INFLUENCE OF FAULTING STYLE ON THE DIRECTIONALITY OF EARTHQUAKE RESPONSE SPECTRA

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Abstract: *Horizontal ground motion intensity varies significantly with changes in orientation, a phenomenon known as ground motion directionality. This variation is important in earthquake-resistant design because most structures have mechanical properties that vary with azimuth. Most of the engineering community's attention on ground motion directionality has focused on forward directivity effects that generate polarization in a strike-normal orientation at locations that are very near the seismic source. However, ground motion directionality can have several other causes that exist regardless of the distance to the seismic source, such as local geologic heterogeneities, topographic irregularities, and the finiteness of earthquake loading. This work studies another such cause that is linked to the theoretical polarization of seismic waves emanating from the source. At distances of engineering significance, ground motion intensity is usually controlled by S waves, which are polarized in orientations that are orthogonal to the direction of propagation, suggesting that ground shaking could be more intense in the transverse orientation, that is, an orientation perpendicular to the imaginary line segment joining the site to the earthquake epicenter. Using the NGA-West2 database, ground motion records from strike-slip earthquakes were indeed found to have orientations of maximum spectral response that occur close to the transverse orientation. On the other hand, records from earthquakes with reverse faulting style do not follow this trend, with orientations of maximum spectral response being essentially random with respect to the transverse orientation. A simple model is presented to transform median spectral accelerations from all orientations (i.e., RotD50), estimated with any ground motion model that provides estimates of RotD50, into spectral accelerations at specific orientations measured with respect to the transverse orientations. These results can then be used to perform improved seismic hazard analyses at specific azimuths, leading to spectral ordinates that become smaller as the orientation of interest rotates away from the transverse orientation towards the radial orientation. This research has significant implications for regions such as California, where strike-slip faults represent a major source of seismic hazard.*

1. Introduction

Although horizontal ground motion intensity varies with orientation, a phenomenon known as ground motion directionality, this intensity is usually oversimplified to be characterized by a single representative value. For example, recent ground motion models (GMMs) usually use the median intensity from all horizontal orientations (e.g., Boore et al., 2014; Parker et al., 2022), whereas earthquake-resistant design codes in the United States instead use the maximum intensity from all horizontal orientations (e.g., ASCE, 2022), which are usually referred to as RotD50 and RotD100, respectively (Boore, 2010). However, the variation of horizontal ground motion intensity can be significant, as evidenced by previous studies focused on spectral accelerations (e.g., Hong and Goda, 2007; Poulos and Miranda, 2022). These variations are relevant for earthquake-resistant design because most structures have mechanical properties that also vary with horizontal orientation. Thus, estimating orientation-dependent ground motion intensities could improve current design practices.

Ground motion directionality has previously been attributed to several possible causes, such as topographic irregularities (Spudich et al., 1996), local geologic heterogeneities (e.g., Bonamassa and Vidale, 1991), the finiteness of earthquake loading (Poulos et al., 2022), and rupture directivity (e.g., Somerville et al., 1997). However, most of these observations have yet to lead to models that can estimate ground motion intensity at given horizontal orientations, probably due to the lack of available data and the difficulty to predict the orientations where intensities are likely to be larger than average.

At distances of engineering significance, earthquake response spectra are usually controlled by S-waves due to their higher amplitude relative to other seismic waves. Theoretical S-wave radiation patterns from a double-couple point source in a homogeneous propagation medium show that ground motions are polarized in an orientation that is transverse to the direction of propagation (Aki and Richards, 2002). This suggests that response spectral ordinates could be higher than average in the transverse orientation, that is, in an orientation perpendicular to the line segment between the earthquake source and the site of interest. Although real earthquakes are not point sources and propagation media and wave propagation processes are much more complex than the theoretical case, the idealized transverse polarization may still be informative when constructing predictive models, especially for cases when the simplifying assumptions are closer to real conditions.

