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RECENT RESEARCH ON DIRECTIONALITY OF EARTHQUAKE GROUND MOTIONS

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Abstract: *Earthquake ground motion intensity varies significantly with changes in orientation. Response spectral ordinates in the direction in which the maximum intensity occurs are on average, depending on the period, between 36% and 127% higher than those in the perpendicular direction. However, this directionality has historically been ignored or not properly accounted in ground motion models or in seismic provisions. Recent studies to quantify and model directionality are summarized. First, results from a statistical study of the directionality are presented. The study was based on computed using 5,065 pairs of horizontal ground motions taken from the database of ground motions recorded in crustal earthquakes in active tectonic regions. Using these results, a fully probabilistic model was developed that provides models for the geometric median, variability and probability distribution of two different parameters that describe the directionality of horizontal components of earthquake ground motions. An alternate measure on intensity referred to as MaxRotD50 is then presented and discussed. The new measure of intensity is particularly well suited for earthquake-resistant design where a major concern for geotechnical and structural engineers is the probability that the design ground motion intensity is exceeded in at least one of the two principal horizontal components of the structure. In the final part, a summary of recent investigations of the orientation in which the maximum spectral occurs is presented. It is shown that style of faulting of the earthquake plays an important role in the directionality of ground motions. In particular, for strike-slip earthquakes the maximum ground motion spectral intensity tends to occur close to the transverse direction. This means that for strike-slip earthquakes, current ground motion models tend to underestimate ground motion intensity in the transverse direction and overestimate ground motion intensity in the radial direction*.

Introduction

One of the largest uncertainties involved in earthquake-resistant design or the evaluation of the performance of existing structures is the estimation of the ground motion intensity. For many years now, we have known that the level of ground motion intensity within the horizontal plane varies with changes in orientation, a phenomenon referred to as ground motion directionality. However, since the development of the first attenuation relationship, (more recently referred to as Ground Motion Models, GMM) by Esteva and Rosenblueth 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 to represent the intensity of the groun motion. In early, GMM this was typically the peak ground acceleration (PGA), but since the 70s we know that a much better characterization is provided by using response spectral ordinates. In particular, the large majority of the modern GMM provide estimates of 5%-damped pseudo-acceleration spectral ordinates which are proportional to the peak displacement of an oscillator relative to the ground and therefore provide a period-dependent information about the intensity of ground motions.

But as mentioned previously, the intensity of ground motions at a site not only changes as a function of the period of the oscillator, but also changes with changes in orientation, that is, with changes in azimuth. However, both in GMM and in seismic provisions the characterization of the ground motion intensity at a site has been greatly simplified by being described by a scalar which is a measure central tendency of the intensity in different orientations. The most common scalar that was used to describe the intensity of an earthquake ground motion at a site was the geometric mean of the intensity (e.g., peak ground acceleration or pseudo-acceleration spectral ordinate) in the two recorded orientations in the horizontal plane. This measure of intensity, although it was extensively used for more than 50 years has three related drawbacks: (1) it depends on the orientation of the horizontal sensors that recorded the motion; (2) its calculation only depends on

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the intensity in two orientations and neglects the remaining intensities that occurred at other orientations; and (3) as the intensity in one of the two components becomes much larger than the other, it can substantially underestimate the mean intensity at the site. In particular, in the case of a fully polarized ground motion in which all of the motion takes place in a vertical plane, one of the horizontal recording sensors would have a null intensity it is aligned with the direction of polarization, then the response spectral ordinate in the orthogonal direction would be zero leading to a geometric mean that it is also zero regardless of the spectral amplitude in the polarized direction. It is primarily, due to these drawbacks that Boore (2010) introduced an alternative measure of horizontal-component ground motion intensity that represents any percentile of the intensity in different orientations that is independent of the orientation of the recording sensors. In the alternative measure of intensity referred to as RotDpp, 5% spectral ordinates are computed for each period of vibration in a range of rotation angles of 180º, which are then sorted to compute the pp-th percentile. In particular, RotD50, corresponds to the median horizontal intensity, that is a level of intensity that, by definition, is exceeded in half of the angles of rotation and is not exceeded in the remaining angles of rotation. This measure of ground motion intensity was selected as the measure of horizontal-component seismic intensity in the NGA-West2 project and since then it has been adopted in the vast majority of the GMM developed in the last ten years to characterize the ground intensity that occur in different directions at a site.

Although there is no doubt that RotD50 is a better characterization of the ground motion intensity that can occur at a site in future earthquakes than the geometric mean computed from intensities in only the two recorded orientations, it still neglects the fact that the ground motion might be significantly higher in certain orientations and much lower in some other orientations. More importantly, it fails to account for how much larger the intensity can be in certain orientations or how much lower in other orientations. In other words, does not includes any quantitative information of the level of directionality in earthquake ground motions. If the level, of directionality is small, RotD50 may provide a good measure of intensity at a site, but if the level of directionality is important, RotD50 could be providing inadequate measures of the intensity of ground motions to be used in earthquake-resistant design on in the estimation of the performance of existing structures located in seismic regions. Therefore, there is a need to know the level of directionality present in earthquake ground motions.

It is not until recent years, that there has been an effort to study and in particular to quantify the directionality of earthquake ground motions. Although in recent years there have been several studies that have examined some aspects of the directionality of ground motions (e.g., Beyer and Bommer 2006; Watson-Lamprey and Boore 2007; Campbell and Bozorgnia 2007; Huang et al. 2008; Boore and Kishida, 2017) most of these studies have been limited to the study of the ratio of the maximum response spectral ordinate from all orientations, RotD100 to measures of central tendency such as GMRotI50 or RotD50. Two notable exceptions are the studies by Hong and Goda, (2007) and by Shahi and Baker (2014) who studied and provided models of the ratios of ground motion intensities that provide information of the variation of ground motion intensity as one rotates away from the orientation in which the maximum intensity (i.e., RotD100) occurs to a perpendicular direction. The objective of this work is to summarize a series of recent studies conducted by the authors in the last four years on the directionality of ground motions. In particular, we aimed at providing a summary of studies on: (1) a comprehensive probabilistic characterization of earthquake ground motions; (2) an alternative measure of ground motion intensity at a site that it is more appropriate for earthquake resistant design than either RotD50 or RotD100 and has an intensity between these two; and (3) studies on the orientation of the maximum response spectral ordinate and its implications.

