EXAMINATION OF DIRECTIONALITY IN THE M_W 6.4, FERNDALE, CALIFORNIA EARTHQUAKE

N. Girmay[1], E. Miranda[1] & A. Poulos[1]

[1] John A. Blume Earthquake Engineering Center, Stanford University, Stanford, CA, USA,
Corresponding Author: ngirmay3@stanford.edu

Abstract: *The horizontal intensity of earthquake ground motions at a given site can significantly vary from one orientation to another. At present, most ground motion models only predict the median intensity from all orientations, which is usually referred to as RotD50. By using this scalar as representative of the intensity that occurred at a site, these models neglect ground motion directionality. Past studies on directivity and directionality have found that the orientation of maximum response spectral ordinates tend to be closer to the strike-normal orientation but only at rupture distances less than 5 km. These prior studies also concluded that the orientation of maximum spectral response becomes entirely random (i.e., uniformly distributed) with respect to the strike-normal orientation at distances longer than 5 km and therefore cannot be determined a priori. As a result of those studies, current seismic criteria in the U.S. specify that when conducting response history analyses for sites located more than 5 km from the rupture, pairs of orthogonal components of ground motions should be applied at a random orientation with respect to the axes of principal response of the structure. However, a recent study using the NGA-West2 ground motion database showed that the orientation of maximum spectral response for strike-slip earthquakes occurs relatively close to the transverse orientation (i.e., transverse to the epicenter-station azimuth). This paper uses recordings from the* M_w *6.4 December 20, 2022, Ferndale, California earthquake, a recent well-recorded strike-slip event, to independently examine the orientation where the maximum spectral response occurs. This orientation is found to be, on average, close to the transverse orientation, therefore confirming prior observations from other earthquakes. Furthermore, results from this investigation show that oscillator response remains strongly polarized even at long distances from the epicenter. Response spectral ordinates in the transverse orientation are, on average, between 1.0 to 1.26 times larger than the median intensity of all orientations, indicating that current ground motion models based on RotD50 systematically underestimate spectral ordinates at orientations equal or close to the transverse orientation. Being able to reliably estimate the orientations where the strong and weak intensities occur will lead to a new generation of improved, orientation-dependent ground motion models.*

1. Introduction

Earthquake ground motions are typically recorded in three orthogonal components: two horizontal components perpendicular to each other and one vertical component. For engineering purposes, simplified quantitative measures of ground motion intensity, referred to as *intensity measures*, are computed from the recorded ground motions. In probabilistic seismic hazard analysis and earthquake-resistant design, by far the most commonly used intensity measure (IM) is the 5%-damped pseudo-acceleration response spectral ordinate. This IM is directly proportional to the peak displacement response of a linear elastic, single-degree-of-freedom (SDOF) oscillator with a given fundamental period and a damping coefficient of 5% of the critical damping. In other words, a ground motion is described as being more intense if, for a given period, it moves an SDOF more than another ground motion. However, it is well-documented that the amplitudes of the horizontal recorded ground motions exhibit significant variations with changes in azimuth in a phenomenon that is called directionality (Hong and Goda, 2007; Poulos and Miranda, 2022b; Shahi and Baker, 2014). For example, while examining baseline correction of digital strong motion records, Boore et al. (2002) observed that there were large differences in peak amplitudes between the two recorded components. Similar observations were noted by Boore and Akkar (2003) and Poulos et al. (2022). Although directionally is widely recognized in numerous studies, it is neglected by current ground motion models (GMMs). Most, if not all, current GMMs provide an estimate for a single scalar measure of ground motion intensity, and therefore essentially neglect directionality effects by not accounting for orientation dependence of amplitude. Consequently, there have been several studies assessing which scalar measure of intensity best represents the ground motion intensity at a given site (e.g., Abrahamson and Silva, 1997; Beyer and Bommer, 2006; Boore, 2010; Boore et al., 1997, 2006; Boore and Kishida, 2016; Joyner and Boore, 1982). Directionality is also entirely neglected in most seismic design codes. A notable exception is the United States where, since 2010, directionality is indirectly accounted for by using some approximate factors to amplify the median intensity from all orientations (RotD50) estimated by GMMs to estimate the maximum intensity within the horizontal plane (RotD100). However, this is still a scalar and is applied in a random orientation with respect to the principal axis of the structure, so it does not properly account for the full orientation dependence of amplitudes or the fact that the design intensity may be exceeded in the principal directions of a structure (Poulos and Miranda, 2022a).

