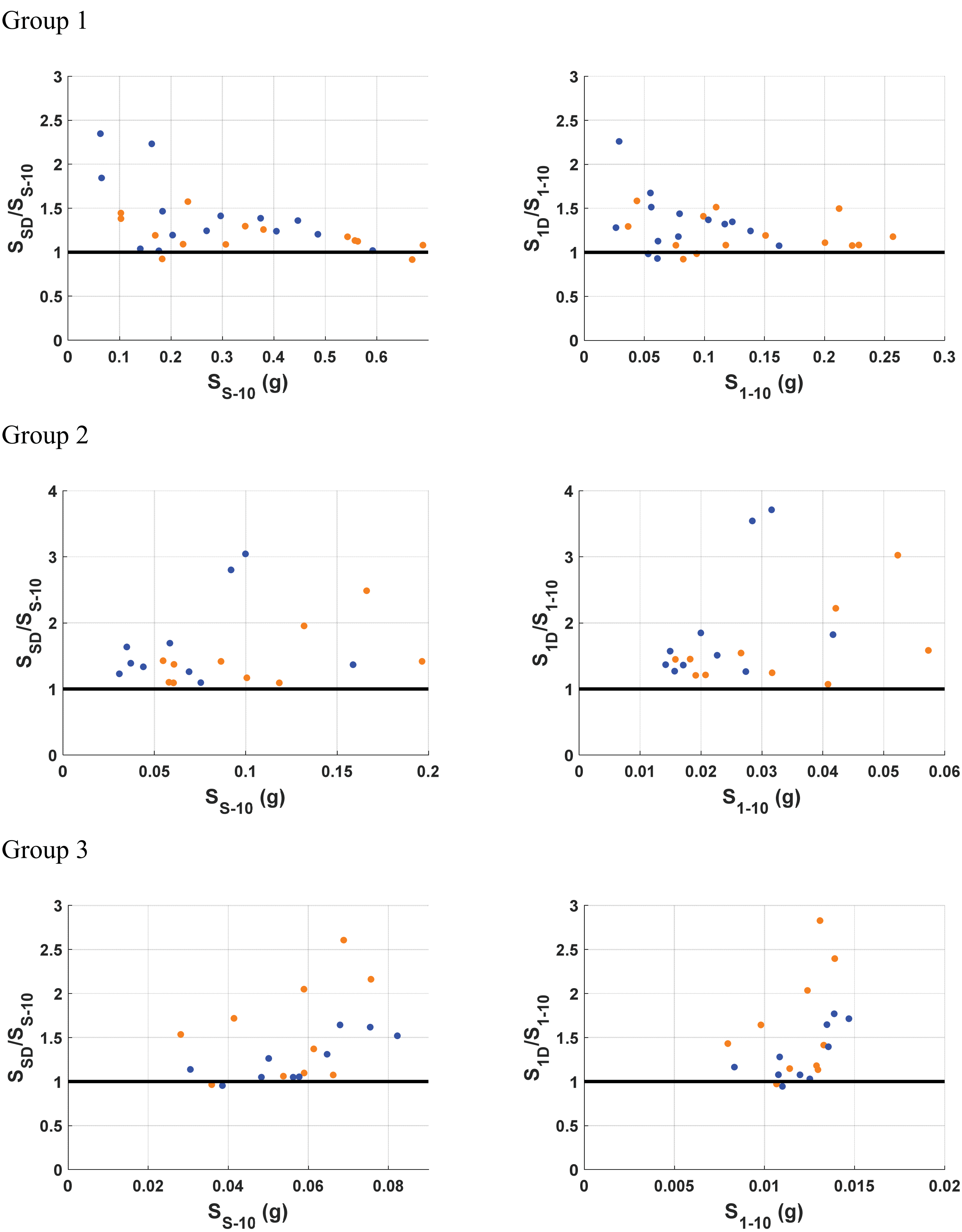

Fig. 3. Comparison of calculated response spectral coefficient values for seismic groups: (a) short-period response acceleration calculated using $K_{s\mu} - \sigma_S$; and (b) long-period response acceleration calculated using $K_{1\mu} - \sigma_1$.

2.665, and K_{1D}, which was 2.648. For the western group, although slightly farther apart, the K_{PGAD} value of 2.785 remained close to the K_{SD} value of 3.072 and the K_1 value of 3.197. All the results are presented in Stucki and Bruneau (2018). The values were somewhat higher when the other western states were considered, at 3.02 and 3.4, respectively, for the 2002 and 2014 USGS data. This finding seems to suggest that the current reduction limit of 2.5 used by the LRFD-SBD was appropriate for the western United States.

