EFFECT OF FOCAL MECHANISM ON THE DIRECTIONALITY OF HORIZONTAL GROUND MOTION INTENSITY

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Abstract

The horizontal intensity of earthquake ground motion intensity varies significantly with changes in orientation in what it is referred to as ground motion directionality. Unfortunately, this directionality has historically been ignored or not properly accounted for in ground motion models and in seismic provisions. This study investigates the implications of directionality in the estimation of ground motion intensity. In particular, it investigates the effect of focal mechanism on directionality by making use of a large number of records obtained in well-recorded recent earthquakes in California, Taiwan, and Türkiye. Results show that for strike-slip earthquakes, it is possible to anticipate the orientations in which current ground motion models tend to underestimate spectral ordinates and orientations in which they overestimate them.

Introduction

Ground motions are typically recorded in three orientations that are perpendicular to each other. For example, free-field recording stations typically record horizontal ground motions in the North-South (NS) and East-West (EW) orientations in addition to recording the motion in the vertical (V) orientation. Motions recorded in these mutually perpendicular orientations allow the calculation of the ground motion time history (also commonly referred to as waveforms) in any other orientation. Of particular interest to geotechnical and structural engineers is the estimation of the ground motion intensity in the horizontal direction. This is because Civil Engineering structures tend to be large and heavy and are foremost designed to resist actions resulting from the effects of Earth's gravity (e.g., dead and live loads acting in the vertical direction), resulting in structures that are typically much stiffer and stronger in the vertical direction than in the horizontal direction, and hence being more vulnerable to horizontal components than to the vertical component of ground motions (e.g., Acosta et al., 2023). Examination of recorded components of any earthquake ground motion reveals that the motion is different in the three recorded orientations and that significant variations in ground motion intensity exist with changes in orientation in the horizontal plane, that is, with changes in azimuth. Unfortunately, although we have known about this directionality since we started recording earthquake ground motions more than 100 years ago, it had not been properly quantified and therefore has historically been essentially ignored or not properly accounted for in ground motion models or in seismic provisions.

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Recently, Poulos and Miranda (2022b) conducted a comprehensive study of the directionality of horizontal ground motions. Their study, which used of 5,065 ground motions recorded in crustal earthquakes having magnitudes equal to or larger than five, provided a probabilistic characterization that included the geometric mean, logarithmic standard deviation, and probability distribution of two ratios that can be used to provide quantitative probabilistic measures of the directionality present in horizontal ground motions. In the first ratio, which was first proposed by Hong and Goda (2007), spectral ordinates in all non-redundant orientations are normalized by the maximum spectral ordinate from all horizontal orientations. This ratio provides information on how the ground motion intensity decreases as one rotates away from the orientation of maximum intensity (or how the ground motion intensity increases as one rotates toward the orientation of maximum intensity). In the second ratio that Poulos and Miranda studied spectral ordinates are normalized by the median of spectral ordinates from all horizontal orientations referred to as RotD50. This second ratio, which was first studied by Shahi and Baker (2014), provides quantitative information on how much larger spectral ordinates get relative to the RotD50 intensity level as one rotates towards the orientation of maximum intensity. Similarly, this ratio also indicates how much lower than RotD50 they become as one rotates toward an orientation that is orthogonal to the orientation of maximum intensity. These studies have shown that there is a significant directionality in horizontal ground motion intensity that, if is neglected, can lead to biased estimates of ground motion intensity (i.e., both systematic underestimations and systematic overestimations). For example, they showed that for a given period the maximum spectral ordinate, maximum from all orientation is, on average, 1.4 times larger than the spectral ordinate in the perpendicular direction for short period structures and 2.2 times larger for long-period structures. However, they observed that in individual ground motions it can be as large as three times larger for short-period structures and as large as five times larger for long-period structures. Hence, these significant variations in horizontal ground motion intensity should not be neglected. For example, they can be comparable or in some cases larger than those occurring from changes in site conditions. Yet, the changes in ground motion intensity with changes in orientation have typically been ignored while the effects of site conditions have been studied and incorporated in seismic provisions for more than 50 years. In their study, Poulos and Miranda (2022b) also derived upper and lower bounds for the two ratios quantifying directionality and developed models for the geometric mean, logarithmic standard deviation (variability) and probability distributions of both ratios.

While the study by Poulos and Miranda (2022b) is the most complete study to date on ground motion directionality, it cannot be applied by itself to estimate spectral ordinates at specific horizontal orientations as it also requires information on the orientation in which the maximum response occurs. This is because the ratios that they studied and the models they developed are a function of the angle to the orientation in which the maximum intensity occurs. Previous studies have found that, for ground motions recorded very close to earthquake ruptures, the maximum horizontal spectral acceleration at mid-to-long periods is likely to be closer to the strike-normal orientation than to the strike-parallel orientation (e.g., Somerville et al. 1997). However, subsequent studies by Shahi and Baker (2014) showed that this trend disappears relatively quickly as the distance to the rupture increases and becomes almost nonexistent for distances to the rupture longer than 5 km. Beyond rupture distances of 5 km, they observed that the angle between the orientation of the maximum intensity and the strike of the causative fault is approximately uniformly distributed, suggesting that there is no angle relative to the strike where the maximum intensity is likely to occur relative to other alternative angles. In a very recent study, Poulos and Miranda (2023a) investigated the effect of style of faulting on the orientation

5,065 records by the style of faulting of the earthquake in which they were recorded, they concluded that, for strike-slip earthquakes, the orientations of maximum intensity tend to occur close to the transverse orientation (that is, an orientation that is perpendicular to a straight line connecting the recording station and the earthquake epicenter). They pointed out that, contrary to an orientation relative to the strike that has been used by most previous studies (i.e., in an orientation that is the same at all recording stations), the transverse orientation is, in general, different for each recording station. They showed that contrary to what happens when the strike is used as a reference, in which the tendency of the maximum orientation to occur close to the strike-normal orientation rapidly dies down with distance, the orientation of maximum spectral response remains close to the transverse orientation even at very long distances from the source. Furthermore, their study showed that, on average, the orientations of maximum response spectral ordinates in strike-slip earthquakes tend to become even closer to the transverse orientation as the period increases. However, they reported that the orientation of maximum spectral response in ground motions recorded in reverse earthquakes did not show any clear trend relative to the transverse orientation. Lastly, they indicated that this interesting trend in the orientation of maximum intensity identified for strike-slip earthquakes could perhaps be considered in future Ground Motion Models (GMMs) and in future Probabilistic Seismic Hazard Analyses (PSHA). Strike-slip earthquakes represent nearly 80% of the earthquakes in California so, if preliminary results by Poulos and Miranda are confirmed, it means that it may be possible to anticipate the orientations in which current GMM tend to underestimate or overestimate response spectral ordinates, hence providing the basis for the development of new, more accurate, direction-specific GMMs.

The objectives of this manuscript are to summarize ongoing studies at Stanford University to further investigate the effect of focal mechanism on the directionality of horizontal ground motions with emphasis on strike-slip earthquakes. The research uses recent well-recorded strike-slip earthquakes in California, Taiwan and Türkiye and is complemented with physics-based ground motion simulations to gain further insights into the controlling factors of ground motion directionality such as earthquake-to-earthquake variability. In particular, in addition to studying event-to-event variability of directionality, we are studying the effects of magnitude and distance on the level of polarization of ground motions and whether information from finite fault models can be used to provide improved ways to estimate the orientation in which the maximum intensity occurs. Additionally, we are developing two alternative promising approaches to incorporate ground motion directionally in GMMs and in PSHA.