One reason that has prevented the development of orientation-dependent GMMs is that the maximum intensity was believed to not have a preferred orientation at source-to-site distances greater than 5 km. Somerville et al. (1997) observed that in the near-field region, response spectral ordinates for oscillators with periods longer 0.6 s tended to be larger in the strike-normal orientation than that in the strike-parallel orientation, which indicated that the maximum intensity may have a preferred orientation aligned with the strike-normal orientation. Other studies conducted in the following years found that there was certainly a higher probability that the orientation of maximum spectral response was close to the strike-normal orientation, but this was only true for rupture distances less than 5 km (Huang et al., 2009; NEHRP Consultants Joint Venture, 2011; Shahi and Baker, 2014). The general conclusion from these studies was that the orientation of maximum horizontal spectral responses as measured with respect to the fault strike is equally likely to occur in all orientations for distances greater than 5 km. As a result, current seismic design standards in the United States imply that the orientation of maximum intensity cannot be estimated at larger source-to-site distances (ASCE, 2013, 2017, 2022).

Poulos and Miranda (2023a) took a contrasting approach to the studies cited above by investigating the orientation of maximum intensity with respect to the epicentral transverse orientation, which is defined as the orientation orthogonal to a line segment connecting the station to the epicenter. Unlike the strike-normal orientation, which is the same for all recording stations, the transverse orientation changes for each site depending on the position of the station relative to the epicenter. Using 2226 ground motions from reverse-faulting and 1966 ground motions from strike-slip earthquakes with a minimum magnitude of five obtained from the NGA-West2 database, they found that the orientation of maximum spectral response was influenced by each earthquake's style of faulting. They found that the response of oscillators subjected to the ground motions recorded during reverse-faulting events did not exhibit a preferred orientation of maximum response. In contrast, for strike-slip earthquakes, the orientation of maximum response tended to be close to the transverse orientation, and this tendency increased further with increasing period of the oscillators. This observation has many implications because it means that the maximum horizontal spectral response does not have an equal likelihood to occur in any orientation (i.e., with a uniform probability distribution), but rather that for strike-slip earthquakes this orientation of maximum intensity can be estimated by the location of the station relative to the epicenter.

The December 20th, 2022, M_w 6.4 Ferndale earthquake had strike-slip faulting and occurred in a well-instrumented region with one of the highest seismicity in California. This moderate-sized earthquake generated a rich set of ground motions and therefore provides an opportunity to independently evaluate prior observations of Poulos and Miranda (2023a) using an earthquake that was not considered in their study. In addition, it provides the opportunity to study the intensity of response spectral ordinates in the transverse orientation as compared to the current code design intensity (RotD100) and the scalar intensity predicted by GMMs (e.g., RotD50). Using the records from this earthquake, this paper investigates the orientation of maximum spectral response and its spatial distribution. Additionally, it quantifies the level of polarization of the ground motions at different epicentral distances and examines response spectral ordinates at the epicentral transverse and radial orientations relative to RotD50 and RotD100 intensities.

2. Earthquake description and ground motions

On December 20, 2022, at 14:34 local time, a M_w 6.4 earthquake struck the coast of Northern California. The earthquake, hereafter called the Ferndale earthquake, occurred due to strike-slip faulting on a fault striking west-southwest with an epicenter located approximately 15 km southwest of the city of Ferndale in the state of California (USGS, 2022). A map of Northern California and the location of the earthquake's epicenter and its corresponding fault is shown in Figure 1. The region shown in the map is at the intersection of three tectonic plates and, consequently, is one of the most seismically active regions in California.

The ground motions from the Ferndale earthquake used in this paper were obtained from the Center for Engineering Strong Motion Data (CESMD, 2022). Only strong motion stations that acceptably represented free-field conditions and had records available in two horizontal components (with the polarity of sensors known) were used in this study. Each record was used up to its maximum usable period (Boore, 2004), which was computed as 1/1.25 times the low-pass frequency, similar to the methods of Abrahamson and Silva (1997). This was necessary to ensure that the records used were suitable for studying the long period range. In addition, to guarantee a strong signal-to-noise ratio for a wide range of periods, only recording stations in which at least one component had a peak ground velocity greater than 1 cm/s were considered. Based on these criteria, 70 recording stations were found usable up to 8 s, and 55 were found usable up to 10 s. A summary of the geographic distribution of stations that were used in this study is shown in Figure 1.