This paper summarizes a study in which maximum horizontal spectral responses were compared to spectral responses in the transverse orientation when using a large number of ground motion records from the NGA-West2 database (Ancheta et al., 2014). Probability distributions were then fitted for the angular difference between the orientation maximum horizontal spectral response and the transverse orientation for different periods. The same database was then used to study how spectral responses at given horizontal orientations depend on the angular distance to the transverse orientation. Finally, a simple regression model was developed to transform RotD50 spectral responses computed with existing GMMs to estimate spectral responses in any specific horizontal orientation.

2. Orientation of maximum horizontal spectral response

Horizontal ground motion accelerations are usually recorded in two perpendicular orientations. The relative displacement of a linear-elastic single-degree-of-freedom oscillator with a given period and damping ratio (assumed to be 5% herein) subjected to both horizontal components of ground motion can be used to compute spectral responses at all other horizontal orientations. For example, Figure 1a shows the relative displacement hodogram of a 10-s oscillator when subjected to a ground motion recorded during the 1999 M_w 7.1 Hector Mine earthquake in the LAX fire station (NGA-West2 record sequence number 1802, Ancheta et al., 2014), together with spectral displacements at all other orientations shown in a polar representation (i.e., the intensity at any given orientation is given by the corresponding distance to the origin). The same dependence on horizontal orientation is shown in Figure 1b, but now in linear representation. For this record and period, spectral responses are strongly dependent on orientation, with spectral displacements ranging from 3.2 cm to a maximum value (RotD100) of 32.8 cm, that is an intensity approximately ten times larger, which occurs in an orientation that is 124° counterclockwise from the East.

Figure 2 shows the orientations of RotD100 at 10 s with black line segments for many stations in Southern California that recorded the same 1999 M_w 7.1 Hector Mine earthquake. As shown in the figure, these orientations of maximum spectral response tend to occur close to the transverse orientations from the epicenter, that is, an orientation perpendicular to the line joining the corresponding site to the earthquake epicenter, depicted by gray lines in Figure 2. The angular difference between these two orientations, measured counterclockwise positive from the transverse orientation, is defined in this study as $\alpha \in [-90°, 90°]$. The absolute value of α (i.e., the angular distance) at each recording station is depicted in Figure 2 by the color of the corresponding circle. If the orientations of RotD100 were fully random with respect to the transverse orientation (i.e., $|\alpha|$ having a uniform probability distribution within 0° and 90°), the mean value of $|\alpha|$ would be 45°, with around half of the stations below 45° (i.e., colored blue) and the other half above 45° (i.e., colored red). However, as seen in Figure 2, almost all stations are colored blue, and the mean $|\alpha|$ value is only 10.4°.