Probabilistic characterization of ground motion directionality

The intensity of horizontal earthquake ground motions varies with changes in orientation (i.e. with changes in azimuth). For engineering purposes, the intensity of a ground motion is characterized as proportional to the peak response of a linear elastic single-degree-of-freedom (SDOF) system with a given damping ratio (assumed to be 5% in this work) and a given period of vibration T. The respond to the ground motion recorded in two perpendicular directions x and y with displacements relative to the ground of $u_x(t)$ and $u_y(t)$, respectively. The response of the SDOF system in any orientation defined by an arbitrary rotation angle θ is a linear combination of the responses in the two as-recorded directions as follows:

$$u_\theta(t) = u_x(t)\cos(\theta) + u_y(t)\sin(\theta) \quad (1)$$

Ground motion models (GMM) and design spectra use pseudo-acceleration response spectral ordinates as measures of ground motion intensity which are defined as

$$Sa(\theta) \; = \omega_n^2 \max_{\forall t} |u_\theta(t)| \tag{2}$$

where ω_n is the circular frequency of vibration of the oscillator.

Ground motion directionality is defined as the change in ground motion intensity within the horizontal plane with changes in orientation. In order to illustrate the directionality in a ground motion figure 1 shows the two-dimensional relative displacement trace of an SDOF system with period of vibration T=1.0s when subjected to ground acceleration histories recorded at the Canoga Park Station in the San Fernando Valley north of Los Angeles in the state of California during the January 17, 1994 Northridge earthquake. The right-hand side of the figure shows the variation of ground motion intensity S_d as a function of the rotation angle, θ, which is also shown in a polar representation in the hodogram shown on the left. The figures also show the median Sa value of all non-redundant orientations (i.e. RotD50) and the intensity in the orientation where the intensity is maximum (i.e. RotD100). In this figure orange circles indicate the spectral intensity in the two recorded orientations. The spectral ordinate in the 196º component (or 16º) is 63% greater than the spectral ordinate in the 106º (or 286º) component illustrating that there can be considerable variations in seismic intensity with changes in direction. Furthermore, the maximum spectral intensity, indicated in the figure by a red triangle and which occurs for an azimuth of 178.5º, is 12.85cm (S_a=0.52g) which is 2.12 times higher than the minimum intensity, which is indicated in the figure by a green triangle and which occurs for an azimuth of 81º and is equal to 6.04cm (S_a=0.24g). The median intensity from all orientations for this record is 9.86 cm (Sa=0.4g) which the maximum intensity exceeds by 30% and is 63% higher than the minimum intensity, illustrating that the ground motion intensity that occurred at this site can be significantly higher or lower than the measure of intensity than we use in GMM to characterize the intensity that occurred at the site during the earthquake.

It is important to know if the level of directionality shown present in the horizontal components of this particular ground motion record is unusually high, unusually low or typical of the directionality of ground motions. This was done by computing the intensity at all non-redundant angles (180angles with a 1º increment) for a large number of recorded ground motions. For this purpose, the authors considered a subset of the NGA2 ground motion database (Ancheta et al. 2014) were selected using the following criteria: (1) originated from crustal earthquakes with magnitude equal or greater than five; (2) recorded in NEHRP site classes B, C, and D; and (3) have reasonably free-field conditions. This selection criteria resulted in 5,065 pairs of horizontal ground motion.

For each pair of horizontal components of ground motion, we computed two measures of ground motion directionality. Both measure of directionality are normalized measures of directionality which provide ratios of ground motion intensity in different orientations with respect to commonly used orientation-independent measured on ground motion intensity.

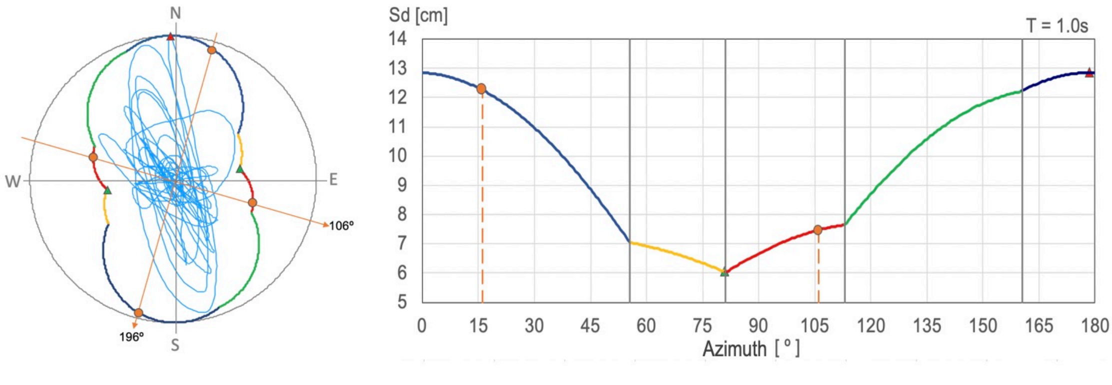

Figure 1. Variation of the intensity of the seismic movement of an elastic oscillator with a period of 1.0 s and 5% of the critical damping when subjected to the ground movement registered at the Canoga Park station during the January 17, 1994 Northridge earthquake. On the left the particle movement and on the right the variation of the pseudo-acceleration ordinates with changes in the azimuth.

The first measure of directionality we studied was the spectral ordinate for different directions (i.e., for different angles) normalized by the maximum intensity of all directions, $Sa_{RotD100}$

$$\eta(\phi) = \frac{Sa(\phi)}{Sa_{RotD100}} \tag{3}$$

where $Sa(\phi)$ is the spectral ordinate at an angle of rotation ϕ measured from the angle at which the maximum spectral ordinate occurs and the maximum intensity of all directions, $Sa_{RotD100}$ is given by.

$$Sa_{RotD100} \equiv \max_{\forall\theta\in[0°,180°]} Sa(\theta) \tag{4}$$

Parameter $\eta(\phi)$ is dimensionless and was first proposed by Hong and Goda (2007) to study the variation of ground motion intensity as one rotates from the orientation of maximum intensity.