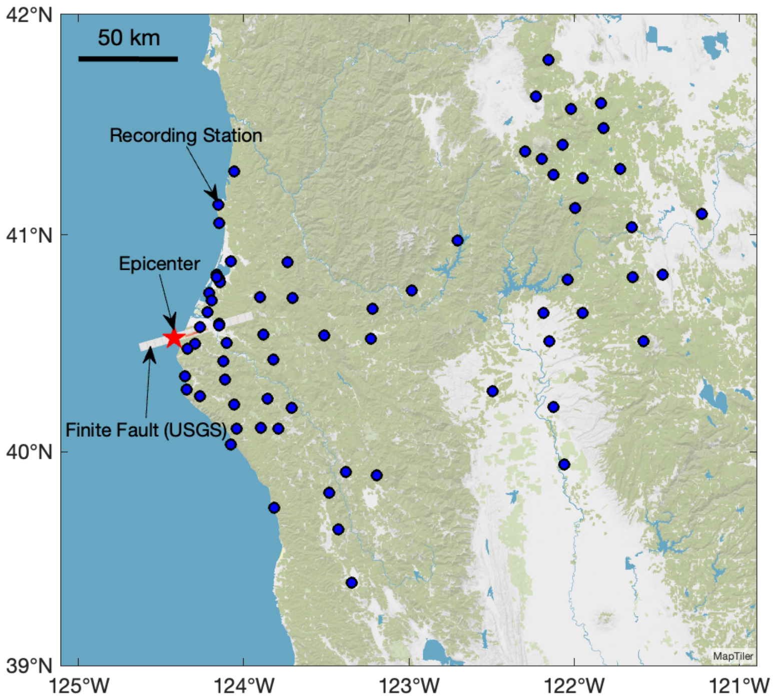

Figure 1. Map of Northern California showing the region studied including the epicenter (red star), recording stations (blue circles), and surface projection of the finite fault rupture.

3. Orientation of maximum spectral response

The spectral response in any azimuth at a given site can be determined by first computing the relative displacement history for each as-recorded component, followed by a geometric combination of the displacement histories into a single waveform at a given orientation, and then repeating this process for different orientations within the horizontal plane (Boore, 2010). The absolute maximum of the rotated displacement history represents the amplitude of response in the associated azimuth. The maximum horizontal spectral response, namely RotD100, represents the maximum response from all non-redundant orientations. As the name implies, the orientation of maximum spectral response is then the azimuth in which RotD100 occurs. In Figure 2, short black lines are used to indicate the orientation of maximum spectral response at each recording station from the Ferndale earthquake. Poulos and Miranda (2023a) define the angular distance of the maximum spectral response from the epicentral transverse orientation as the angle α, which ranges between -90° and 90°. In their work, the sign of α indicates whether RotD100 is clockwise or counterclockwise with respect to the transverse orientation; however, this study uses the angular distance $|\alpha|$ which does not distinguish between clockwise or anticlockwise orientation. In Figure 2, the color of each circle is used to indicate $|\alpha|$ for oscillators with different periods of vibration, with blue signifying that RotD100 orientation is close to the transverse orientation and red signifying that RotD100 orientation is closer to the radial orientation (i.e., along a line connecting the site to the epicenter). The grey circles centered around the epicenter are spaced at 50 km intervals and demonstrate how the orientation of the transverse orientation varies based on the position of each station relative to the epicenter.