Current Measures of Ground Motion Intensity

For engineering purposes, the most commonly used measure of ground motion intensity is the 5%-damped pseudo-acceleration response spectral ordinate. By definition, this corresponds to the product of the peak displacement (relative to the ground) of a 5%-damped oscillator times the square of its natural circular frequency, ω_n. Since its calculation involves lightly damped oscillators the pseudo-acceleration response spectral ordinate is very similar to the peak absolute acceleration of the oscillator. Since the development of the response spectrum by Biot in the

1930s (Biot, 1933, Chopra, 2007; Trifunac 2008) there has been an interest in estimating pseudo-acceleration response spectral ordinates in the horizontal direction for oscillators with different periods of vibration for different combinations of earthquake magnitude, distance to the source and site conditions. In recent years the influence of the style of faulting mechanism has also been added as a predictor variable. However, since the development of the first attenuation relationship (now referred to as GMMs) sixty years ago (Esteva and Rosenblueth, 1964), the estimation of ground motion intensity at a site in future earthquakes has been typically limited to the estimation of a single scalar such as peak ground acceleration, *PGA*, to represent the intensity of the ground motion in the horizontal direction. The same is true for fifty years of development of GMMs estimating response spectral ordinates (e.g., Douglas, 2003) in which, for a given period, a single scalar, $S_a(T)$, is predicted to represent the intensity of the ground motion in the horizontal direction.

Until about 15 years ago, the most common way of computing the scalar representing the ground motion intensity at a site in the horizontal direction was the geometric mean of the intensities in the two as-recorded horizontal directions. This involved either using the geometric mean of the *PGA* in the two as-recorded horizontal directions (e.g., geometric mean of the *PGA* in the NS and EW orientations) or the geometric mean of pseudo-acceleration spectral ordinates, $S_a(T)$, in the two as-recorded horizontal directions (e.g., geometric mean of the $S_a(T)$ computed from ground motions recorded in the NS and EW orientations). Boore et al. (2006) noted that the geometric mean of response spectra computed from two orthogonal horizontal components of motion depends on the orientation of the sensors as installed in the field. Furthermore, they noted that as ground motions become very linearly polarized, the geometric mean was not an adequate measure of intensity as it tended to underestimate the ground motion intensity at a site. Their study pointed out how, in the case of a fully linearly polarized ground motion in which one of the recording sensors is aligned with the direction of polarization, the spectral ordinate in the perpendicular direction would be zero leading to a geometric mean that it is also zero regardless of the spectral amplitude in the polarized direction. In order to address these shortcomings associated with the use of the geometric mean and those of other alternative measures of central tendency of the intensities in horizontal components, Boore (2010) proposed an alternative measure of seismic intensity that is known as RotD50, which corresponds to the median of the intensity of all possible non-redundant orientations. By definition, this intensity level is exceeded in half of the horizontal orientations and is not exceeded in the other half of the orientations and is independent of the orientation of the sensors at the recording stations. This new measure of intensity was selected as the scalar to measure ground motion intensity of horizontal components in the NGA-West2 project (Bozorgnia et al., 2014). Since then, this measure of intensity has also been adopted in most GMMs (e.g., NGA-East, NGA-Sub), and the latest generation of seismic maps in the United States are based on probabilistic seismic hazard analyses using RotD50 (Petersen et al., 2020).

Despite the advantages of RotD50 over the use of the geometric mean or other measures of central tendency based on geometric means (e.g., GMRotI50 or GMRotD50) as measures of ground motion intensity in the horizontal direction, it still only provides a scalar measure of intensity at a site. This means that it does not provide information about how much larger than RotD50 the ground motion intensity was in certain orientations nor of the orientations in which this happened or how much lower the intensity was in other orientations or the orientations in which the intensity was lower than RotD50. It is of utmost importance to realize that structures such as buildings or bridges or earth structures such as levees and earth dams do not “feel” the geometric mean of recorded intensities, nor do they “feel” the median intensity from all horizontal directions. Instead, the peak response of these structures depends on the intensity of the ground motion in all directions. Of particular interest to engineers is the estimation of the ground motion in the principal directions of the structure (e.g., longitudinal and transverse direction of a structure) as mode shapes usually are aligned to these orientations as a result of the stiffness of individual structural elements and their spatial distribution within the structure, such that the horizontal motion at any point in the structure can be estimated from the ground motion intensity in these principal components. It should be noted that this continues to be true in cases where coupling between torsional and translational modes of vibration exists as the response of the structure can still be obtained from the motion along the principal components of the structure, which for most structures tends to be perpendicular to each other.

Engineers, both structural engineers and geotechnical engineers, are interested in determining the probability of exceeding specific limits states in structures. For example, structural engineers are interested in determining the probability that the peak story drift ratio in a building does not exceed the maximum allowed by the code or a level that may jeopardize the stability of the structure. Therefore, engineers need estimations of ground motion in the principal components of their structures and not the median intensity of all orientations which by itself does not allow the determination of the probability of exceeding these limit states. Therefore, today’s GMMs provide incomplete information that neglects ground motion directionality.

Concerned with intensities that could be significantly larger than RotD50 intensities for sites located close to the rupture, several investigators started to quantify how much larger the intensities could be above those estimated by GMMs (e.g., Beyer and Bommer 2006; Watson-Lamprey and Boore 2007; Campbell and Bozorgnia 2007; Huang et al. 2008). Based on these studies and on the work of Project 07 of the Building Seismic Safety Council, ASCE-7 introduced, starting with the 2010 version of this national standard, the use of the maximum intensities for the design of structures in seismic regions as opposed to using the geometric mean of the two recorded components (ASCE, 2010). The maximum intensity, also referred to as RotD100, corresponds to the maximum intensity from those that occur at all horizontal orientations. Since there are currently no GMMs that provide probabilistic estimates of RotD100, ASCE 7 makes use of approximate period-dependent amplification factors to estimate RotD100 intensities from RotD50 which are used in GMMs and seismic hazard maps computed by USGS. The latest version of ASCE 7 (i.e., version 2022), makes use of amplifications from the FEMA P-2082 document (BSSC, 2020), which are based on studies by Shahi and Baker (2014), where the period-dependent amplification factors vary from 1.19 for a period of 0.1s to 1.26 for a period of 5s. The proposal to switch from RotD50 (or GMRotI50) to RotD100 for design of buildings in the United States has been controversial. On one hand, some such as Huang et al. (2011), noted that the use of maximum spectral demand for force-based design is not overly conservative since there is typically an axis where the spectral demands are equal or close to the maximum intensity RotD100. On the other, many others have pointed out that the use of RotD100 is overly conservative as it assumes that the orientation of RotD100 coincides precisely with at least one of the principal directions of the building which is very unlikely (Stewart et al., 2011) and suggested using GMRotI50 for design. Since the orientation of the RotD100 is a continuous random variable, the probability of it adopting a particular discrete value is actually zero. Poulos and Miranda (2022a) noted that only a very small fraction of structures are axisymmetric, that is, structures that have a vertical cylindrical symmetry in which the structure has the same properties (i.e., mass moment of inertia, lateral stiffness, lateral strength, etc.) when rotating about a vertical axis. For this kind of structures, they noted that there is consensus that the maximum intensity should be used for design. Hence, they advocated that rather than applying an amplification factor to obtain the maximum intensity for all structures as currently done in ASCE 7-22, it is better to only apply the amplification factors to the very small fraction of structures that are axisymmetric. However, they pointed out that using GMRotI50 or RotD50 for the design of all other types of structures is not adequate either because it has a high probability of being exceeded in one of any two orientations that are orthogonal to each other. By using the same ground motion set of 5,056 records previously described, they computed the mean of the probability that the RotD50 will the exceeded in either one of two orthogonal directions (e.g., on either the longitudinal or transverse direction of a building or bridge) is very high and varies from 92% for oscillators with a period of 0.1s to 98% for oscillators with a period of 10 s. This is because horizontal ground motions tend to experience their minimum intensity in an orientation approximately perpendicular to the orientation of maximum intensity. Therefore, as the ground motion is rotated the ground motion intensity tends to increase in one of the principal axes of the structures at the same time in which it decreases in the perpendicular direction leading to very large probabilities of exceeding the RotD50 in one of the two perpendicular directions. They also noted that for a large proportion of the records, this probability was 100%, that is, it does not matter the angle of rotation, the RotD50 is always exceeded in one of the two perpendicular orientations. To overcome this underestimation in ground motion intensity, they proposed a new measure of ground motion horizontal intensity, referred to as MaxRotD50, which corresponds to the median value of the maximum spectral ordinate of two orthogonal directions computed for all possible horizontal orientations. Their proposed measure of intensity is always between the median (RotD50) and the maximum (RotD100) spectral ordinate and, on average, it is, depending on the period of vibration, approximately 12 to 20% higher than Rot50 and approximately 6% lower than RotD100 (Poulos and Miranda 2021). Hence, the adoption of MaxRotD50 could lead to lower costs of construction in seismic regions relative to current costs based on the use of the maximum (RotD100) intensity.