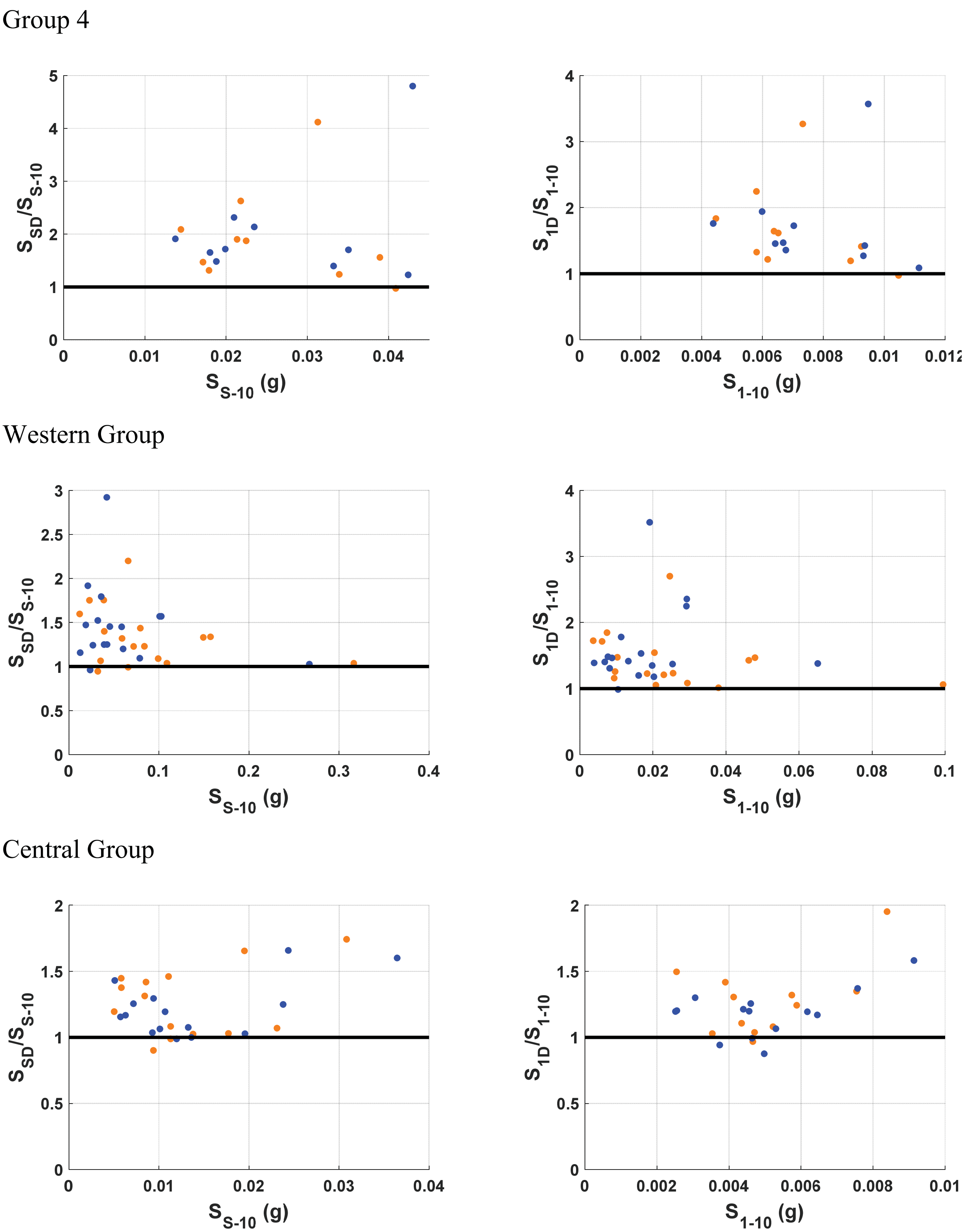

Fig. 3. (*Continued.*)

Unlike those of the seismically active regions found on the west coast, the spectral ratios observed in seismic Groups 3 and 4 indicated a considerably larger variation in the maximum probable ground motion between return periods for seismically active areas on the east coast. This difference was a consequence of strong ground motion that has occurred on the east coast [e.g., the 1886 Charleston, South Carolina, earthquake (Obermeier et al. 1985)], which was felt over a larger area than the area where ground motion has been felt in the western United States (Bollinger 1973; Marsh et al. 2014), but the frequency of such large magnitude earthquakes has been lower in the eastern United States than in the western United States (Algermissen 1969).