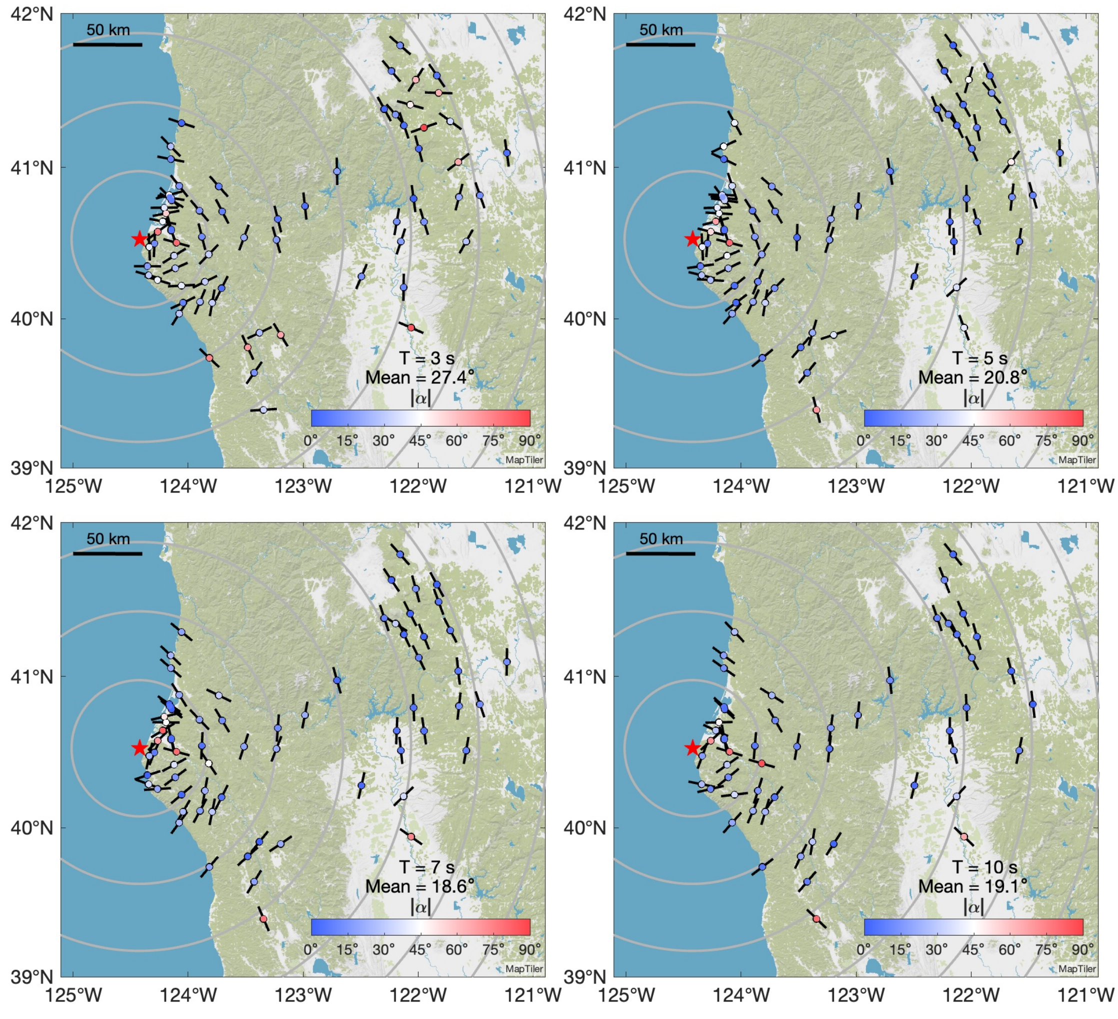

Figure 2. RotD100 orientation of 5%-damped linear elastic oscillators subjected to recordings from the M_w 6.4 Ferndale earthquake, as indicated by the short black lines, and their angular distance from the transverse orientation, as indicated by the circle's color at each station. Mean $|\alpha|$ and oscillator period are shown in the bottom right corner, and grey circles show epicentral transverse orientations.

Several notable observations can be made from Figure 2. First, it is apparent that stations that are in proximity to each other tend to have RotD100 orientations that are similar. Second, the RotD100 orientations appear to form an approximately circular pattern around the epicenter which is similar to the grey circles centered around the epicenter, indicating that the orientation of maximum intensity occurs close to the transverse orientation for most stations. A quantitative measure of the angular distance between the RotD100 orientation and epicentral transverse is indicated by the color of the small circle at each recording station. Most stations across all periods are blue in color, indicating that the orientation of RotD100 is close to the transverse orientation. Furthermore, as the period of the oscillator increases, more stations become colored blue, indicating that the orientation of maximum spectral response gets closer to the transverse orientation with increasing period. Visually, this means that the short black lines become increasingly aligned with the grey circles.

A third interesting observation from Figure 2 is that blue-colored stations are present not only near the epicenter but also at distances far from the epicenter (e.g., around 300 km). For all four periods considered, there does not seem to be a trend of changing colors with increasing distance from the epicenter, which suggests that RotD100 orientations may be close to the transverse orientation at most rupture distances.