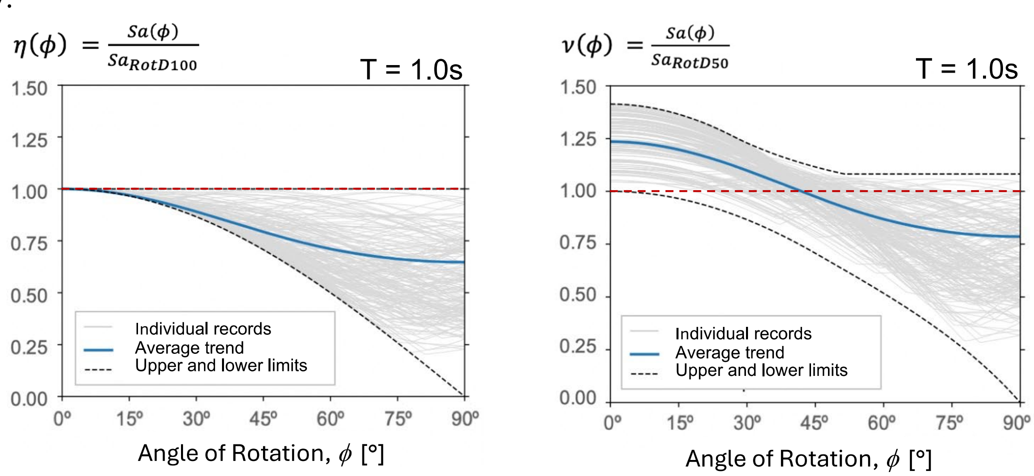

Figure 1. Directionality of pseudo-acceleration spectral ordinates for 5%-damped oscillators with a period of vibration of 1s computed from horizontal components of 100 recorded ground motions as a function of the angle of rotation from the orientation of maximum spectral ordinate: on the left when normalized by RotD100 of each record; on the right when normalized by RotD50 of each record.

Directionality in Recorded Ground Motions in the NGA2 Database

As mentioned in the introduction, spectral ordinates computed from horizontal components of recorded ground motion exhibit important variations in amplitude as a function of orientation. Although we have known about these variations for many years, it is not until recently that we have properly quantified them. Most previous studies have only focused on the ratio of the maximum spectral ordinates from all orientations, RotD100, to the median intensity from all horizontal orientations, RotD50, or some other measure of central tendency such as the geometric mean of the recorded orientations (GMRotI50 or GMRotD50). Although this ratio provides some information about the directionality of earthquake ground motions, it leaves out many other important aspects of the directionality of ground motions. For example, the calculation of the probability of exceedance of a spectral ordinate in a specific direction (e.g., the longitudinal or transverse direction of a bridge, building, or dam) requires information on the variation of ground motion intensity with changes in orientation. An example of this variation is shown in Figure 1 which presents the variation of pseudo-acceleration spectral ordinates computed for 5%-damped oscillators with a period of vibration of 1s when subjected to horizontal components of 100 recorded ground motions as a function of the angle of rotation from the orientation of maximum spectral ordinate. Since in general the level of intensity in different earthquakes can be different from site to site within an earthquake or from one earthquake to another, focus on directionality can be achieved by normalizing the spectral ordinates. Hence the figure on the left presents ratios $\eta(\phi)=Sa(T,\phi)/Sa_{RotD100}(T)$ where for each record spectral ordinates are normalized by the maximum intensity from all horizontal orientations (RotD100 of the record). Meanwhile the figure on the right presents ratios $\nu(\phi)=Sa(T,\phi)/Sa_{RotD50}(T)$, in which for each record, spectral ordinates are now normalized by the median of spectral ordinates from all orientations, RotD50 of the record.

Both ratios provide information on the ground motion intensity as one rotates away from the orientation in which the maximum spectral ordinates occur. From the figure on the left one can rotate 20° from the orientation of maximum intensity and the intensity, on average, only decreases by about 10%. In contrast, when rotating to 45° the average reduction is now about 20% and when rotating 90° (i.e., to an orientation perpendicular to that of the maximum intensity), the average reduction in intensity is 35%, which is significant. Previous studies by Hong and Goda (2007) and by Poulos and Miranda (2022b) showed that the average reduction in ground motion intensity as one rotates away from the orientation of maximum intensity is period dependent and increases from about 27% for a period of vibration of 0.1s to about 56% for a period of vibration of 10s. This means that on average the maximum intensity is, depending on the period of vibration between 37% and 117% larger than in the perpendicular orientation. Furthermore, they showed that this ratio $\eta(\phi)$ has specific lower and upper limits corresponding that bound all ground motions and therefore do not have a lognormal distribution such as that can be assumed for RotD50 spectral ordinates. Hong and Goda (2007) studied the probability distribution for the case in which $\phi=90°$ and concluded that it could be approximated by a Beta distribution and Poulos and Miranda (2022b) more recently extended this to all values of ϕ. The geometric mean of these ratios computed for 5,065 ground motion records is shown in Figure 2 along with a model that captures this directionality using a relatively simple functional form with period-dependent coefficients, C_1, C_2 and C_3 (for details of the model and its parameters the reader is referred to Poulos and Miranda 2022b).