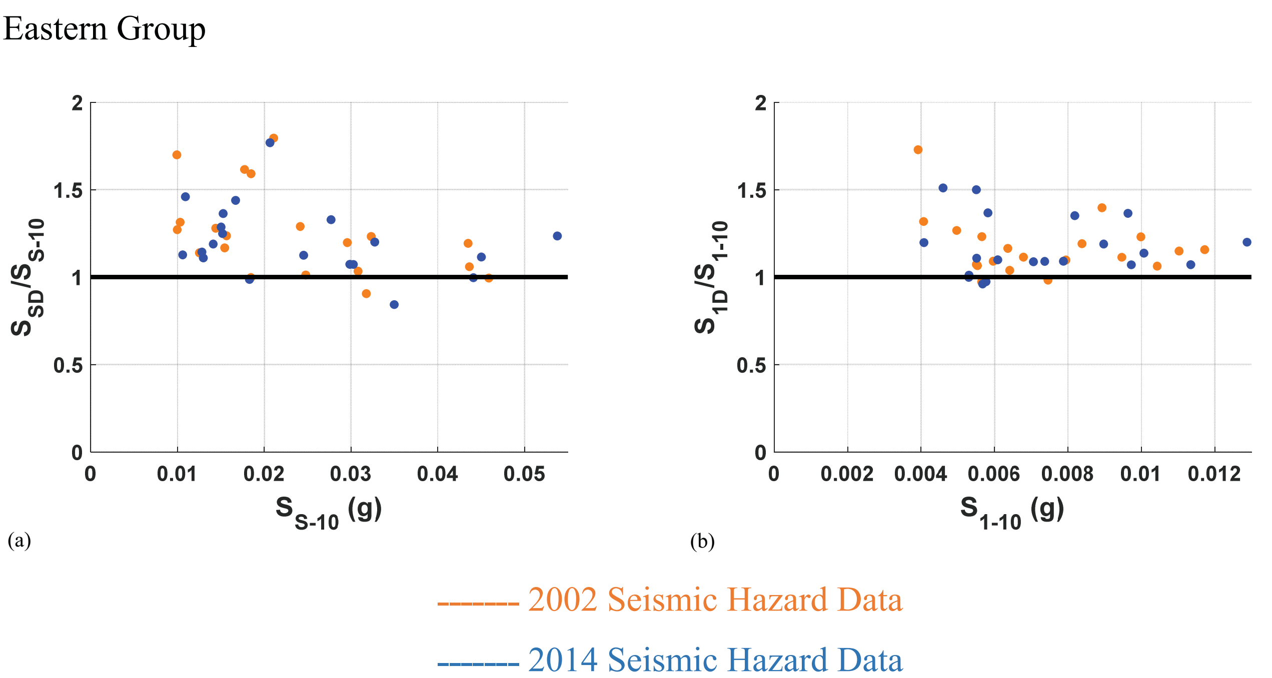

Fig. 3. (*Continued.*)

In one interesting observation, the standard deviation from the mean spectral ratio of the eastern group for the 2014 USGS hazard data was slightly smaller than that for Group 1. This finding was somewhat unexpected because of the greater geographic area covered by the eastern group, the lower seismicity of east coast earthquakes, and the close proximity to known active faults at the site locations of Group 1. Despite an increase in variation for spectral ratios between the 2002 and 2014 hazard data for Group 1, why this has led to a decrease in variation in the results obtained for the eastern group was unclear. Compared to those in the 2002 data set, the spectral ratios of the return periods in the 2014 data set were generally greater for seismic groups in the western United States and smaller for the seismic groups in the central and eastern United States. Possible explanations for the decrease in spectral ratios found in the eastern and central seismic groups include (1) an updated probabilistic modeling methodology used by the USGS and updated ground motion prediction equations introduced in 2014 for the east coast seismic model; (2) ground motion equations for spectral periods that decayed more quickly for the central and eastern United States with the updated methodology (Petersen et al. 2014); and (3) recent increase in earthquakes of Magnitude 3 or greater in the eastern United States (Petersen et al. 2014).

The results using values reduced by one standard deviation from the mean spectral ratio of each seismic group appeared appropriate when examining Fig. 3, with spectral reduction factors achieving a conservative reduction in most instances. Although seismic groups with smaller variations from the mean spectral ratio values corresponded more closely with the spectral reduction factors, and thus, achieved a more accurate spectral reduction, the seismic groups with larger variations from the mean spectral values had large standard deviations that were subtracted from the mean to ensure conservative spectral reduction. The largest standard deviations were observed, using the 2002 hazard data, in seismic Groups 3 and 4, with a mean standard deviation of 4.10 for seismic Group 3 and a mean standard deviation of 5.09 for seismic Group 4. It is noteworthy that these mean standard deviations included the data corresponding to the peak ground acceleration, which were not presented in previous sections of this paper. Despite the relatively large