The distribution of $|\alpha|$ at each period shown in Figure 2 is represented in the form of histograms in Figure 3. These histograms provide information on the probability distribution of the angle in which the maximum intensity occurs relative to the transverse orientation. It is apparent that the empirical distribution for $|\alpha|$ is highly skewed towards small values for all periods considered, with the largest density concentrated at small $|\alpha|$ values. In each subfigure, a dashed horizontal red line is provided to indicate a uniform probability distribution with a mean $|\alpha|$ of 45°, which represents the theoretical shape of the histogram should the orientation of maximum spectral response with respect to the transverse orientation be equally likely to occur in any orientation. The clear deviation of the empirical probability distribution from this dashed red line and the observed mean $|\alpha|$ significantly below 45° clearly indicates that the orientation of maximum spectral response for this earthquake is not uniformly distributed. Another notable observation from Figure 3 is that the distribution appears to get more skewed and the mean $|\alpha|$ tends towards smaller mean values with increasing period, indicating that the orientation of maximum spectral response gets closer to the transverse orientation with increasing period.

To better understand the influence of oscillator period on the orientation of maximum spectral response, Figure 4 shows the mean $|\alpha|$ at each period (shown by the blue line) and the corresponding interquartile range (shown by the shaded band). This figure confirms that $|\alpha|$, on average, decreases with increasing period and remains consistently well below 45°, indicating that the orientation of maximum spectral response occurs close to the transverse orientation. Poulos and Miranda's (2023a) primary motivation for studying the orientation of maximum spectral response with respect to transverse orientation was that S-waves in a homogenous propagation medium from a theoretical double couple strike-slip point source with a vertical dip have SH radiation patterns that are larger in magnitude when compared to SV radiation patterns. Using the epicenter

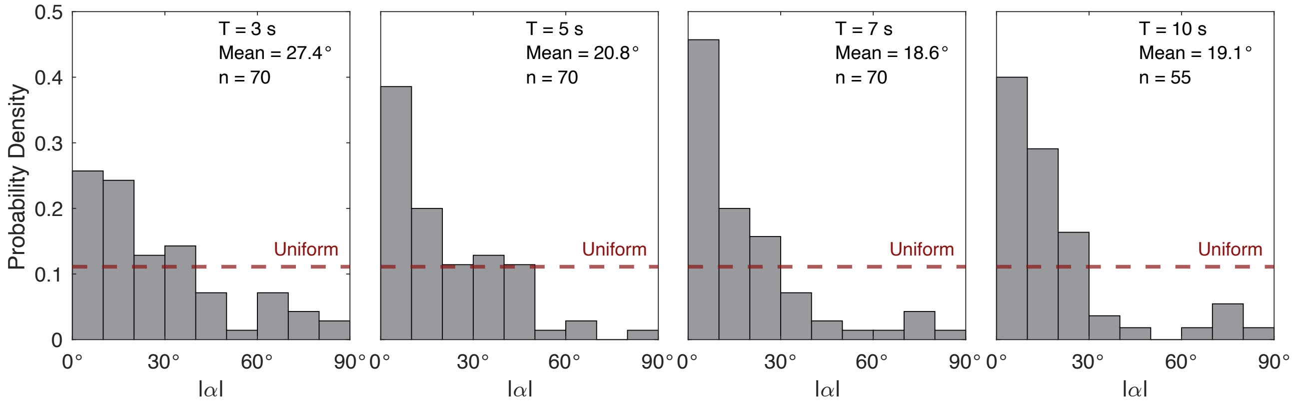

Figure 3. Probability distribution of the angular distance between orientation of RotD100 and transverse orientation for 5%-damped linear elastic oscillators with four different periods subjected to ground motion records from the Ferndale earthquake. Each panel indicated the oscillator period (T), mean $|\alpha|$, and number of records (n) for each case.