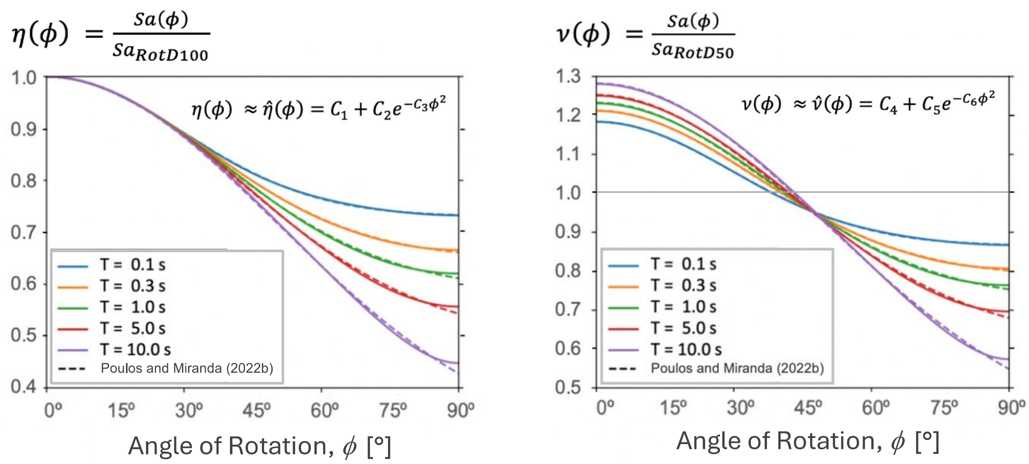

Figure 2. Geometric mean of directionality parameters η and ν for five different periods of vibration as a function of the angle of rotation from the orientation of maximum spectral ordinate. Solid lines show the empirical data, and dashed lines correspond to the model proposed by Poulos and Miranda (2022b).

As illustrated in Figure 1, the record-to-record variability of $\eta(\phi)$ is, as expected from its definition, null at the orientation where the maximum spectral ordinate occurs, that is at ϕ=0° and increases as one rotates away from the orientation of RotD100 toward a perpendicular orientation (that is as ϕ increases toward 90°). Poulos and Miranda (2022b) quantified this variability and noticed that it is also period dependent and increases with increasing period. They also developed a model to estimate this variability, again using a relatively simple functional form and period-dependent coefficients. This variability, which they quantified using the logarithmic standard deviation of the normalized spectral ordinates η(ϕ) is shown in Figure 2 along with their model where the variability is approximated using a rational function (i.e., ratio of polynomials). As shown in the figure, their model captures very well this variability which is also necessary to estimate the probability of exceedance of a spectral ordinate in specific orientations.

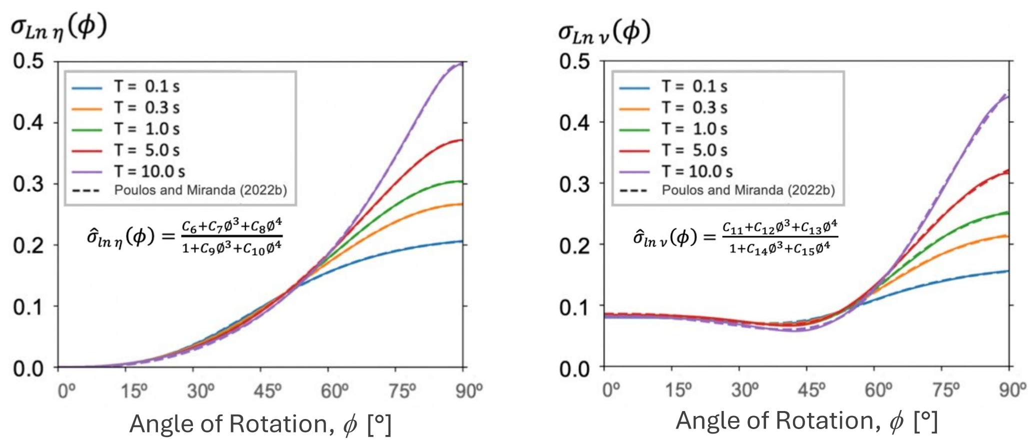

Figure 3. Standard deviation of natural logarithms of η (shown on the left) and ν (shown on the right) for five different periods of vibration as a function of the angle of rotation from the orientation of maximum spectral ordinate. Solid lines show the empirical data, and dashed lines correspond to the model proposed by Poulos and Miranda (2022b).

The second ratio, $\nu(\phi)=Sa(T,\phi)/Sa_{RotD50}(T)$, which is shown in Figure 1 on the right, also provides information on the ground motion intensity as one rotates away from the orientation in which the maximum spectral ordinates occurs. However, in this case the spectral ordinates are normalized by the RotD50 intensity. Therefore, these ratios can be viewed as modification factors to the ground motion intensities estimated by current GMMs to provide estimates of how much lower or higher the ground motion intensity can be relative to the one provided in current GMMs and used in current PSHAs at any horizontal orientation. This ratio was first studied by Shahi and Baker (2014), by Boore and Kishida (2017) and more recently more thoroughly quantified and modeled by Poulos and Miranda (2022b). The geometric mean of these ratios from the latter study along with their proposed model is shown in Figure 2 on the right. This figure shows again how ground motions become more polarized and therefore exhibit a greater directionality as the period of vibration increases. However, as shown in this figure, these ratios exhibit a different behavior for angles of rotation close to the orientation of RotD100 (that is for angles close to ϕ=0°), than for angles in the perpendicular orientation with the period dependency being stronger in the latter as one approaches ϕ=0°. Shahi and Baker (2014) studied the variability of this ratio but only for ϕ=0° and Poulos and Miranda (2022b) extended this to all angles and also studied the lower and upper limits and the probability distribution of these ratios. Empirical results of the variability of $\nu(\phi)$ for five period of vibration are compared to their proposed model on the right-hand side of Figure 3 showing that their model provides very good estimations of this variability which is necessary to estimate the probability that a spectral ordinate will be exceeded at a specific orientation.

Spectral Ordinates at Specific Orientations

Using the study and models of Poulos and Miranda (2022b), which provides a comprehensive probabilistic characterization of normalized spectral ordinates $\eta(T,\phi)$ and $\nu(T,\phi)$, one can obtain an estimate of the median spectral ordinate at any period T and rotation angle ϕ using the following equation:

$$Sa(T,\phi) \approx \hat{\eta}(T,\phi) \cdot Sa_{RotD100}(T) \tag{1}$$

where $Sa(T,\phi)$ is the 5%-damped spectral ordinate for an oscillator with period T at an angle ϕ measured from the orientation of maximum oscillator response either in the clockwise or counter-clockwise direction, $\hat{\eta}(T,\phi)$ is the approximate geometric mean of the ratio $\eta(T,\phi)=Sa(T,\phi)/Sa_{RotD100}(T)$ from the study by Poulos and Miranda (2022b) (shown in dashed lines on the left-hand side of Figure 2), and $Sa_{RotD100}(T)$ is the maximum spectral ordinate (maximum of all orientations). Since there are no direct GMMs for the latter, one can approximate as follows

$$Sa_{RotD100}(T) \approx \hat{\nu}(T,\phi=0°) \cdot Sa_{RotD50}(T) \tag{2}$$

where $\hat{\nu}(T,\phi=0°)$ is the geometric mean of the ratio of the RotD100 to the RotD50, which can be obtained from the studies by Shahi and Baker (2014), by Boore and Kishida (2017) or by Poulos and Miranda (2022b), and $Sa_{RotD50}(T)$ is the median spectral ordinate at period T from any recent GMM based on RotD50 (e.g., ASK14, BSSA14, CY14, CB14, etc.) Substituting (2) into (1) we obtain

$$Sa(T,\phi) \approx \hat{\eta}(T,\phi) \cdot \hat{\nu}(T,\phi=0°) \cdot Sa_{RotD50}(T) \tag{3}$$

Alternatively, one can also obtain an estimate of the median spectral ordinate at any period T and rotation angle ϕ using the following equation:

$$Sa(T,\phi) \approx \hat{v}(T,\phi) \cdot Sa_{RotD50}(T) \quad (4)$$

where $\hat{v}(T,\phi)$ is the approximate geometric mean of the ratio $\nu(T,\phi)=Sa(T,\phi)/Sa_{RotD50}(T)$ from the study by Poulos and Miranda (2022b) and shown in dashed lines on the righthand side of Figure 2.