The second parameter that we studied as a measure of directionality was the spectral ordinate for different orientations normalized by the mean of all the intensities of the record between 0 and 180º

$$\nu(\phi) = \frac{Sa(\phi)}{Sa_{RotD50}} \tag{5}$$

where $\nu(\phi)$ is the spectral ordinate at an angle ϕ measured from the angle at which the maximum spectral ordinate occurs $Sa_{RotD100}$ and Sa_{RotD50} is the average of all intensities between 0 and 180º

$$Sa_{RotD50}(T_i) = \underset{\forall\theta\in[0°,180°)}{\text{Median}}\, Sa(T_i,\theta) \tag{6}$$

Figure 2 shows both of these non-dimensional measures of directionality for the Canoga Park record. These graphs show how spectral ordinates decrease as the orientation moves away from the azimuth where the maximum intensity occurred. The curves in blue show this tendency to decrease the spectral intensity with clockwise increments in rotation from 0 to 90º, while in orange this variation is shown the tendency with counter clockwise rotations. It can be seen that the decrease in seismic intensity as we move away from the azimuth where the maximum intensity occurred is very similar, but not the same if we turn in one direction or the other. Likewise, it can be seen that there is not always a decrease in intensity with the increase in the angle ϕ. On the figure on the left it can be seen that upon reaching the perpendicular direction, for this period of vibration and record, the intensity basically decreases to about half of the maximum intensity, that is $\eta(90º) \approx 0.5$. It can be seen that, for angles of rotationϕ less than 40º, for this record and period the seismic intensities exceed the average of all intensities, while for anglesϕ greater than 50º, the seismic intensities are lower than the average of all intensities. On the figure on the right, it can be seen that the maximum normalized spectral ordinate is 30% larger than the mean of all intensities (ν_{max}=1.3) while the minimum ordinate of all directions is 39% less than the mean of the intensities in all directions (ν_{min}=0.61).

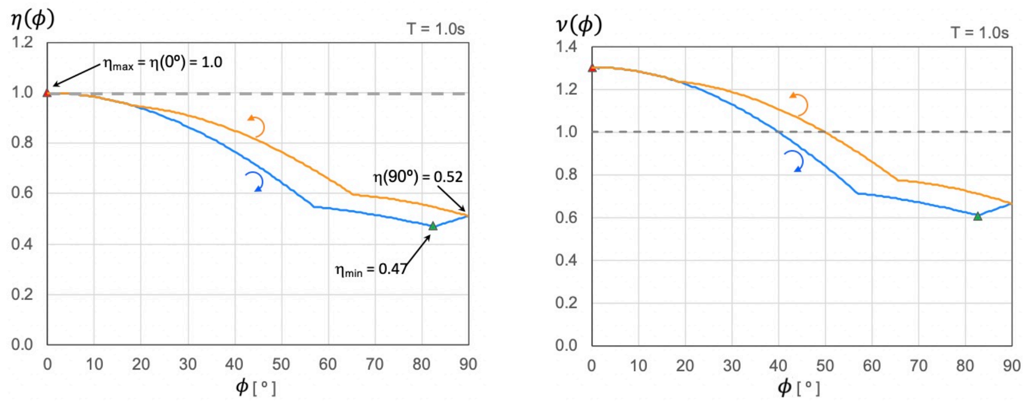

Figure 2. Directionality of the intensity of the peak response of an elastic oscillator with a period of 1.0s and 5% damping when subjected to the Canoga Park record of the 1994 Northridge earthquake. On the left the variation of spectral ordinates normalized by the maximum intensity (0.52g for this record and period) on the right the variation of the ordinates normalized by the median of all ordinates (0.4g for this record and period).

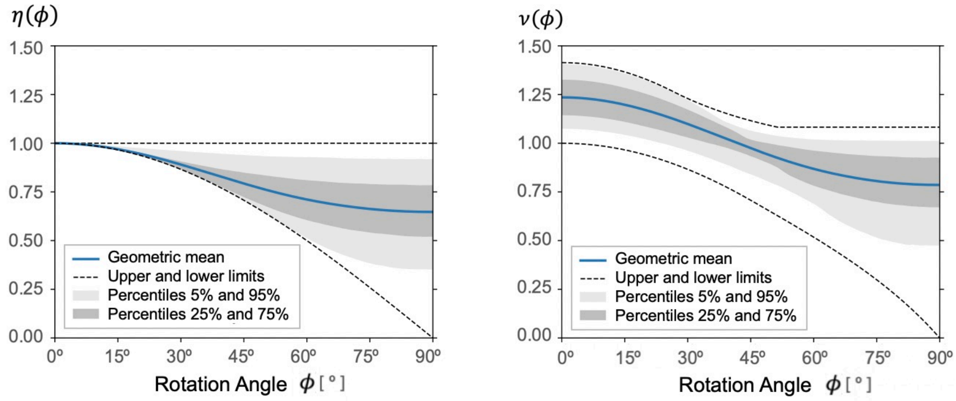

Figure 3. Statistical results of the directionality of the intensity of the horizontal seismic movement of oscillators with a period of 1.0 s of 5,065 records obtained in crustal earthquakes. On the left, spectral ordinates normalized by the maximum spectral ordinate of each record ($Sa/Sa_{RotD100}$) and, on the right, spectral ordinates normalized by the median of the intensity of all the directions of each record (Sa/Sa_{RotD50}).

For each pair of records, spectral ordinates were calculated for elastic one-degree-of-freedom systems with 5% damping and for40 periods logarithmically spaced between 0.01 s and 10 s and using rotation angles between 0º and 180º with increments of 1º, for a total of 7,200 spectral ordinates for each pair of records. Then, for each vibration period, the maximum spectral ordinate was identified $Sa_{RotD100}$ and the azimuth in which said spectral ordinate occurs, as well as the median of the180 intensities, Sa_{RotD50}, corresponding to each angle of rotation ϕ. For each pair of records and each vibration period, we then obtained 180 values of spectral ordinates normalized by the maximum intensity, that is, 180 values of the dimensionless directionality parameter $\eta(\phi)$ and 180 values of spectral ordinates normalized by the median of the intensities, that is,180 dimensionless directionality parameter values $\nu(\phi)$. This process was repeated for each of the 5,065 pairs of records to obtain a little more than 30 million values of $\eta(\phi)$ and an equal number of values of $\nu(\phi)$.