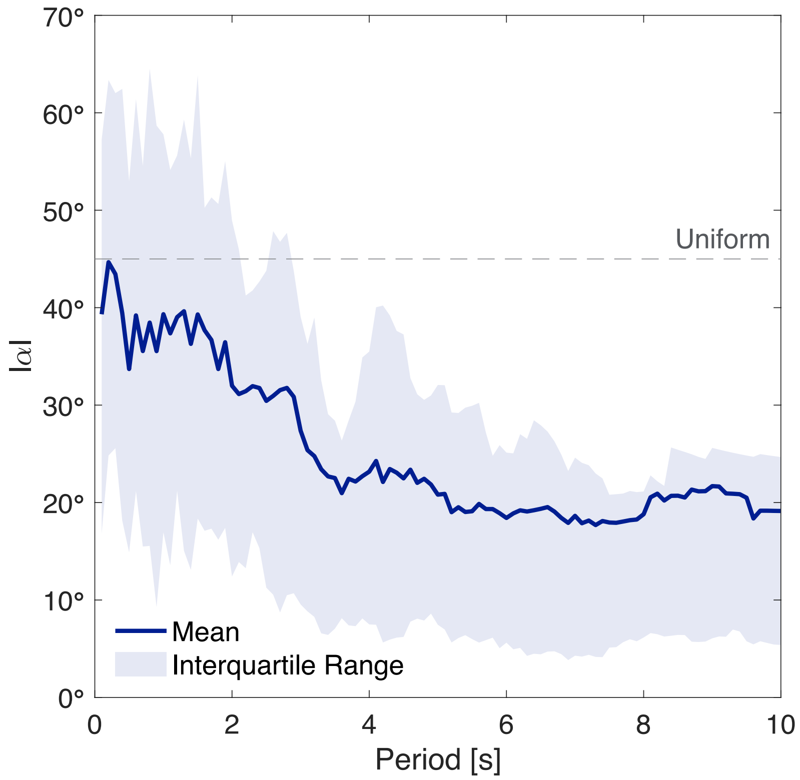

Figure 4. Influence of oscillator period on the mean angular distance between the orientation of RotD100 and the transverse orientation for the Ferndale earthquake. The shaded band around the mean represents the interquartile range.

as the point source, the transverse orientation coincides with the orientation of SH waves. Therefore, the observations regarding the orientation of maximum spectral response made in this earthquake may be explained by the polarization of S-waves. Figure 4 shows that mean $|\alpha|$ is larger in the short-period range when compared to the long period range, which may be explained by wave scattering. Higher frequencies have wavelengths that are shorter, which makes them more sensitive to heterogeneities in the medium through which they propagate (i.e., the Earth's crust).

Whereas Figure 4 shows the mean variation of $|\alpha|$, Figure 5 shows the fraction of stations where the orientation of maximum spectral response falls within $\pm\theta$ degrees of the transverse orientation at each oscillator period. Included in the plot is a dashed horizontal line for each θ, representing the fraction of stations that would have RotD100 orientation $\pm\theta$ of the transverse orientation should RotD100 be equally likely to occur in any orientation. At periods longer than 5 s, more than 40% of stations had an orientation of RotD100 that was within $\pm 10°$ of the transverse orientation, which jumps significantly to 60% of stations being within $\pm 15°$ of the traverse orientation, and to 70-80% being within $\pm 25°$ of the transverse orientation. In the short period range, most periods had probability of stations with RotD100 orientation $\pm\theta$ of the transverse orientation above the uniform probability line, further implying that the orientation of RotD100 is systematically close to the transverse orientation for all periods.

4. Ground motion intensity at the transverse and radial orientations

The previous section convincingly shows that the orientation of maximum spectral ordinates for the Ferndale earthquake was systematically close to the transverse orientation, consistent with the findings of Poulos and Miranda (2023a) for strike-slip earthquakes in the NGA-West2 database. Current GMMs typically provide estimates of RotD50 intensities, which are then amplified by approximate period-dependent correction factors to estimate the RotD100 intensities used in the design code. As discussed in the introduction, one reason that has prevented the development of orientation-dependent GMMs is that the orientation of maximum response was thought to not have a predominant orientation at distances greater than 5 km from the rupture. Knowing the orientations of strongest and weakest intensities could aid the development of orientation-dependent GMMs by providing a reference orientation from which amplification factors to the RotD50 intensity predicted