Equations (3) and (4) appear to provide, along with estimates from current GMMs, all the information necessary to obtain estimates of spectral ordinates at specific orientations (for example, at the longitudinal and transverse orientation of a bridge, building or dam). However, this is not the case, because the orientation of the maximum intensity at a site (i.e., the orientation or azimuth of RotD100) is, in general, not known in advance. Therefore, the angle between the orientation of RotD100 and the orientation of interest is not known either. There have been some studies that have studied the orientation of maximum ground motion intensity. An early study was carried out by Penzien and Watabe (1974) who used a very small sample of ground motions consisting of only six records, each from a different earthquake, and suggested that the orientation of maximum Arias intensity (Arias, 1970), occurs approximately in the radial orientation, that is, an orientation joining the site with the epicenter. Kubo and Penzien (1979) conducted a follow-up study in which they computed the orientation of maximum Arias intensity (i.e., major principal component of the ground motion) using fifteen ground motions recorded during the 1971 M_w 6.6 San Fernando earthquake. They noted that, although the correlation was not strong, there was a tendency for the direction of the major principal axis or, in some cases, the intermediate principal axis to point in the direction of the slip zone, but noted that the correlation was not nearly as strong as previously reported by Penzien and Watabe (1974). More recent studies by Rezaeian and Der Kiureghian (2012) indicate that this hypothesis of major principal axes oriented toward the epicenter, which was based on very limited data, is not to be supported by more recent, larger, ground motion datasets.

Somerville et al. (1997), while studying rupture directivity effects, found that spectral accelerations of oscillators with periods longer than 0.6 s were systematically larger in the strike-normal orientation than in the strike-parallel orientation for sites that are close to faults. A few years later, Howard et al. (2005) found that the orientation that maximizes the mean response spectrum for periods between 0.5 and 3 s, and hence also maximizes the Housner spectral intensity (Housner, 1952), differs from the strike-normal orientation. Similarly, Watson-Lamprey and Boore (2007) using the Next Generation Attenuation (NGA) ground-motion database, found that the orientation of maximum spectral acceleration rarely coincides with the strike-normal orientation, especially for source-to-site distances greater than 3 km. Shahi and Baker (2014) used the NGA-West2 ground-motion database and found that except for oscillators with periods of vibration longer than 1 s and source-to-site distances less than 5 km, the angle between the orientation of RotD100 and the strike of the fault is essentially random, having an approximately uniform probability distribution. More recently, Poulos and Miranda (2023a), also used the NGA-West2 ground-motion database and found that the orientation of maximum spectral ordinate, that is the orientation/azimuth where $Sa_{RotD100}$ occurs, is influenced by the style of faulting of the earthquakes that produced the ground motions. They found that for strike-slip earthquakes, the orientations of RotD100 tend to occur close to the transverse orientation and that this trend becomes stronger, with orientations becoming closer to the transverse orientation, as the period increases. For example, they found that the angle between the orientation of RotD100 and the transverse orientation is, on average, 36° for oscillators with a period of 2s but decreases to only 23° for oscillators with a period of 10 s. However, their study concluded that for reverse earthquakes, there is no particular trend in the orientation of maximum spectral response relative to the transverse orientation, with mean differences to the transverse orientation very close to 45° and probability distributions close to a uniform distribution. In their study, Poulos and Miranda (2023a) also fitted probability distributions to the empirical data of angular difference between the orientation of RotD100 and the transverse orientation for ground motions recorded in reverse and and-strike earthquakes. Examples of these probability distributions are shown in Figure 4.

Probability distributions by Poulos and Miranda (2023a) can then be used to estimate the pseudo-acceleration spectral ordinate at any specific orientation/azimuth θ, as follows

$$Sa(T,\theta) \approx Sa_{RotD50}(T) \cdot \int_{-\pi/2}^{\pi/2} \hat{\nu}(T,\phi) \cdot p(\gamma) d\gamma \tag{5}$$

where ϕ is the angle between θ and the orientation of RotD100, $p(\gamma)$ is the probability of the maximum spectral ordinate occurring at angle $\gamma = \phi - \alpha$ which can be approximated as

$$p(\gamma) = \frac{\cosh\left[\tau \cos(\phi-\alpha)\right]}{\pi I_0(\tau)} \tag{6}$$

where $I_0()$ is the modified Bessel function of order 0 and τ is a parameter that depends on the style of faulting and the period of vibration.

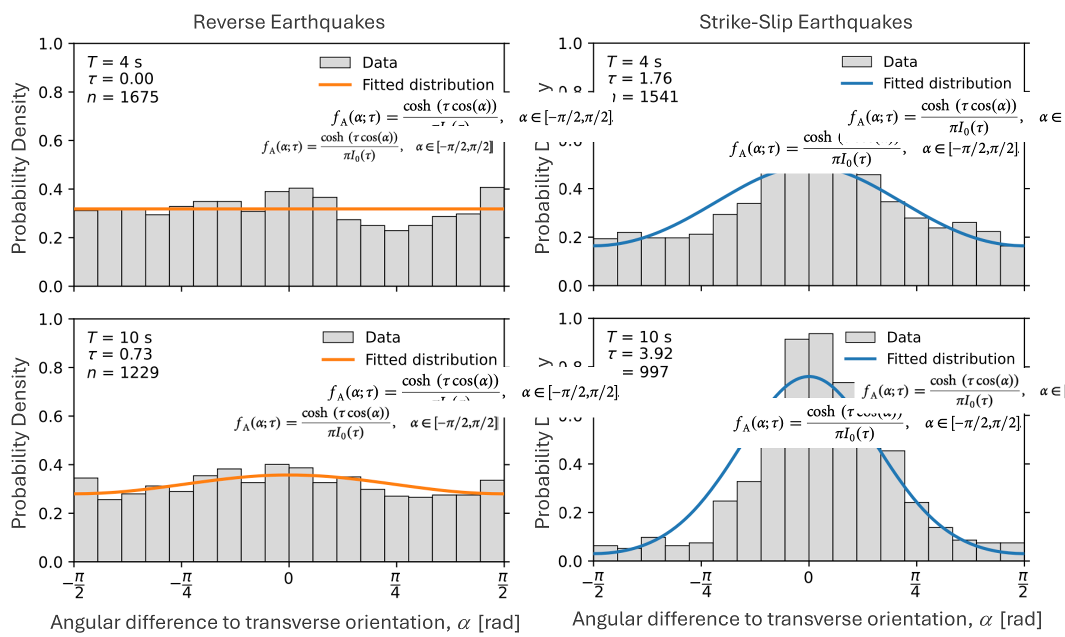

Figure 4. Empirical and fitted distributions of the angular differences between the transverse orientation and the orientations of RotD100 for periods of 4 s (on top) and 10 s (bottom) for reverse earthquakes (on the left) and strike-slip earthquakes (on the right). The period (T), fitted parameter of the distribution (τ), and number of records used for each case (n) are presented within each panel.