Table 4. Mean value of the three spectral reduction factors for USGS seismic hazard data sets by seismic group

	USGS hazard data set	
Seismic group	2002	2014
1	2.50	2.74
2	2.60	2.84
3	6.72	6.45
4	5.56	3.84
Western	3.02	3.40
Central	5.45	4.56
Eastern	4.94	4.14

standard deviations, a conservative spectral reduction was apparent when examining Fig. 3. The relatively large variations found in seismic Groups 3 and 4 resulted in greater subtractions from the mean spectral ratio values when using Eqs. (5) and (6) to obtain the seismic group spectral reduction factors. This effect was observed when examining the results of seismic Group 3 in Fig. 3, which showed that the calculated response spectral coefficients were greater than the USGS-obtained response spectral coefficients for 9 of the 10 site locations for both the 2002 and 2014 hazard sets. A similar effect was observed for seismic Group 4, such that when comparing calculated versus obtained spectral response coefficients, all 10 site locations had greater calculated spectral response coefficients for the short- and long-period responses with the 2014 hazard data. With the 2002 hazard data, 9 of 10 site locations had greater short- and long-period response coefficients.

The spectral ratio of the 1,000-year return period to the 100-year return period was observed to increase from west to east across the continental United States, reflecting the greater variation between return periods at site locations for the seismic groups in the central and eastern United States. This finding was not unexpected given the previous seismic hazard curve observations (Judd and Charney 2014). The trend of increasing the spectral ratio from west to east correlated most closely with the 2002

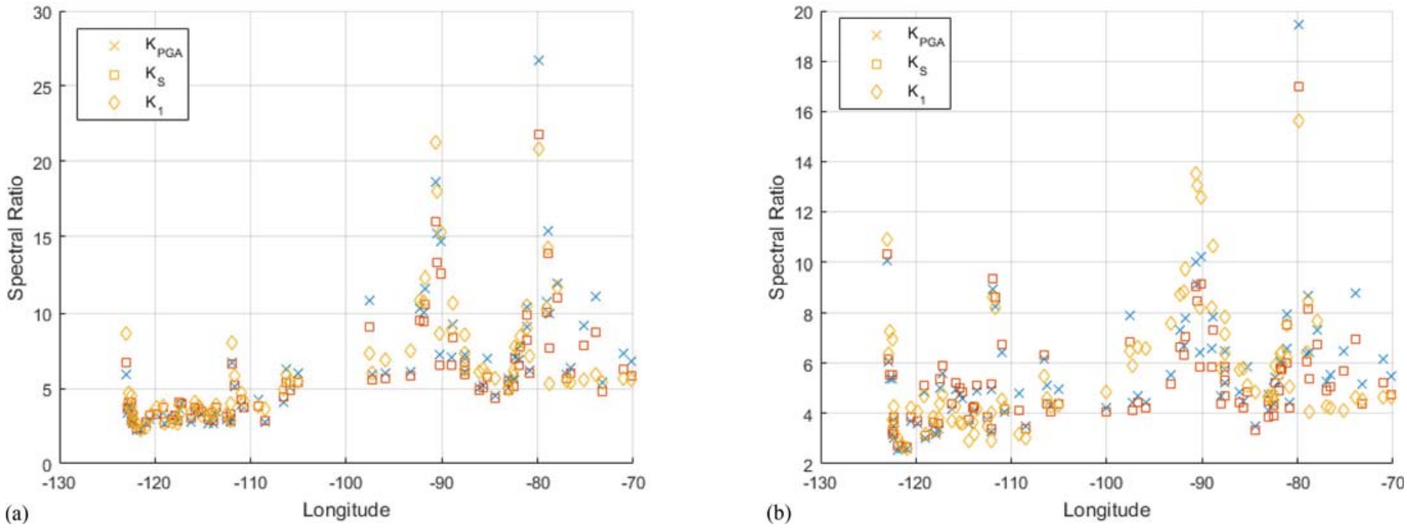

Fig. 4. Spectral ratio as a function of longitude for the 100 site locations corresponding to USGS seismic hazard data sets: (a) 2002; and (b) 2014.

USGS hazard data set. Fig. 4 shows the plot of the average of the spectral ratios K_S, and K_1 as functions of longitude; in addition, results obtained for K_{PGA} (peak ground acceleration) were also presented in this figure [complete details on the results obtained for the peak ground acceleration were provided in Stucki and Bruneau (2018)]. In examining Fig. 4, a linear relationship between longitude and spectral ratio seemed possible, which suggested that future research could investigate the development of a function relating the two ratios.