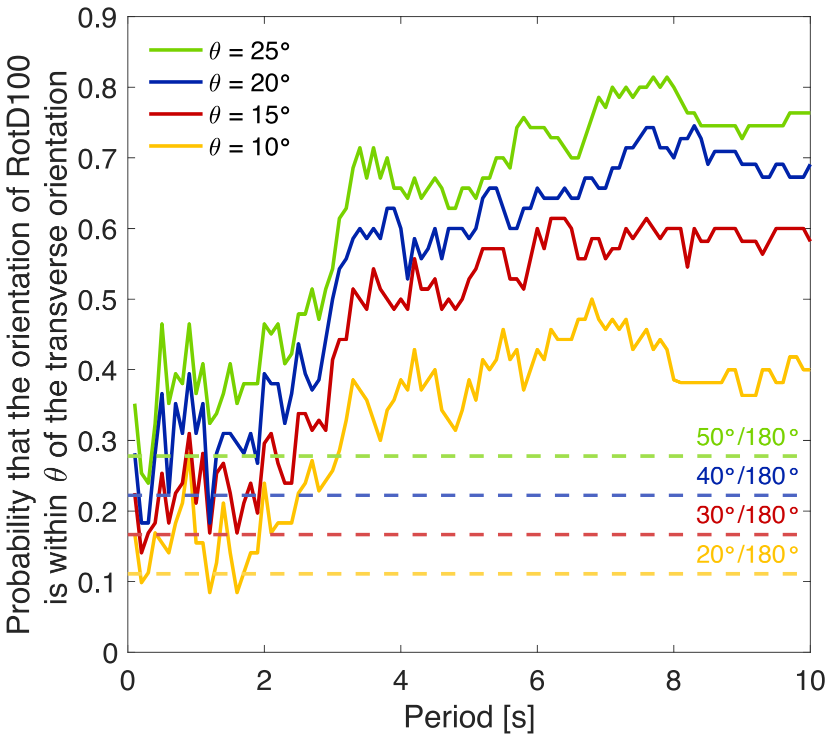

Figure 5. Fraction of stations where the orientation of RotD100 falls within $\pm\theta$ *of the transverse orientation. Dashed lines represent the expected fraction of stations if the orientation of RotD100 was equally likely to occur in any orientation.*

by current GMMs can be computed for all orientations. If the transverse orientation is to be used as an estimate for the orientation of maximum intensity, then it is important to study how the intensity in this orientation compares to the RotD50 intensity. This comparison can be made by computing the ratio of the intensity at the transverse orientation with the median intensity of all orientations (i.e., computing Sa_T/Sa_{RotD50}). Figure 6 shows the influence of the oscillator period on the mean ratio of Sa_T/Sa_{RotD50} (transverse) or Sa_R/Sa_{RotD50} (radial) and

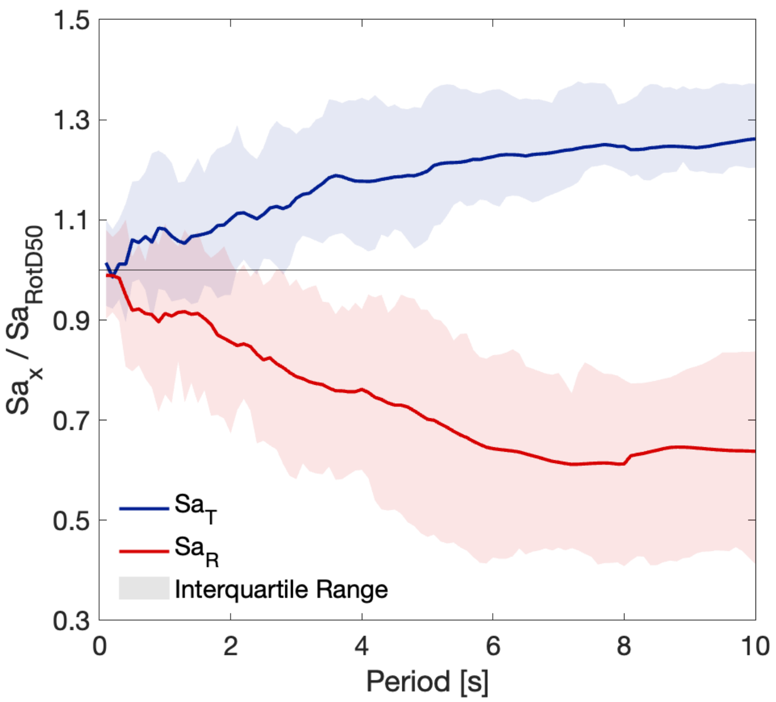

Figure 6. Influence of the period of vibration on the mean ratio between the intensity in the transverse or radial orientation and the RotD50 intensity.

the corresponding interquartile range. Since the maximum intensity at any orientation is RotD100, then the maximum value that Sa/Sa_{RotD50} can have is $\sqrt{2} = 1.41$, which corresponds to a perfectly linearly polarized ground motion. This figure shows that intensity in the transverse and radial orientation is, on average, close to RotD50 for oscillators with periods of vibration less than 0.3 s. However, as the oscillator period increases, the mean intensity in the transverse orientation increases such that it is between 1.0 to 1.26 times the RotD50 intensity, whereas the intensity in the radial orientation exhibits a notable reduction relative to RotD50. It is also apparent that the interquartile range for Sa_T/Sa_{RotD50} is narrower than that of Sa_R/Sa_{RotD50}, indicating that the transverse orientation has lower variability compared to the radial orientation. The overall implication of this figure is that the mean intensity in the transverse orientation in this earthquake was systematically greater than the median intensity predicted by GMMs for almost all oscillator periods, whilst the intensity in the radial orientation was systematically lower than the median intensity. This motivates a case for the development of modification factors to existing GMMs so that spectral response in any orientation can be estimated with respect to the transverse orientation for strike-slip earthquakes, which would eliminate systematic over or underestimation of intensities in specific orientations.