Figure 3 presents statistical results of both directionality parameters for the 5,065 pairs of records. The geometric mean of the dimensionless directionality parameters $\eta(\phi)$ and $\nu(\phi)$ are shown in blue lines as a function of the angle of rotation ϕ along with the lower and upper bounds of these parameters. For further details of the derivation and values of these limits, the reader is referred to Poulos and Miranda (2022c). The figure the regions shown in dark grey delimited by the 25% and 75% percentiles concentrate half of the records and the region in light grey between the 5% and 95% percentiles concentrate 90% of the records There is a very small variability of the parameter $\eta(\phi)$ for angles of rotation between 0º and 30º where the intensity decreases only a little as you move away from the direction in which the maximum intensity occurred. The variability of $\eta(\phi)$ increases as the angle of rotationϕ is increased.

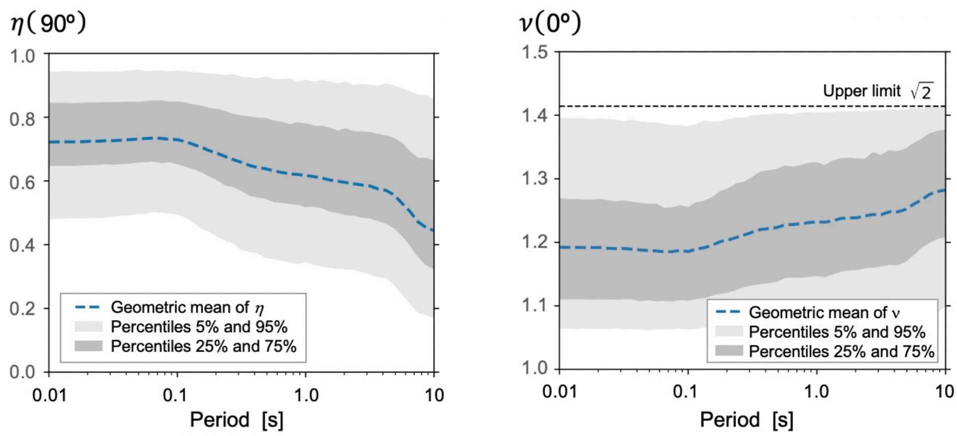

Figure 4. Effect of the period of vibration on the geometric mean and variability of the directionality of the intensity of the seismic movement in horizontal components of 5,065 records of crustal earthquakes. On the left, ratio of the maximum intensity to that which occurs in the perpendicular direction and on the right, ratio of the maximum intensity and the median intensity in all directions.

The left side of figure 4 shows the influence of the vibration period of the system on the dimensionless directionality parameter η(90º) which provides information on how much smaller the spectral ordinates in the component are in the orientation perpendicular to the orientation where the maximum intensity occurs with respect to the maximum intensity. By definition, this value is always between 0 (when the movement is perfectly polarized, that is, when movement occurs only in one vertical plane) and 1 (when the intensity is exactly the same in both perpendicular components. Both extremes, that is, the upper and lower limit values do not actually occur in recorded earthquake motions, although some rare records do approach these limits. It can be seen that the geometric mean of η(90º) depends on the vibration period of the system, that is, it is different for different periods of vibration and tends to decrease with increasing periods, and although the directionality level is important for all periods, it is particularly important for vibration periods greater than 1.0s. The figure, the region in dark grey also corresponds to the region delimited by the 25% and 75% percentiles of η(90º) in which half of the registers are contained. For example, for a period of 1.0s, in half of the records the spectral ordinate in the component perpendicular to the maximum intensity is between 22% and 49% smaller than the maximum intensity. These results clearly show that the ground motion intensity changes from one component to its perpendicular component significantly and therefore should not be neglected.

The graph on the right of figure 4 shows the statistical results of ν(0º) which provides information about how much larger the maximum ordinate is (maximum of the intensity from all rotation angles) with respect to the median of all directions (i.e., with respect to RotD50 which used in modern GMM). By definition, this value is always greater than 1.0 and always less than$\sqrt{2}$. The upper limit occurs for a perfectly polarized motion in which the entire history of relative displacements of the oscillator only occurs in vertical plane. It can be seen that, although in reality perfectly polarized motions do not occur, several records are not far from this situation and therefore are close to this upper limit. As shown in the figure the geometric mean of the parameter ν(0º) grows from values of the order of 1.19 for structures with periods of 0.1s to values of 1.28 for a period of 10s. This implies that for half of the records the maximum spectral ordinate will be approximately between 20% and 30% of the median intensity from all orientations at the site. The graph on the right of Figure 4 also shows the regions delimited by the 25% and 75% percentiles (which contain half of the records) and by the 5% and 95% percentiles (in which 90% of the records fall).

Although the variabilities of the dimensionless parameters η(90º) and ν(0º) shown in figure 4 appear to be large, for almost all the periods they correspond to coefficients of variation or logarithmic standard deviations that are less than 0.1, which represents a much smaller variability than the variability of the spectral ordinates for a given magnitude and distance and type of terrain that usually have coefficients of variation greater than 0.6. That is, we can estimate the directionality of the spectral ordinates (the change in amplitude with angle of rotation) much better than we can estimate the amplitude of the spectral ordinates.

Figure 5 shows the effect of the period of vibration of the SDOF system on the geometric mean of dimensionless directionality parameters $\eta(\phi)$ and $\nu(\phi)$. It can be seen that, regardless of the period of vibration, the geometric mean of these directionality parameters reflects a monotonic decrease in the seismic intensity as the orientation rotates away from that in which the maximum intensity occurred. As previously mentioned, the directionality of the spectral ordinates increases as the vibration period increases, that is, the variation of the spectral ordinates with changes in the angle of rotation is greater as the period of vibration increases. The directionality is especially large for periods of vibration greater than 1.0s. For example, for a period of 10s the parameter $\eta(\phi)$ decreases from 1.0 at ϕ = 0º, that is, from the maximum intensity, up to a value η(90º) average of only 0.44, which implies that for T=10s the maximum intensity is on average 2.27 times larger than that which occurs in the perpendicular direction. Meanwhile, for short periods like 0.1s the spectral ordinates vary on average from 18.4% above the median intensity of all orientations to 14% below the median intensity, in contrast with what happens for a period of 10s for which the spectral ordinates vary, on average, from 28.3% above the median intensity of all orientations to 43.1% below the median intensity. Indicating that current GMM significantly underestimate the ground motion intensity in some orientations and significantly overestimate the ground motion in other orientations. Current GMM only estimate the median intensity of all orientations and therefore neglect this significant variability in intensity with changes in orientation.