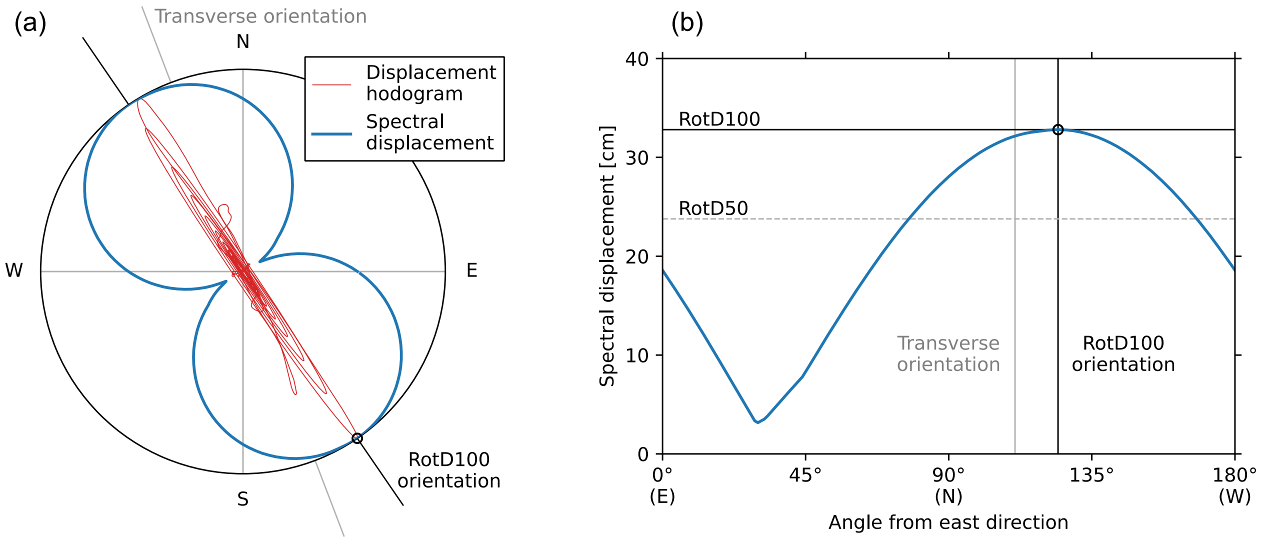

Figure 1. Variation with horizontal orientation of spectral displacement at 10 s from an example ground motion recorded during the 1999 M_w 7.1 Hector Mine earthquake in the LAX fire station. Spectral displacements are shown using an (a) polar and (b) linear representation.