Considering the lateral variation in spectral ratios with longitude across the continental United States, the corresponding spectral reduction factor values between the eastern seismic group, central seismic group, and seismic Groups 3 and 4, as well as the corresponding spectral reduction factor values shown for the three west coast seismic groups, the results seemed to suggest that one spectral reduction factor can be used for the western United States and a different one can be used for the central and eastern United States. With the understanding that simplicity was likely desired by the engineers who chose not to obtain a spectrum from the USGS website, one spectral reduction factor is proposed for the western United States and a different spectral reduction factor is proposed for both the central and eastern United States. In this case, seismic Groups 1 and 2 along with the western group were considered as the western United States, and seismic Groups 3 and 4 along with the central and eastern groups were considered as the central and eastern United States. For further simplification, it was proposed to use a single factor to reduce all three of the design parameters: PGA, S_S, and S_1.

As previously explained in this section, a single spectral reduction factor of 2.5 seemed appropriate for the western United States irrespective of whether or not it was applied to seismic maps derived from the 2002 or the 2014 hazard data set. For the 2014 seismic hazard data, a conservative spectral reduction was obtained for every examined point in the western United States using a reduction value of 2.5. Using the spectral reduction factor of 2.5 for the western United States with the 2002 seismic hazard data resulted in a conservatively reduced spectrum with the exception of the

- nonconservative reduction of the short-period response acceleration coefficient by 7.2 and 6.42% (for San Jose and Sacramento, respectively) and
- nonconservative reduction of the long-period response acceleration coefficient by 9.2 and 3.09% (for Sacramento and Modesto, respectively).

Despite different seismological structures between the South Carolina fault line and the New Madrid fault, for the central and eastern United States a single spectral reduction factor of 3.75 was found to reduce the short-period response acceleration coefficient conservatively. The long-period response acceleration coefficient for every site location with both the 2002 and 2014 USGS hazard data sets, with the exception of one site (Atlanta) when using 2014 hazard data for which the value would be 11.51%, was nonconservative for the short-period response coefficient. It is noteworthy that, in the context of designing temporary bridges in low to moderate seismic regions, a difference of 10% in the seismic design force considered was insignificant for all practical purposes.

Figs. 5 and 6 show the comparison of the spectral response coefficients calculated using the proposed spectral reduction factors of 2.5 for the western United States and 3.75 for the central and eastern United States with spectral response coefficients that could have been alternatively obtained from the USGS website. The vertical axes of these figures show the calculated short-period response acceleration coefficient, S_{SD}, and the long-period response acceleration coefficient, S_{1D}, divided respectively by the obtained short-period response acceleration coefficient, S_{S-10}, and long-period response acceleration coefficient, S_{1-10}. A bold line is shown at the value of one, with points above the line representing a conservative reduction of the response spectrum using the spectral reduction factors, and points below the line representing a nonconservative reduction. Fig. 5 was generated with the 2002 USGS seismic hazard data, and Fig. 6 was created with the 2014 USGS seismic hazard data.

Seismic Groups by AASHTO Seismic Performance Zone

In addition to seismic groups defined by geographic location, an alternative method was examined (Stucki and Bruneau 2018) in which the same 100 locations were divided into seismic groups by the AASHTO seismic performance zone.

When comparing Figs. 4 and 7, a linear trend was more apparent when the spectral ratio was a function of longitude than when it was a function of long-period response acceleration. Because of the more distinct trend between spectral ratio and the geographic location, it was not recommended that spectral reduction factors be determined on the basis of the magnitude of the long-period response acceleration. For these aforementioned reasons and for brevity, the results obtained when the 100 sites were divided into groups defined by the AASHTO seismic performance zones were not included in this paper.

Example

A brief example shows how to obtain the spectral reduction factors for temporary bridges using the proposed method. The spectral reduction factor for the central and eastern United States, as suggested in the previous section, of 3.75 and denoted as K_D was used to calculate the applicable response spectrum for an example temporary bridge in Charleston, South Carolina. It is noteworthy that this was one of the locations used in the study to derive the spectral reduction factors. For the design spectrum values, A_S, S_{SD}, and S_{1D}, the design values for the temporary bridge response spectrum were denoted corresponding to the peak ground acceleration, short-period response spectral acceleration, and long-period response spectral acceleration defined in Article 3.10.4.2 of the AASHTO LRFD-BDS.

As was done in previous sections, site Class B was assumed for this example; site class is defined in Article 3.10.3.1 of the AASHTO LRFD-BDS. The latitude and longitude for the site, in decimal degrees, and the peak ground acceleration, short-period response acceleration, and long-period response acceleration corresponding to a 7% probability of exceedance in 75 years are presented in Table 5. The 2002 USGS seismic data were used for this example.