In order to account for the important level of directionality shown in figures 3 to 5 of response spectral ordinates of the horizontal components computed from recorded ground motions we develop a probabilistic model to characterize this directionality. We first conducted nonlinear regression analyses to obtain equations to estimate the geometric mean of dimensionless directionality parameters $\eta(\phi)$ and $\nu(\phi)$ as a function of the period of vibration of the oscillator and of the angle of rotation ϕ. That is, equations to approximate curves shown in continuous lines in figure 5. The same functional form was proposed for both parameters and given by:

$$\eta(\phi) \;\approx \hat{\eta}(\phi) = C_1 + C_2 e^{-C_3\phi^2} \tag{7}$$

$$\nu(\phi) \;\approx \hat{\nu}(\phi) = C_4 + C_5 e^{-C_6\phi^2} \tag{8}$$

where $\hat{\eta}(\phi)$ and $\hat{\nu}(\phi)$ are the approximate values of the geometric mean of the dimensionless directionality parameters $\eta(\phi)$ and $\nu(\phi)$, ϕ is the angle of rotation measured from the angle at which the maximum spectral ordinate occurs $Sa_{RotD100}$ and C_1, C_2, C_3, C_4, C_5 and C_6 are constants that vary with the period of vibration and that were determined with the Levenberg-Marquardt method (Moré, 1978). Period-dependent constants C_1 to C_6 are available in the appendix and electronic supplement of Poulos and Miranda (2022c). Figure 5 compares the statistical results of parameters $\eta(\phi)$ and $\nu(\phi)$ calculated from the 5,065 pairs of seismic records compared to their approximate values $\hat{\eta}(\phi)$ and $\hat{\nu}(\phi)$ calculated with equations (7) and (8). It can be seen that these equations, despite their simplicity and requiring only three constants, provide an excellent approximation of the statistical results.

We also obtained approximations to the logarithmic standard deviations of the dimensionless directionality parameters $\eta(\phi)$ and $\nu(\phi)$ as a function the period of vibration of the oscillator and the angle of rotation ϕ. Again, the same functional form was proposed for both parameters shown in these equations:

$$\sigma_{ln\,\eta}(\phi) \;\approx \hat{\sigma}_{ln\,\eta}(\phi) = \frac{C_6 + C_7\emptyset^3 + C_8\emptyset^4}{1 + C_9\emptyset^3 + C_{10}\emptyset^4} \tag{9}$$

$$\sigma_{ln\,\nu}(\phi) \;\approx \hat{\sigma}_{ln\,\nu}(\phi) = \frac{C_{11} + C_{12}\emptyset^3 + C_{13}\emptyset^4}{1 + C_{14}\emptyset^3 + C_{15}\emptyset^4} \tag{10}$$

where $\widehat{\sigma}_{n\,h}(\phi)$ and $\widehat{\sigma}_{n\,n}(\phi)$ are the approximate values of the logarithmic standard deviations of dimensionless directionality parameters $\eta(\phi)$ and $\nu(\phi)$, ϕ is the angle of rotation measured from the angle at which the maximum spectral ordinate occurs $Sa_{RotD100}$ and C_6 to C_{15} are constants that are also available in the appendix of Poulos and Miranda (2022c). That reference also includes expressions to approximate the correlation of the parameters $\eta(\phi)$ and $\nu(\phi)$ with those that occur in an oscillator with the same period of vibration but at another rotation angle, or for a given rotation angle but for another period of vibration, as well as information of the probability distribution of directionality parameters $\eta(\phi)$ and $\nu(\phi)$ that can be approximated with a four-parameter Beta probability distribution. Figure 6 shows a comparison of statistical results of the parameters $\sigma_{n\,h}(\phi)$ and$\sigma_{n\,n}(\phi)$ calculated from the 5,065 pairs of ground motion records to their approximate values $\widehat{\sigma}_{n\,h}(\phi)$ and $\widehat{\sigma}_{Ln\,n}(\phi)$ calculated with equations (9) and (10). It can be seen that these equations, despite being also relatively simple, provide again an excellent approximation of the statistical results.

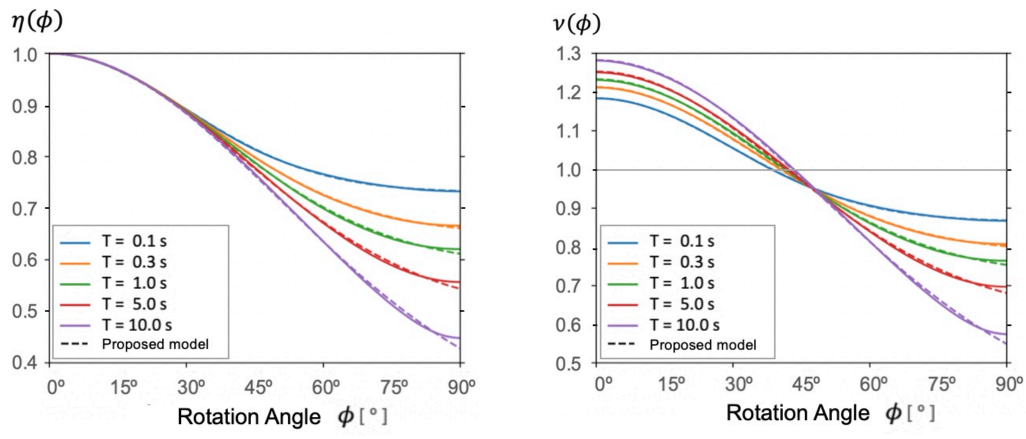

Figure 5. Comparison between the geometric mean of normalized spectral ordinates calculated from 5,065 pairs of records with those calculated with the proposed equations. On the left, spectral ordinates normalized by the maximum spectral ordinate of each record and, on the right, spectral ordinates normalized by the median intensity of all directions of each record.