Directionality in Recent Strike-Slip Earthquakes

The study by Poulos and Miranda (2023a) was based on the NGA2-west ground motion database which includes crustal earthquakes up to 2011. As part of the ongoing investigation, we are expanding this database to include recent well-recorded strike-slip events in California and elsewhere. These events provide an important opportunity to independently evaluate the observations by Poulos and Miranda. We are considering three events in California, which include the two largest events in the 2019 Ridgecrest sequence and the 2022 Ferndale earthquake. Although there have been several other well-recorded events in California with magnitudes larger than five, such as the 25 October 2022, M_w 5.1 earthquake on the Calaveras fault, we selected those that have a large number of stations with maximum usable periods equal to or larger than 10s. The first event in the Ridgecrest doublet occurred on 4 July 2019 at 17:33 UTC (4 July 10:33 local time) and had a M_w 6.4. Meanwhile, the second (strongest) event occurred on 6 July 2019 at 03:19 UTC (5 July 20:19 local time) and had a magnitude M_w 7.1. These events occurred on different faults approximately perpendicular to each other and are located about 200 km north of Los Angeles. Ground motion records were obtained from Rekoske et al. (2020). The orientation of the maximum horizontal pseudo-acceleration spectral ordinates (orientation of RotD100) for oscillators with periods of vibration between 0.1 and 10s was computed from horizontal components from all strong motion stations that recorded these events. For each station, the angular difference between the orientation of RotD100 and the transverse orientation (which, in general, is different for each recording station), α, was computed and studied statistically. Figure 5 shows these orientations of maximum horizontal pseudo-acceleration spectral ordinate of oscillators with a period of 10 s computed using ground-motion records from the 2019 M_w 6.4 (on the left) and M_w 7.1 Ridgecrest events (on the right). The color inside the circles at each recording station indicates the angular difference of the RotD100 orientation with respect to the transverse orientation.

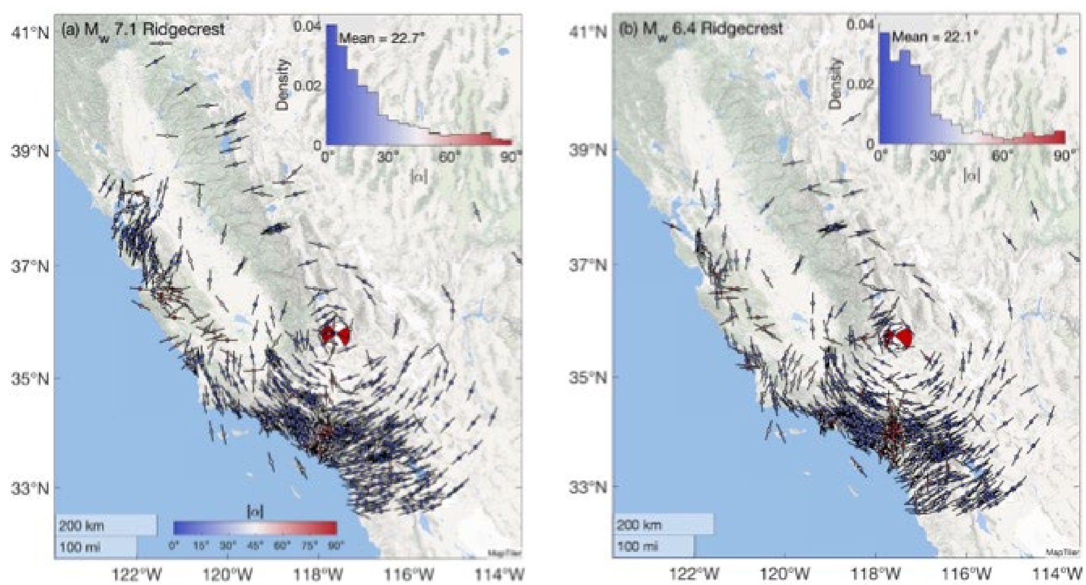

Figure 5. Orientations of the maximum horizontal pseudo-acceleration spectral ordinates of oscillators with a period of 10 s computed using ground-motion records from the 2019 M_w 6.4 (on the left) and M_w 7.1 Ridgecrest events (on the right). The color inside the circles at each recording station indicates the angular difference of the RotD100 orientation with respect to the transverse orientation. Empirical probability densities of the angular distance |α| are also shown for both earthquakes.

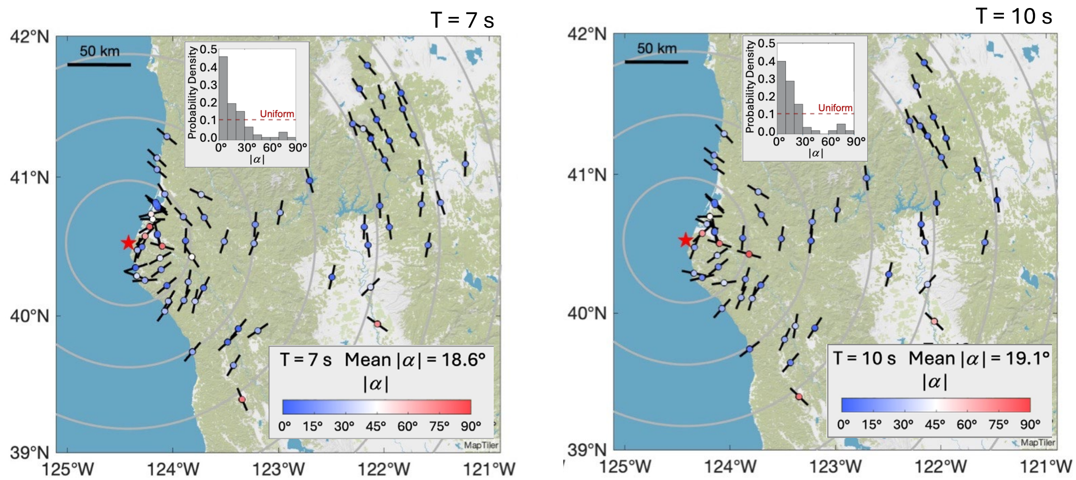

Figure 6. Orientations of the maximum horizontal pseudo-acceleration spectral ordinates of oscillators with period of 7s (left) and 10 s (right) computed using ground-motion records from the 2022 Mw 6.4 Ferndale, California earthquake. The color inside the circles at each recording station indicates the angular difference of the RotD100 orientation with respect to the transverse orientation, $|\alpha|$. Empirical probability densities of the angular distance $|\alpha|$ are also shown for both periods.

Empirical probability densities of the absolute value of the angular difference, $|\alpha|$, are also shown for both earthquakes in Figure 5. It can be seen that the probability distributions are highly skewed. For most of the stations, the RotD100 intensity occurs at orientations that are very close to the transverse orientation (indicated by blue circles in Figure 5) with mean $|\alpha|$ of 21.4° for both events, consistent with prior observations by Poulos and Miranda (2023a).

The Ferndale earthquake occurred on December 20, 2022. At 14:34 local time, a M_w 6.4 earthquake struck the coast of Northern California due to strike-slip faulting on a fault striking west-southwest with an epicenter located approximately 15 km southwest of the city of Ferndale, California. Ground motions used to study the earthquake were obtained from the Center for Engineering Strong Motion Data (CESMD) database. 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 which was computed as 1/1.25 times the low-pass frequency. 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. Figure 6 shows these orientations of maximum horizontal pseudo-acceleration spectral ordinate of oscillators with a period of 7 s (on the left) and 10 s (on the right). Again, the color inside the circles at each recording station indicates the angular difference of the RotD100 orientation with respect to the transverse orientation, $|\alpha|$. Empirical probability densities of $|\alpha|$ are again also shown in the figure for both periods. Similarly to the two Ridgecrest events, the probability distributions are highly skewed and, for most of the stations, the RotD100 intensity occurs at orientations that are very close to the transverse orientation of each station, with mean $|\alpha|$ of 18.6° and 19.1° for periods of 7 s and 10 s, respectively. Again, this is consistent with prior observations by Poulos and Miranda (2023a) for other earthquakes in the NGA-West2 database. For more information on directionality of ground motions recorded during the 2022 Ferndale earthquake, the reader is referred to Girmay et al. (2024a).