The long-period response spectral acceleration of 0.153 g for the 1,000-year return period corresponded to seismic perform-

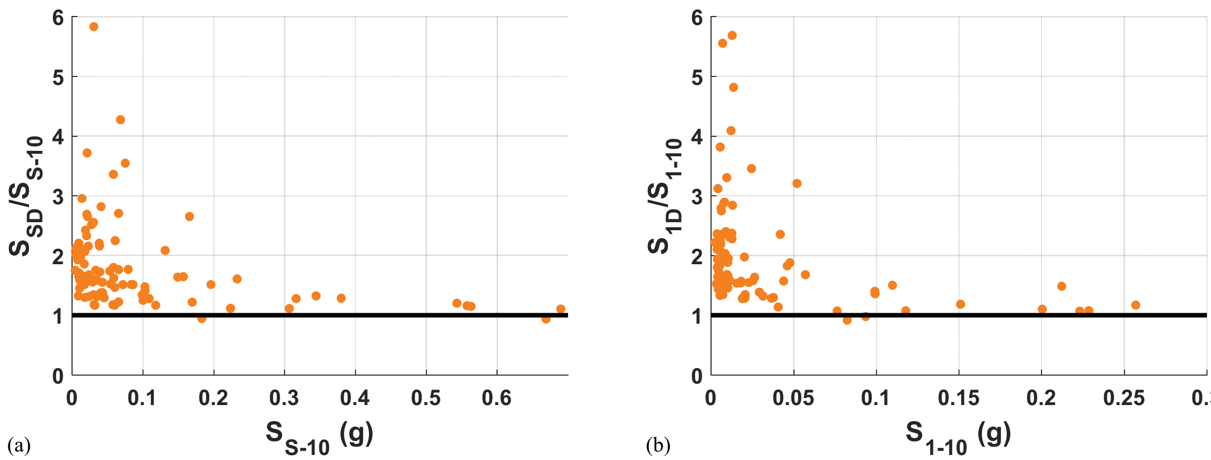

Fig. 5. For the 2002 USGS seismic hazard data, a comparison of the calculated response spectral coefficient values with values obtained using the spectral reduction factors of 2.5 and 3.75 for the western United States and for the central and eastern United States, respectively: (a) short-period response acceleration; and (b) long-period response acceleration.

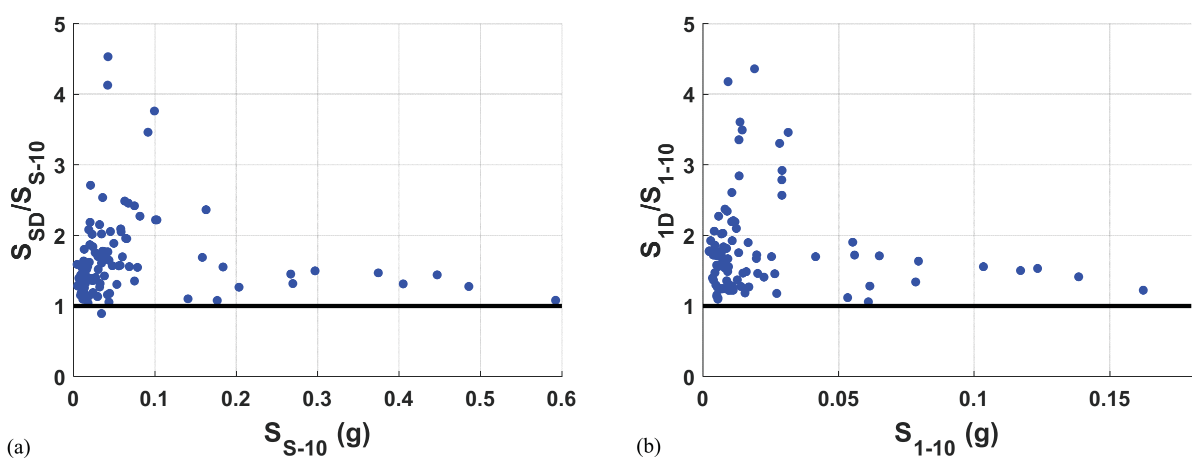

Fig. 6. For the 2014 USGS seismic hazard data, a comparison of the calculated response spectral coefficient values with values obtained using the spectral reduction factors of 2.5 and 3.75 for the western United States and for the central and eastern United States, respectively: (a) short-period response acceleration; and (b) long-period response acceleration.