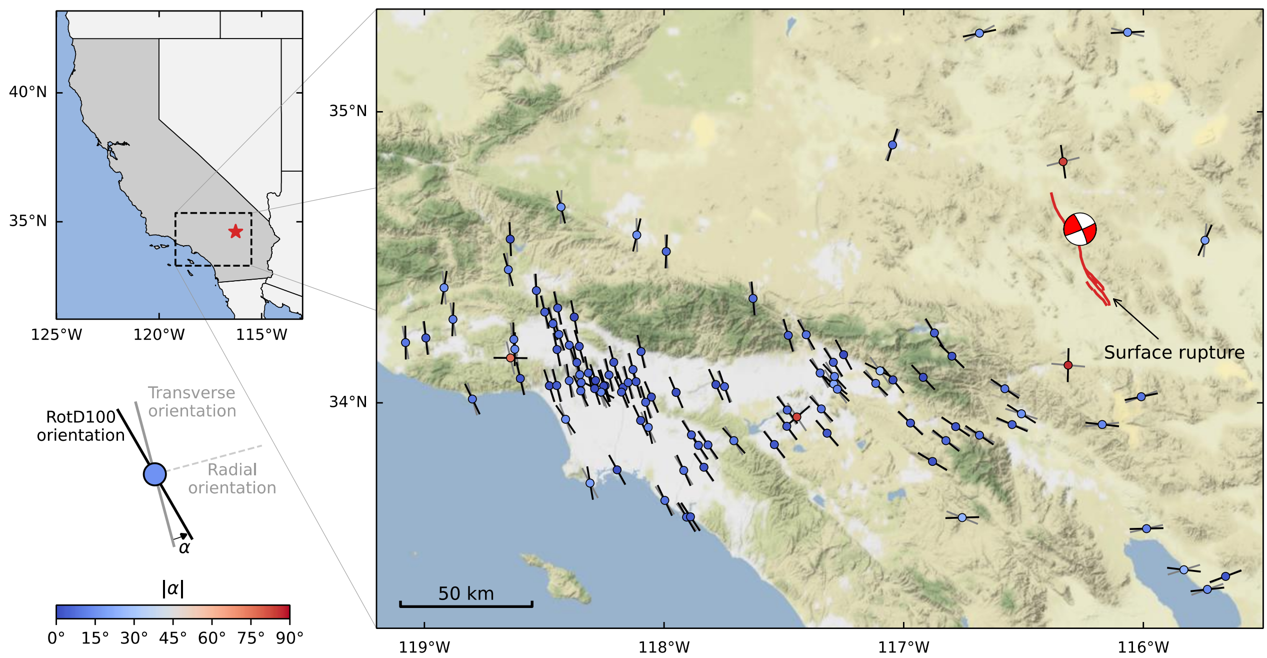

Figure 2. Orientations of RotD100 at 10 s of ground motions recorded during the 1999 M_w 7.1 Hector Mine earthquake. Circles represent the location of recording stations, and their colors represent the angular distance between the RotD100 and transverse orientations. Black and gray line segments represent the RotD100 and transverse orientations, respectively. The surface rupture is from Treiman et al. (2002). Map tiles are by Stamen Design, under CC BY 3.0, and basemap data are by OpenStreetMap, under ODbL.

To obtain more statistically significant results, this work was based on a large number of ground motion records from the NGA-West2 database (Ancheta et al., 2014). The records were selected from earthquakes with $M_w \geq 5.0$; were recorded at stations with NEHRP site class B, C, or D; and reasonably represent free field conditions following the criteria used by Boore et al. (2014). The records were grouped by style of faulting, resulting in 1962 records from 74 strike-slip earthquakes and 2220 records from 35 reverse earthquakes. Records from earthquakes with normal and oblique faulting were not used due to their relatively low number in the database. Figure 3 shows the mean and median values of $|\alpha|$ as a function of period for the two considered styles of faulting. The mean of records from earthquakes with reverse faulting remains close to 45° throughout the range of periods, suggesting that the orientations of RotD100 have no clear trend with respect to the transverse orientations, at least in aggregate terms. On the other hand, the mean of records from earthquakes with strike-slip faulting, such as the 1999 M_w 7.1 Hector Mine earthquake shown in Figure 2, is significantly lower than 45° and tends to decrease as the period gets longer, meaning that, in strike-slip earthquakes, the orientations of RotD100 tend to be close to the transverse orientation and become even closer as the period increases. The α values from strike-slip earthquakes were used to fit an axial normal distribution (Arnold and SenGupta, 2006) at different periods, as shown in Figure 4. Further details about the fitted probability distributions are presented in Poulos and Miranda (2023a).

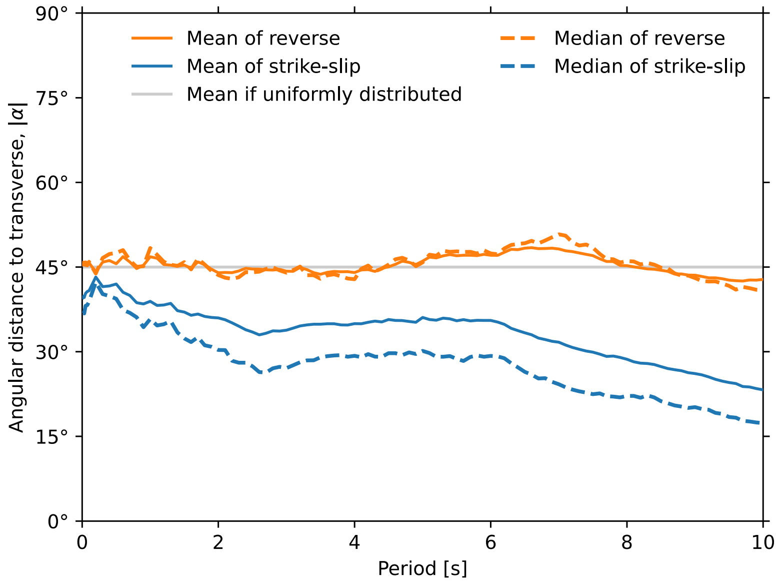

Figure 3. Mean and median angular distance between the RotD100 and transverse orientations as a function of period. The statistics are computed separately for records from earthquakes with reverse and strike-slip faulting.