Taiwan is located in one of the most seismically active regions of the world where the Eurasia plate converges with the Philippine Sea plate. The M_w 6.9 Chihshang earthquake occurred on September 18, 2022, in the Longitudinal Valley in eastern Taiwan and was preceded by a M_w 6.5 earthquake that occurred approximately 17 hours before the mainshock. Unlike the well-known 1999 M_w 7.6 Chi-Chi earthquake, which had a reverse focal mechanism, the 2022 mainshock had a strike-slip focal mechanism with a rake angle of 25°. This recent mainshock occurred on two interacting crustal faults along the Longitudinal Valley suture, including the west-dipping Central Ridge fault and the east-dipping Longitudinal Valley fault having a strike approximately parallel to the eastern coast of Taiwan. The Taiwan Strong Motion Instrumentation Program (TSMIP) has a dense network of strong motion digital accelerograph stations which produced a large set of records from this earthquake and therefore provides an excellent opportunity to study the directionality of earthquake ground motions, particularly the orientations of maximum spectral response. A set of 338 records was selected, instrument corrected, and then bandpass filtered using a fourth-order Butterworth filter with corner frequencies of 0.05 and 35 Hz in both horizontal components. For each record, the two orthogonal horizontal components were used to obtain bidirectional relative displacements of 161 linear elastic 5%-damped oscillators with linearly spaced periods between 0 and 10 s. The orientations of maximum horizontal pseudo-acceleration spectral ordinates (orientation of RotD100) were then computed at each recording station and for each period. Figure 7 shows an example of these orientations for oscillators with periods of vibration of 5 s and 10 s. As shown in this figure and similar to the two Ridgecrest and Ferndale events, RotD100 orientations tend to occur close to the transverse orientation for most stations. Also shown in the figure is the probability distribution of the angular difference between the transverse orientation and the RotD100 which are strongly skewed toward 0°. These indicate that RotD100 orientations occur close to the transverse orientation with mean angular differences from the transverse orientation of 31.4° and 18.7° for periods of 5s and 10s, respectively. For more information on directionality of ground motions recorded during the 2022 Chihshang earthquake, the reader is referred to Poulos and Miranda (2024).

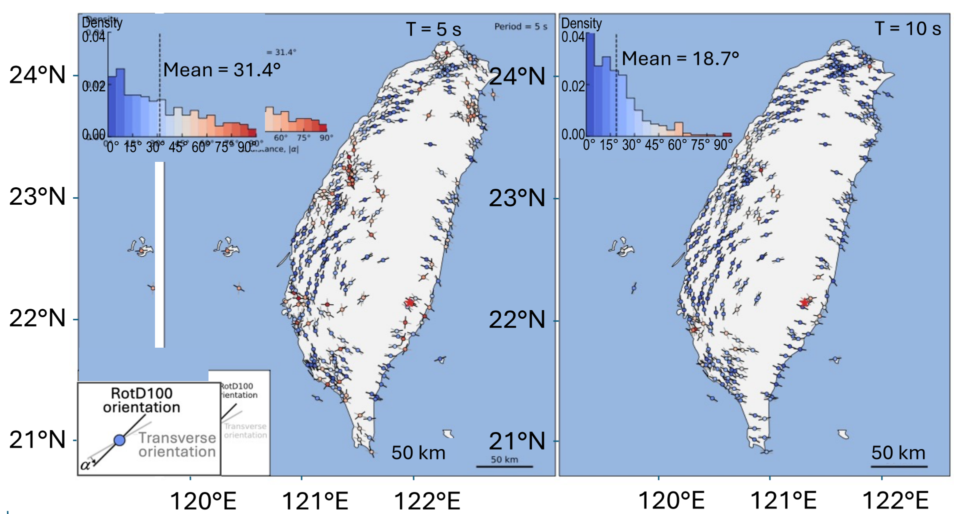

Figure 7. Orientations of maximum horizontal pseudo-acceleration spectral ordinates of oscillators with period of 5s (left) and 10s (right) computed using ground-motion records from the 2022 M_w 6.9 Chihshang, Taiwan earthquake. The color inside the circles at each recording station indicates the angular difference of RotD100 orientations with respect to the transverse orientation, $|\alpha|$. Empirical probability densities of the angular distance $|\alpha|$ are also shown for both periods.

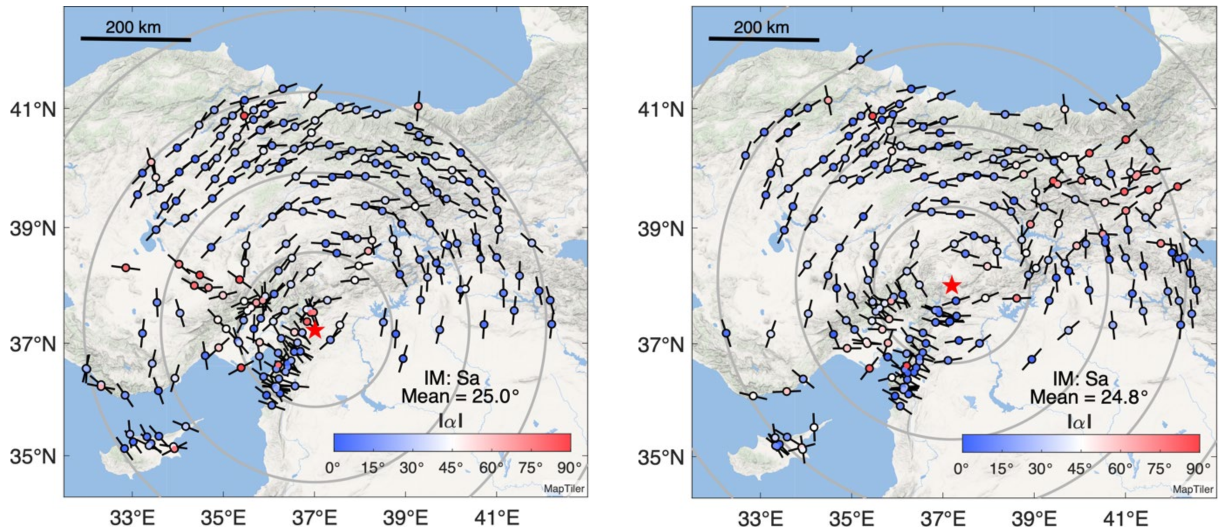

Figure 8. Orientations of the maximum horizontal pseudo-acceleration spectral ordinates of oscillators with period of 10s computed using ground-motion records from the 2023 M_w 7.8 (left) and M_w 7.5 (right) Kahramanmaras, Türkiye earthquake doublet. The color inside the circles at each recording station indicates the angular difference of orientations of RotD100 with respect to the transverse orientation, $|\alpha|$. Mean angular distances $|\alpha|$ are also shown for both events.