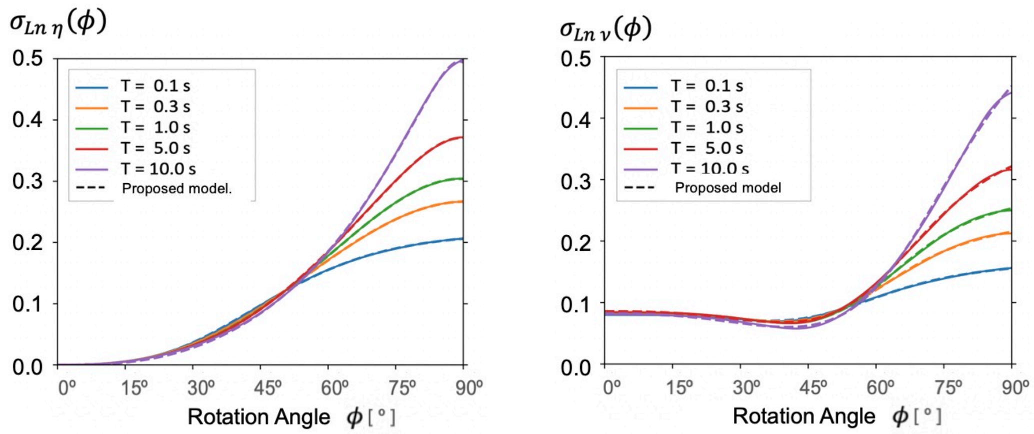

Figure 6. Comparison between the logarithmic standard deviations of directionality parameters $\eta(\phi)$ and $\nu(\phi)$ calculated from 5,065 ground motion records with those calculated with equations 9 and 10. On the left, spectral ordinates normalized by the maximum spectral ordinate of each record, and on the right, spectral ordinates normalized by the median of the intensity of all orientations of each record.

Proposal of an Intensity Measurement for Earthquake Resistant Design

In one of the first studies to quantify some aspects of directionality of recorded earthquake ground motions Huang et al. (2008) noted that spectral ordinates corresponding to the maximum intensity of all orientations (i.e. RotD100) substantially exceed GMRotI50 intensities (that were used in the NGA project at the time) in the near-fault region, which has significant implications for seismic design and seismic performance assessment. As a result of that study the maximum direction was adopted for use in earthquake-resistant design in the United States (ASCE, 2010). Since there are currently no GMM to estimate RotD100 response spectral ordinates, ASCE 7 makes use of approximate period-dependent amplification factors to estimate RotD100 seismic hazard curves and design spectral ordinates in general by amplifying seismic hazard curves and response spectral ordinates based on RotD50 intensities. The latest version of the ASCE-7 National Standard in the U.S. (ASCE, 2022) makes use of amplification factors from Shahi and Baker (2014) which range from 1.19 in the short period spectral region to 1.29 for a period of 10.0s.

The adoption of the RotD100 intensity as the basis for design triggered strong discussions in the engineering seismology and engineering communities in the U.S. For example, Stewart et al. (2011) described the adoption of the maximum direction as a basis for design as controversial. They argued that the use of the maximum direction for design introduces an overly conservative bias to design ground motions because it effectively assumes that the azimuth of maximum ground motion coincides with the directions of principal structural response, which is unlikely. They asserted that the 10% to 30% increase in ground motion intensity from the use of RotD100 instead of GMRotI50 affects the costs of new construction and retrofits. They estimated these increments would then lead to additional construction costs on the order of magnitude of 1% that would correspond to an added premium of $500 million US dollars per year in California alone. They argued that the use of the existing USGS probabilistic ground motion maps which are the time were based on the use of GMRotI50 to characterize the seismic intensity at a site combined with NEHRP site and risk factors represents the most reasonable (probabilistically most consistent) basis currently available for evaluating design ground motions along the principal axes of structures.

The authors agree with Stewart et al. (2011) that it is too conservative to design all buildings and structures in general using the maximum intensity RotD100, especially given that only a very small fraction of structures (probably less than 1%) are axisymmetric, that is, structures having a vertical cylindrical symmetry in which the structure has the same properties (i.e. mass, lateral stiffness, lateral strength) when rotating about a vertical axis, design ground motions should be based on the maximum direction intensity. Some examples of this type of structures include cylindrical liquid storage tanks (e.g. water tanks, oil tanks, liquid natural gas tanks, wine tanks, etc.), spherical storage tanks, vertical pressure vessels, isolated cylindrical storage silos, dome structures, cylindrical or truncated conical chimneys and stacks, hyperbolic cooling towers in power plants, water reservoir cylindrical intake towers, cylindrical containment structures in nuclear power plants, and isolated cylindrical structures in oil refineries (e.g. distillation columns, fluid catalytic cracking units, hydrocracker units, coker units, etc.). For this reason, it would make more sense to apply a multiplier larger than 1 when designing this small fraction of structures that are a axisymmetric rather than overdesigning the large majority (approximately 99%) of the structures.

On the other hand, one must carefully evaluate if making use of a measure of central tendency of the intensity of all directions such as GMRotI50 or RotD50 used in most modern GMM for design of structures is appropriate. Most buildings have two orthogonal horizontal principal directions and are the peak deformations in these principal directions that are the primary concern of structural engineers. This is because damage to beams, structural walls, diagonal bracing elements and many other structural elements is primarily the result of deformations in the plane of these elements. For this reason, practically all codes limit peak lateral deformations and one of the primary concerns of structural engineers when designing structures to resist earthquakes is the probability that peak deformations along the orthogonal horizontal principal directions that they used in design are exceeded during an earthquake.

In a recent study, the authors computed the probability that the RotD50 intensity will be exceeded in either a given direction or in the perpendicular direction (e.g., on either the longitudinal or transverse directions of a structure) by using the same subset of the NGA2 ground motion database previously described. By definition, the RotD50 intensity will be exceeded for half of the orientations at a site and will not be exceeded in the remaining half of the orientations. However, when computing the probability that the RotD50 intensity on either the longitudinal or transverse directions of a structure the resulting probabilities are very different. Figure 7 presents some properties of these probabilities as a function of period, which shows that the fraction (i.e, the percentage) of rotation angles where RotD50 is exceeded in either the longitudinal (L) or transverse (T) direction of a structure is significantly higher than 50%. In particular, the mean percentage of these rotation angles ranges from approximately 91% for short periods to 98% for 10 s. Furthermore, the figure on the right hand side of Figure 7 shows the fraction of records in the intensity exceeds RotD50 in either the L or T direction regardless of the orientation of the structure with respect to the ground motion. As shown in this figure, this percentage varies from approximately 47% for periods of0.1s to about 85% for periods of 10 s.

Results presented in figure 7 have profound implications in engineering practice. In particular, Poulos and Miranda (2022c) have shown that RotD50 intensities associated with return periods commonly used in design such as 475 and 2475 years (i.e., 10% and 2% probability of exceedance in 50 years, respectively) have significantly lower return periods when considering not the median intensity of all directions but based on the probability that will be exceeded on one of two orthogonal directions. In an example, it was shown that the probability of exceeding RotD50 ground motions intensities in at least one of the principal axes of the structure were 14.4% in 50 years instead of the 10% in 50 years implicit in a seismic hazard map based on RotD50 (i.e., 44% higher) and 3.3% in 50 years instead of the 2% in 50 years implicit in a seismic hazard map based on RotD50 (i.e., 65% higher).