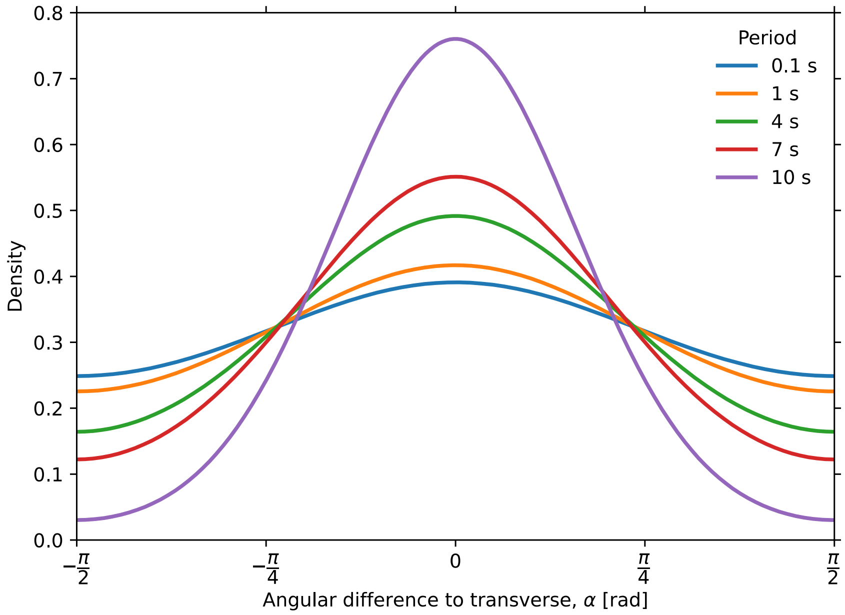

Figure 4. Probability density functions fitted to the angular differences between the transverse orientation and the orientation of maximum spectral response using ground motion records from strike-slip earthquakes.

3. Spectral responses in any given horizontal orientation

Based on the observation that, for strike-slip earthquakes, the orientations of RotD100 tend to be close to transverse orientation, one would expect spectral responses in the transverse orientation to be, on average, larger than the median spectral response from all horizontal orientations (i.e., RotD50). Conversely, one would expect spectral responses in the radial orientation (i.e., the orientation perpendicular to the transverse orientation) to be, on average, smaller than the RotD50 intensity. For example, Figure 5 shows spectral displacements and spectral accelerations as a function of period for the same ground motion record as Figure 1. Shaded areas represent the complete range of possible spectral responses from all horizontal orientations, from RotD00 to RotD100. For periods longer than approximately 3 s, response spectra in the transverse orientation are larger than RotD50 and are very close to RotD100, whereas response spectra in the radial orientation are smaller than RotD50 and close to the minimum from all orientations. Moreover, the shaded areas tend to widen as the period becomes longer, indicating that the response tends to be more linearly polarized.