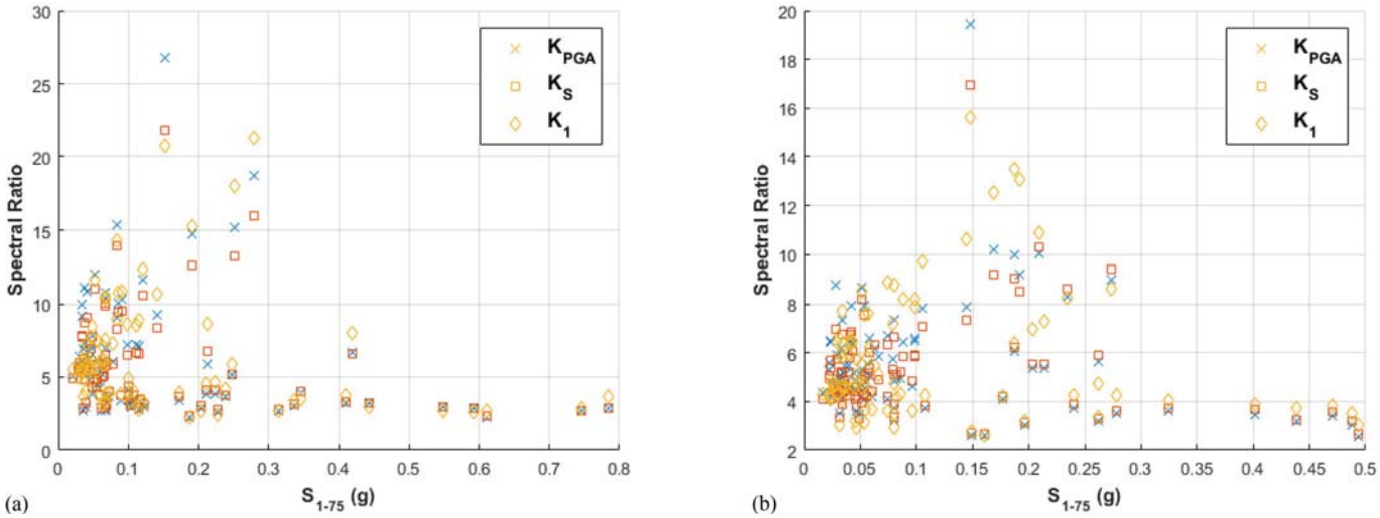

Fig. 7. Spectral ratio as a function of the long-period response acceleration coefficient corresponding to a 7% probability of exceedance in 75 years for the 100 site locations corresponding to the USGS seismic hazard data sets from: (a) 2002; and (b) 2014.

Table 5. Coordinates and spectral coefficients corresponding to the 1,000-year return period used in the example

Parameter	Value
Latitude (°N)	32.78
Longitude (°W)	79.93
PGA_{75} (g)	0.39
S_{S-75} (g)	0.69
S_{1-75} (g)	0.153

ance Zone 2 defined in Article 3.10.6 of the AASHTO LRFD-BDS. As previously stated in the "*Spectral Reduction Factors*" section as an assumption, the site could not be redefined as seismic performance Zone 1 on the basis of the reduced response spectrum.

The design response spectrum corresponding to the temporary designation of the bridge was determined. The single spectral reduction factor suggested for the central and eastern United States in the previous section was used to calculate the design acceleration coefficient, A_S; the design short-period response acceleration coefficient, S_{DS}; and the design long-period response acceleration coefficient, S_{1D}. First, the site factors, presented in Tables 3.10.3.2–1, 3.10.3.2–2, and 3.10.3.2–3 of the AASHTO LRFD-BDS, must be applied. Given the previously stated assumption of site Class B, the three site factors were all equal to unity.

AASHTO LRFD-BDS Eqs. (3.10.4.2–2), (3.10.4.2–3), and (3.10.4.2–6) were then used, as follows, with the number *75* in each subscript referring to a 7% probability of exceedance in 75 years

$$A_{S-75} = F_{\text{pga}}\,\text{PGA}_{75} = 0.39\,g \qquad \text{[AASHTO Eq. (3.10.4.2–2)]}$$

$$S_{SD-75} = F_a\,S_{S-75} = 0.69\,g \qquad \text{[AASHTO Eq. (3.10.4.2–3)]}$$

$$S_{1D-75} = F_v\,S_{1-75} = 0.15\,g \qquad \text{[AASHTO Eq. (3.10.4.2–6)]}$$

The spectral reduction factor was then used to calculate the design response coefficients corresponding to the bridge's temporary designation as follows:

$$A_S = \frac{A_{S-75}}{K_D} = 0.104\,g$$

$$S_{SD} = \frac{S_{SD-75}}{K_D} = 0.184\,g$$

$$S_{1D} = \frac{S_{1D-75}}{K_D} = 0.041\,g$$

From this point, the design response spectrum was determined in the same manner as was done for a permanent bridge. It is noteworthy that, although in this example the site classification of seismic performance Zone 2 (seismic design Category B if using the LRFD-SBD) cannot be redefined, if the site had been classified as seismic performance Zone 3 or 4 (seismic design Categories C or D if using the LRFD-SBD), then on the basis of the 1,000-year return period, reclassification could have been performed as long as the site was not redefined as seismic performance Zone 1 (seismic design Category A if using the LRFD-SBD).