The February 2023 Kahramanmaras, Türkiye earthquake sequence produced one of the largest sets of records to date from strike-slip earthquakes with moment magnitudes greater than 7.5. Hence, this earthquake sequence provides a unique opportunity to study the directionality of 5%-damped response spectral ordinates, and particularly the orientation of maximum oscillator response. We studied ground motion records from the M_w 7.8 and M_w 7.5 events obtained from the Turkish Accelerometric Database and Analysis System (TADAS) (AFAD, Turkish Disaster and Emergency Presidency, 2023a, 2023b). To ensure a strong signal-to-noise ratio for a broad range of periods, only recordings where at least one component had a peak ground velocity (PGV) greater than 1 cm/s were used. To guarantee that the records studied are appropriate for investigating the long-period range, each record was used to compute oscillator responses up to its maximum usable period, which is taken as 1/1.25 times the high-pass cutoff frequency. All ground motions were first visually inspected to remove waveforms with recording issues such as late start and/or early termination. A total of 231 records for the M_w 7.8 event and 222 records for the M_w 7.5 met all these criteria. Examples of orientations of the maximum horizontal pseudo-acceleration spectral ordinates of oscillators with a period of 10s computed using ground-motion records from the 2023 M_w 7.8 (left) and M_w 7.5 (right) Kahramanmaras Türkiye earthquake doublet are shown in Figure 8. Again, the color inside the circles at each recording station indicates the angular difference of the RotD100 orientation with respect to the transverse orientation, $|\alpha|$. Consistent with observations from other strike-slip earthquakes, for most stations the orientation of maximum oscillator response occurs close to the transverse orientation. For more information on directionality of ground motions recorded during the 2023 Kahramanmaras, earthquake doublet, the reader is referred to Girmay et al. (2024b).

While the Ridgecrest, Ferndale, California events, as well as the Chihshang, Taiwan and the Kahramanmaras, Türkiye earthquake doublet, have produced valuable opportunities to further study the directionality of horizontal components of ground motions, some of the results are influenced by the spatial distribution of recording stations. To complement and further study the directionality of horizontal components of ground motions and, in particular, the spatial distribution of orientations of maximum response, the effect of hypocenter location, and the effect of rupture propagation direction, we are also using physics-based ground motion simulations obtained from SCEC's CyberShake Study 15.12 (Graves et al., 2011). We used ground motion simulations for 334 stations around greater Los Angeles for five different rupture variations across two strike-slip ruptures, totaling 1,670 records. The rupture simulations studied include M_w 6.95 and M_w 7.45 events with several variations along the Elsinore fault zone. This major active fault zone is part of the right-lateral strike-slip San Andreas fault system in southern California, stretching over 200 km from the south-east boundary of the LA basin to the Mexican border. For each rupture variation, the velocity seismograms at each station were downloaded and then numerically differentiated to obtain acceleration waveforms, which were then used to compute the relative displacement response of 5%-damped oscillators.

An example of the orientation of maximum spectral response of 5%-damped oscillators with periods of 5 s (shown on the left) and 10 s (shown on the right) computed using physics-based ground motions generated from a simulation of a M_w 6.95 rupture on the Elsinore fault is shown in Figure 9. The fault trace is indicated by the green line and the simulation involves the Whittier and Glen Ivy segments and rupturing from north to south. The angular difference between the RotD100 orientation and the transverse orientation of each station, $|\alpha|$, is indicated by the color inside the circles at each virtual recording station. The regular grid arrangement of these stations allows us to gain further insights into the orientation of maximum oscillator response. These figures also show large concentric circles in grey centered around the epicenter (indicated by the green star) that indicate epicentral transverse orientations. These grey circles, along with the color in the small circles, make it apparent that, for most stations, the orientation of maximum oscillator response occurs close to the transverse orientation. It is interesting to note that for some stations near the epicenter, the orientation of RotD100 occurs close to the fault parallel direction. This is in contrast with the current assumptions in ASCE 7 for near-fault sites, where the maximum ground motion intensity is assumed to occur in the fault-normal orientation. For more information on directionality of physics-based ground motion simulations, the reader is referred to Girmay et al. (2024c).

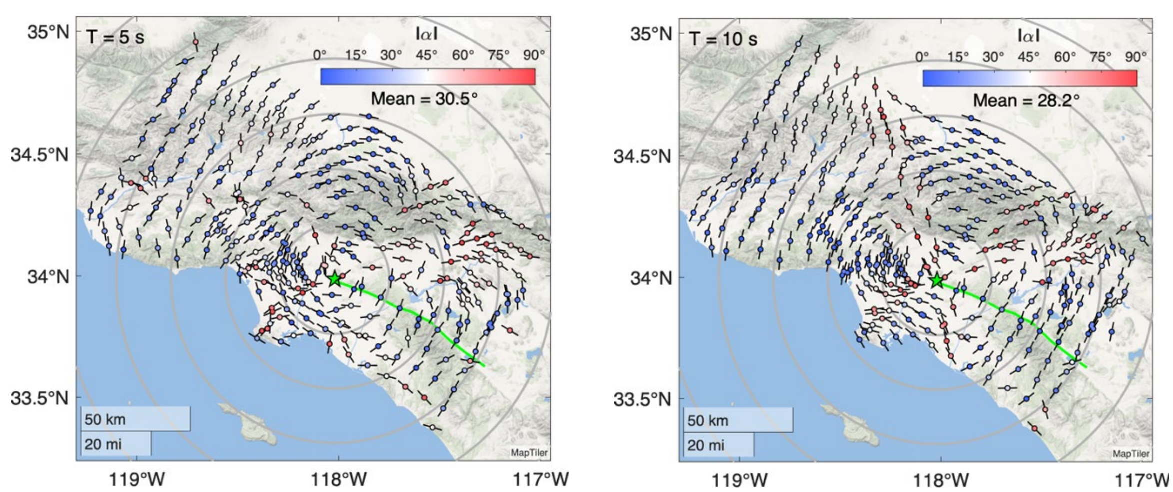

Figure 9. Orientation of maximum spectral response of 5%-damped oscillators with periods of 5 s (left) and 10 s (right), computed with physics-based ground motions generated from a simulation of a M_w 6.95 rupture on the Elsinore fault. The large grey circles centered around the epicenter indicate epicentral transverse orientations.

Summary and Conclusions

The directionality of response spectral ordinates of horizontal components of records in recent well-recorded strike-slip earthquakes has been studied. Results are complemented by investigating the directionality in physics-based ground motion simulations from the CyberShake Study 15.12, developed at the Southern California Earthquake Center (SCEC). Results show that ground motions are strongly polarized not only close to the rupture but up to distances as large as 400 km from the rupture. There is a slightly larger level of polarization for stations within 20 km from the rupture, but for the most part the level of polarization of horizontal components remains practically constant.

The new ongoing studies confirm that for strike-slip earthquakes, that is those in which the slip is primarily horizontal, it is possible to estimate the orientation in which the maximum spectral ordinates will occur. This orientation can be estimated from the location of the epicenter relative to the site. Results show that, for the large majority of the stations, the orientation of maximum oscillator response tends to occur within 30° of the transverse direction. Conversely, the orientation of minimum spectral response tends to occur close to the radial orientation. For large magnitude earthquakes that involve very long ruptures, such as the main event with moment magnitude 7.8 in 2023 Türkiye doublet, a slightly better estimate of the orientation of maximum response can be obtained if the horizontal surface projection of the point of maximum slip is used for computing the transverse orientations instead of the epicenter.

Results from this ongoing investigation indicate for strike-slip earthquakes, which represent approximately 80% of the earthquakes in California, current ground motion models tend to underestimate ground motion intensity in orientations close to the transverse direction and tend to overestimate ground motion intensity in orientations close to the radial direction. These findings are encouraging as they indicate that it is possible to develop new, more accurate, ground motion models where the current biases are eliminated or at least significantly reduced by estimating ground motion intensities at specific orientations.

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