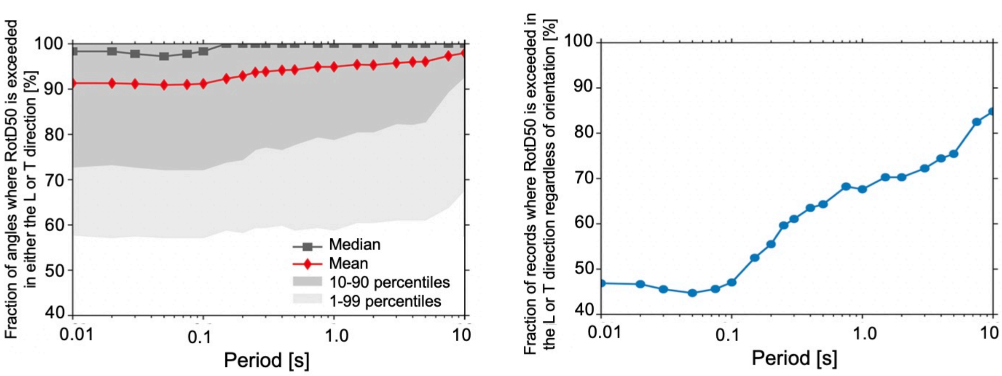

Figure 7 Fraction of angles of rotation where the RotD50 intensity is exceeded in either the longitudinal or transverse direction as a function of structural period. On the left, median, mean, and percentiles of these fractions and on the right percentage of records where RotD50 is exceeded in the longitudinal or transverse direction for all possible rotation angles.

In order to avoid the over conservativism when using the maximum intensity of all orientations (RotD100) but to avoid the possible unconservative design when using RotD50, the authors recently proposed an alternative measure of seismic intensity that is more appropriate for earthquake resistant design. The proposed intensity has a level on intensity that is between RotD50 and RotD100, but it is closer to the latter than to the former. Following the naming convention proposed by Boore et al. (2006), the new intensity measure is referred to as MaxRotDpp, where the Max indicates the maximum of the two horizontal components and pp is used to indicate that the intensity is the pp-th percentile for all non- redundant rotation angles and is computed independently for each structural period. The proposed measure of ground motion intensity at a given site can be easily computed following these steps:

1. Select a structural period and damping ratio. Compute the relative displacement of an SDOF system in two orthogonal horizontal directions (e.g. the as-recorded directions).
2. Compute $Sa(\theta)$ for all non-redundant rotation angles, that is, between 0º and 180º using Equations 1 and 2. Increments of 1 degree are enough to obtain stable results. Calculate the maximum Sa between two orthogonal directions in a range of 90° using the following equation

$$Sa_{Max}(\theta) = max\{Sa(\theta), Sa(\theta + 90°)\} \tag{11}$$

3. Finally, compute MaxRotDpp as the pp-th percentile of the computed $Sa_{Max}(\theta)$ values. For example, the median value (i.e. 50th percentile) is denoted by MaxRotD50.

Since $Sa(\theta)$ repeats every 180° of the rotation angles, and both principal directions of the building (L and T) are separated by 90° (because they are orthogonal), the maximum $Sa(\theta)$ between the intensity occurring in the longitudinal direction and the intensity occurring in the transverse direction repeats every 90°. Thus, computing the maximum in the second step only needs to consider rotation angles in a range of 0º and 90° to account for all non-redundant directions.

Unlike the approach adopted in ASCE 7 (2010, 2022) which uses RotD100 for the design of all structure, we propose using MaxRotD50 and to use RotD100 only for the small fraction of structures that are axisymmetric. In Poulos and Miranda (2021) we computed ratios of the new intensity MaxRotD50 with most commonly used measures of ground motion intensity at a site. In that study we showed that the influence of magnitude and distance is relatively small (further results are available in Poulos et al. 2022b) are therefore one can obtain relatively good estimates of MaxRotD50 by modifying the results of current GMM based on RotD50 using the following equation (Poulos and Miranda, 2021)

$$\frac{Sa_{MaxRotD50}(T)}{Sa_{RotD50}(T)} = \begin{cases} 1.12 & T \le 0.1\,s \\ 1.155 + 0.0152\log(T) & 0.1\,s < T \le 10s \end{cases} \tag{12}$$

The new measure of intensity MaxRotD50 has several important advantages over other alternative measure of ground motion intensity at a site such as GMRotI50 or RotD50. Some of these advantages are: (1) The proposed intensity has a 50% probability of being exceeded in either the longitudinal direction or in the transverse direction of the structure and, therefore, the return period of an ordinate of the design spectrum based on this intensity level would coincide with the probability that the response spectral ordinate is exceeded either in the longitudinal direction or in the transverse direction of the structure, that is, the return period is of greater interest for the design or evaluation of a structure; (2) Unlike the geometric mean or quadratic mean of the two intensities at the orientation of the sensors, the new measure of intensity proposed does not depend on the orientation of the sensors; and (3) Avoids over-conservative designs such as one based on RotD100 for structures that are not axisymmetric since such design assumes that the maximum intensity will coincide either with the longitudinal or transversal direction of the structure.

In most structures, the seismic response is strongly dominated by the first-mode response in each of its principal directions, that is, by the first-mode response in the longitudinal direction and the first-mode response in the transverse direction. This occurs even when there is some degree of coupling with the first torsional mode of the structure and is particularly true for response parameters such as maximum story drift. Similarly, the seismic response is strongly dominated by the first-mode response even when the structure experiences some level of nonlinearity, so using the proposed measure of intensity will be better correlated with the peak deformation in the structure than using RotD50 or other measures of central tendency of the the ground motion intensity in different orientations.

Orientation of maximum response spectral ordinates

In their landmark paper, Somerville et al. (1997) found that spectral accelerations at 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 the source and proposed a first directionality model based on these observations. A few years later, Howard et al. (2005) found that even for ground motions very near to the source, the orientation that maximizes the mean response spectrum for periods between 0.5 s and 3 s, and hence also maximizes the Housner spectral intensity, differs from the strike-normal orientation. Using a relatively small sample of 15 ground motions with strike-slip faulting and 14 ground motions with reverse faulting they found mean differences between the orientation of largest spectral intensity and the strike-normal orientation of 21° and 29°, respectively. Similarly, Watson-Lamprey and Boore (2007) used the NGA ground motion database to show that the orientation of maximum spectral acceleration rarely coincides with the strike-normal orientation, especially for source-to-site distances greater than 3 km.