The reference periods for the response spectrum were then calculated using the equations shown in Fig. 3.10.3.1–1 of the LRFD-BDS, as follows:

$$T_S = \frac{S_{1D}}{S_{SD}} = 0.222\,\text{s}$$

$$T_0 = 0.2T_S = 0.044\,\text{s}$$

Finally, a plot of the design response spectrum was determined using LRFD-BDS Eqs. (3.10.4.2–1), (3.10.4.2–4), and (3.10.4.2–5) to define the elastic seismic coefficient, C_{sm}, for the applicable period, as

$$C_{sm} = A_S + (S_{SD} - A_S)\cdot\left(\frac{T_m}{T_0}\right) \text{ for } T_m \leq T_0 \qquad \text{[AASHTO Eq. (3.10.4.2–1)]}$$

$$C_{sm} = S_{DS} \text{ for } T_0 \leq T_m \leq T_S \qquad \text{[AASHTO Eq. (3.10.4.2–4)]}$$

$$C_{sm} = S_{1D} \div T_m \text{ for } T_S < T_m \qquad \text{[AASHTO Eq. (3.10.4.2–5)]}$$

Conclusion

Ratios of the seismic spectral demands corresponding to 7% probability of exceedance in 75 years used to design new bridges and to 10% probability of exceedance in 10 years proposed for the design of temporary bridges were developed for 100 locations across the contiguous United States. These data were then used to identify factors that could be conservatively used for the seismic design of temporary bridges.

It was found that spectral values for new bridges could be reduced by 2.5 for temporary bridges located in regions corresponding to the western United States and by 3.75 in the central and eastern United States. This finding was consistent with the current spectral reduction limit of 2.5 specified by AASHTO Article 3.6 of the guide (and pointed to a possible modification to the AASHTO bridge design specifications, which had used a more restrictive value of 2.0), but it was unduly conservative for sites located in the central and eastern United States.

The spectral reduction factors of 2.5 and 3.75 were found to be appropriate, while still conservative, in that they resulted in a response spectrum with greater response accelerations than a spectrum obtained directly from the USGS website for almost every 1 of the 100 locations examined in this study (with a few exceptions, none more than approximately 10% nonconservative).

Appendix. Regional Differences in Seismic Acceleration Response Spectra and Hazard Curves for the Continental United States

Response spectra for the eastern and central United States could be characterized as having a higher frequency content, on average, than characteristic response spectra for the western United States (Chung and Bernreuter 1981; Judd and Charney 2014). This situation can be explained, in part, by the observed areas of higher attenuation in the western United States and areas with relatively lower attenuation in the central and eastern United States (Benz et al. 1997; Chung and Bernreuter 1981; Solomon and Toksöz 1970). An idealized demarcation line between the two contrasting attenuation behaviors could be taken as the border of the Great Plains and the North American Cordillera (Mitchell 1975). Attenuation is the decrease in amplitude as a wave propagates because of energy losses (Burland et al. 2012). For near-field seismic events, attenuation was generally comparable between the eastern and western United States, but for the far-field events, a pattern of higher attenuation in the western United States was observed (Chung and Bernreuter 1981). One attribute typical of the central and eastern United States is that of a greater felt area than an earthquake of similar magnitude than is felt in the western United States (Marsh et al. 2014). Regional variations in attenuation have been attributed to differences in the volume of water in pore spaces (Mitchell 1975) and in ground absorption (Chung and Bernreuter 1981), high heat-flow regions corresponding with higher rates of attenuation (Mikami and Hirahara 1981), and variations in crustal structure (Gregersen 1984).

Attenuation has been a factor in both probabilistic and deterministic seismic design, and attenuation rates have been used to estimate ground motions for earthquake design parameters (Campbell 1997). In the central and eastern United States, greater uncertainty in attenuation and response exists because of a relatively low frequency of earthquakes in comparison with the western United States (Judd and Charney 2014). The lower attenuation exhibited in the central and eastern United States, combined with a greater average distance from the event-generating faults, led to seismic hazard curves that were dominated by far-field events, particularly as the spectral period increased (Judd and Charney 2014). In 2014, Judd and Charney (2014) observed temporal differences in the seismic hazard curves and found that the average ratio of spectral acceleration for a 72-year return period to the maximum considered event (MCE) was 20% for the western United States and 10% for the eastern United States. Such a factor of 2 was significant for designing structures at a low-return period when using values derived from a long-return period spectrum.

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