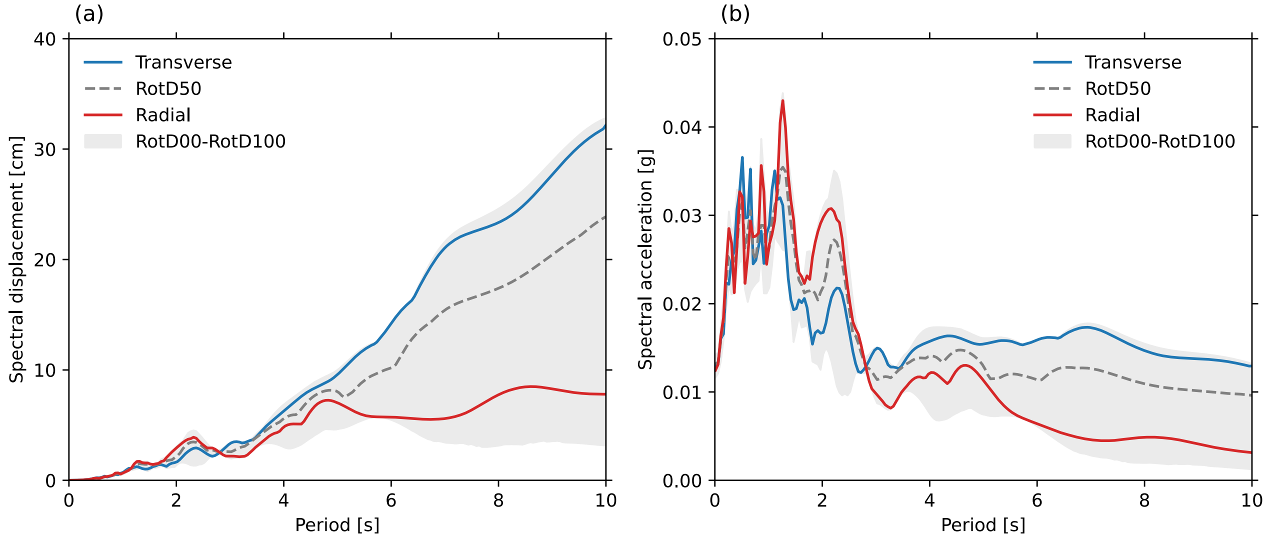

Figure 5. Variation of the response spectra from the example ground motion with horizontal orientation. (a) Spectral displacement and (b) spectral acceleration.

The orientation of interest at a particular site (e.g., the principal orientations of a building) will probably not coincide with the transverse or the radial orientation. Thus, spectral responses at given orientations are studied as a function of their angular distance to the transverse orientation, defined here with angle θ. Given that most modern GMMs use RotD50, the amount by which this intensity should be multiplied to obtain spectral responses at any angular distance θ is given by the following γ ratio:

$$\gamma(\theta) = \frac{SA(\theta)}{SA_{\mathrm{RotD50}}} \tag{1}$$

where SA_{RotD50} is the RotD50 spectral response, and $SA(\theta)$ is the spectral response in an orientation that is at an angle of θ away from the transverse orientation. The geometric mean of the γ ratio was computed at each angle θ and for several periods, resulting in the solid lines shown in Figure 6. As expected, the geometric mean γ ratios tend to decrease as the orientation of interest moves away from the transverse orientation, and this variation becomes more important as the period gets longer. To simplify the use of these results, Figure 6 also presents the following simple regression model that was fitted to the empirical data:

$$\hat{\mu}_\gamma(\theta) = c_1 + c_2 \cos(2\theta) + c_3 \cos(4\theta) \tag{2}$$

where $\hat{\mu}_\gamma$ is the estimated geometric mean γ ratio; and c_1, c_2, and c_3 are the parameters of the model, which were fitted for each period independently and can be found in the supplemental material of Poulos and Miranda (2023b). These geometric mean ratios can be used to modify the mean logarithm provided by any GMM that was developed to estimate the RotD50 intensity in order to obtain values corresponding to spectral accelerations at a specific orientation θ:

$$E[\ln SA(\theta)] = E[\ln SA_{\mathrm{RotD50}}] + \ln \mu_\gamma(\theta) \tag{3}$$

where $E[\cdot]$ represents the expectation function, and μ_γ is the geometric mean of the γ ratio, which can be estimated by $\hat{\mu}_\gamma$ computed with Equation (2). Although the simple model proposed in Equation (2) only depends on the angle θ and the period and not on predictor variables usually used in GMMs, such as magnitude and source-to-site distance, the dependence on these variables was found to be minor to moderate (Poulos and Miranda, 2023b). Poulos and Miranda (2023b) also provide expressions that can be used to modify the logarithmic standard deviation provided by GMMs.