The difference in intensity between the transverse and radial orientation can be better understood by computing the ratio of the spectral response in the radial orientation to the spectral response in the transverse orientation (i.e., Sa_R/Sa_T). Figure 7 shows the influence of the oscillator period on the mean Sa_R/Sa_T for the Ferndale earthquake. It is clear that the ratio is below 1 for most period ranges, indicating that the intensity in the radial orientation is typically smaller than the intensity in the transverse orientation; this ratio also gets smaller with increasing period. For oscillator periods greater than 2 s, it can be inferred from the interquartile ranges that there is at least a 75% probability that the spectral response in the transverse orientation will be larger in the transverse than in the radial orientation.

An oscillator's response is polarized if the intensity in a given orientation is notably larger than the response in other orientations. Since the transverse orientation on average estimates the orientation of RotD100, the ratio in Figure 7, provides a proxy measure of the level of polarization of the ground motions. In this earthquake, for oscillators with periods greater than 0.5 s, the intensity in the radial orientation, on average, is between 54% (at long periods) and 92% (at short periods) of that in the transverse orientation, suggesting significant polarization. The extent of polarization can be visualized by the bidirectional response trace provided by Girmay et al. (2023a). The high level of polarization in this earthquake are consistent with that observed in other recent strike-slip earthquakes (e.g., Girmay et al., 2023b, 2024).

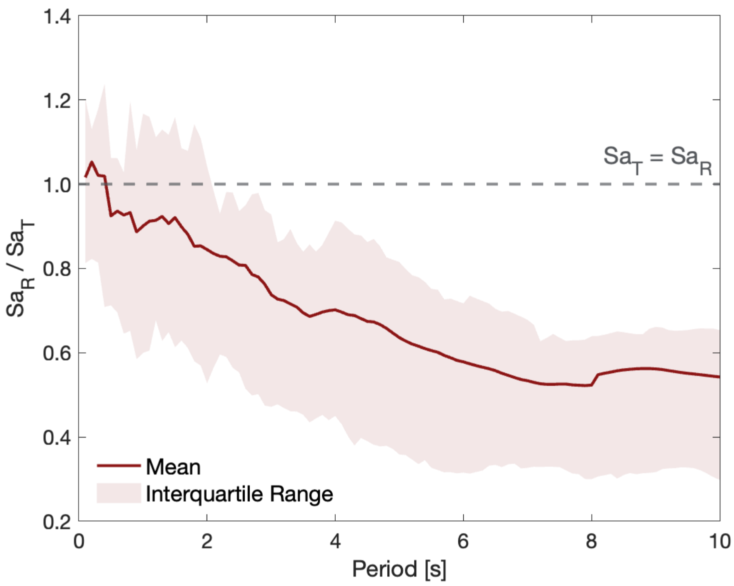

Figure 7. Influence of the oscillator period of vibration on the mean ratio between the intensity in the radial orientation and the intensity in the transverse orientation.

5. Summary and conclusions

This work evaluated the directionality of response spectral ordinates of 5%-damped oscillators when subjected to ground motions recorded during the December 20, 2022, M_w 6.4 Ferndale earthquake. The orientation of maximum spectral response and its spatial distribution, as well as the intensity in specific orientations, were studied.

The orientation of maximum spectral response was found to be systematically close to the epicentral transverse orientation (i.e., the orientation orthogonal to a line connecting the station to the epicenter) for the earthquake. On average, the orientation of maximum spectral response got closer to the transverse orientation as the oscillator period increased. In addition, the geographic distribution of the orientation of maximum response did not exhibit noticeable spatial trends, remaining close to the epicentral transverse orientation at all rupture distances. These observations are consistent with those of Poulos and Miranda's (2023a) for strike-slip earthquakes in the NGA-West2 database.

Oscillator response, on average, was found to be polarized for a wide range of periods. The mean intensity in the transverse orientation for this earthquake was found to be systematically greater than the median intensity (RotD50) predicted by GMMs for almost all oscillator periods, ranging from 1.0 times at low periods to 1.26 times larger at longer periods. This motivates the need to develop modification factors to existing GMMs so that spectral response in any orientation can be estimated with respect to the transverse orientation (e.g., Poulos and Miranda, 2023b).

6. Acknowledgments

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