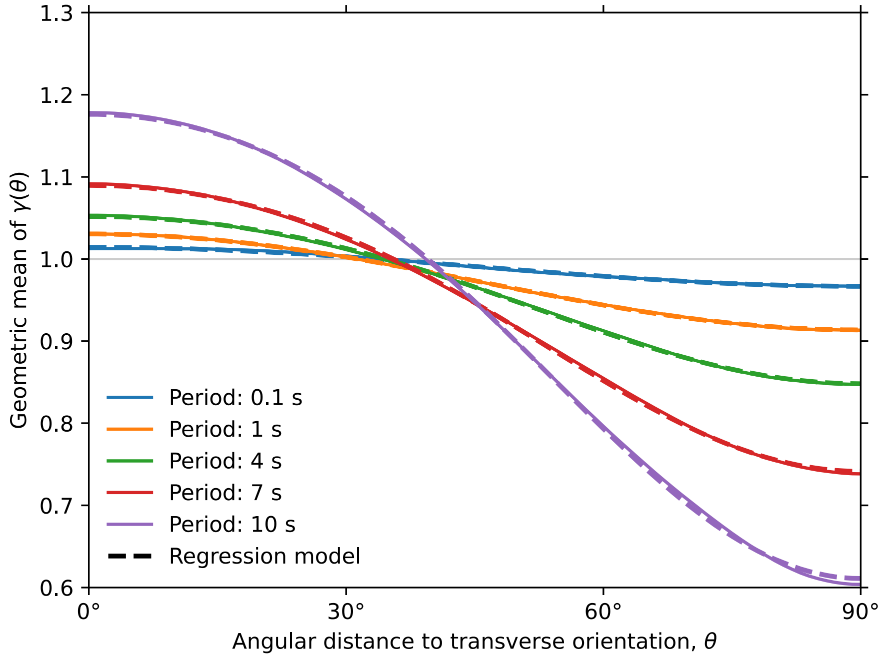

Figure 6. Geometric mean of the γ ratio as a function of angle θ for different periods. Only ground motions recorded during strike-slip earthquakes are considered. Dashed lines correspond to the regression model developed by Poulos and Miranda (2023b).

4. Conclusions

This paper summarizes recent findings about the effect of faulting style on the directionality of horizontal earthquake response spectra (Poulos and Miranda, 2023a; Poulos and Miranda, 2023b). Records from strike-slip earthquakes were found to have orientations of maximum spectral response that tend to occur close to the epicentral transverse orientation, that is, an orientation that is perpendicular to the line segment joining the site of interest to the earthquake epicenter, with this tendency being more apparent as the period of the oscillator become longer. Records from reverse earthquakes, on the other hand, do not exhibit this trend, with orientations of maximum spectral response that seem to be uniformly distributed with respect to the transverse orientation. Probability distributions were fitted for the angular difference between the orientation of maximum spectral response and the transverse orientation, which, can be used to sample the orientation of maximum spectral response as a function of the locations of the epicenter and of the site of interest.

For strike-slip earthquakes, spectral responses in the transverse and radial orientation were found to be, on average, larger and smaller than the median (RotD50) intensity, respectively. Moreover, on average, spectral responses were found to decrease as the orientation of interest moved away from the transverse orientation to the radial orientation. Thus, spectral responses at specific horizontal orientations were computed as a function of the angular distance to the transverse and then normalized by the RotD50 intensity. This ratio can be used to modify results obtained from current GMMs developed for the RotD50 intensity to estimate spectral accelerations at specific horizontal orientations.

These findings are particularly relevant for earthquake-resistant design purposes, especially for structures with long fundamental periods of vibration (e.g., tall buildings and bridges) in regions of the world where the seismic hazard is controlled by seismic sources that generate strike-slip earthquakes (e.g., California). The results provided here can be used to estimate spectral accelerations at specific orientations (azimuths) of interest, such as the principal orientations of a structure, which in turn could be used to estimate the seismic hazard at these orientations, providing a better estimate of seismic demand on a structure than what can be estimated using current RotD50 intensities.

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