More recently, using the NGA-West2 ground motion database, Shahi and Baker (2014) showed that the angle between the orientation of maximum intensity and the fault strike was essentially random, having a practically uniform probability distribution except for oscillators with periods of vibration longer than 1 s and source-to-site distances less than 5 km, where they observed a tendency of the orientation of maximum intensity to be closer to the strike-normal orientation than to the fault-parallel orientation. Based on this last study, seismic design provisions in the U.S. specify that when conducting response history analyses for structures located more than 5km from the source, the orientation of the selected ground motions should be randomly selected.

In a very recent study, we revisited this issue. In particular, we studied if there are cases in which one can anticipate the orientation of the maximum horizontal ground motion intensity at a site. For this purpose, we used the same subset of the NGA-West2 database previously described consisting of 5,065 pairs of horizontal components of ground motions recorded during earthquakes with magnitude magnitudes equal or greater than 5.0 at stations with NEHRP site classes B, C, and D; and that reasonably represent free-field conditions. We computed 5% response spectra only up to the smallest maximum usable period of the two recorded horizontal components at each site resulting in a decreasing number of usable records as the period increases. The ground motions were grouped by their style of faulting, which was defined based on the rake angle reported within the NGA-West2 database. Reverse earthquakes were assumed to have rake angles, λ, within [60°, 120°] and strike-slip earthquakes were assumed to have rake angles that are within 30° of a horizontal slip vector (i.e., λ = 0°, λ = 180°, or λ = −180°).

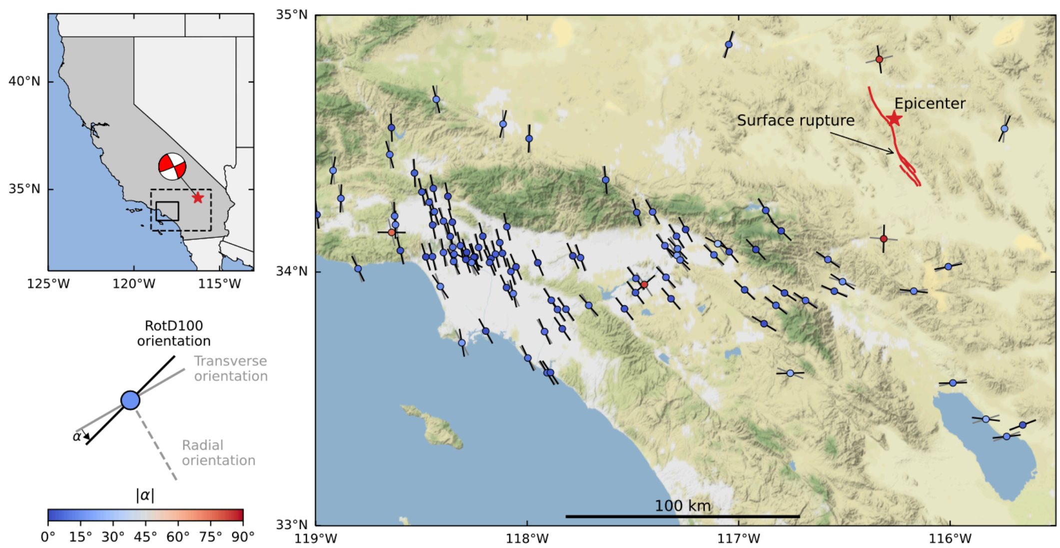

Figure 8. Orientations of maximum spectral response for oscillators with 5% damping and periods of 10 s subjected to the horizontal components of ground motions recorded during the 1999 M_w 7.1 Hector Mine earthquake in the state California in the United States (modified from Poulos and Miranda, 2023a).

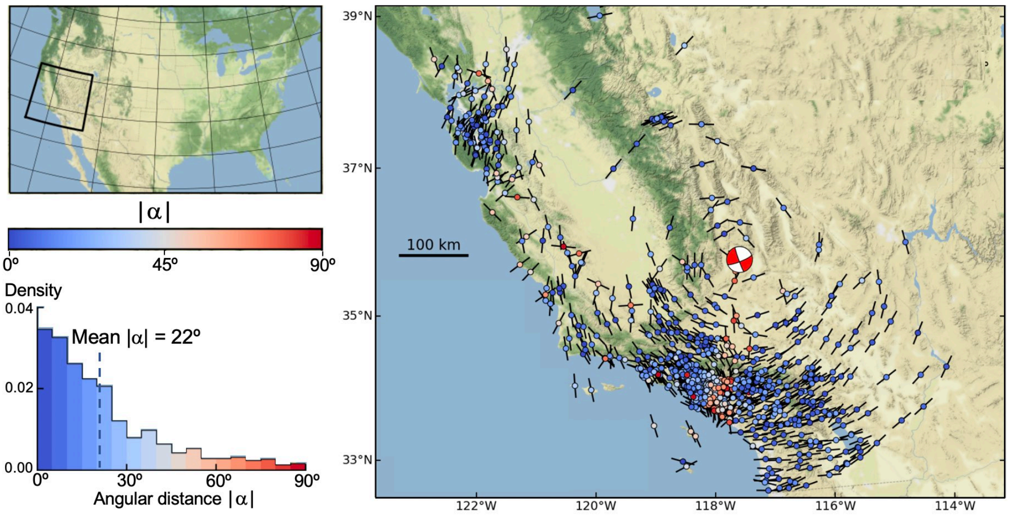

Figure 9. Orientations of maximum spectral response for oscillators with 5% damping and periods of 10 s subjected to the horizontal components of ground motions recorded during the 2019 M_w 7.1 Ridgecrest earthquake in the state California in the United States (modified from Poulos and Miranda, 2023b).

Records from oblique and normal earthquakes were not considered for these statistics due to their relatively low number in the database. We found (Poulos and Miranda, 2023a) that style of faulting has an important effect on the orientation of maximum spectral intensity. In particular, we found that for strike-slip earthquakes, the orientations of maximum response spectral intensity tend to be close to the transverse orientation, i.e., an orientation that is perpendicular to the line segment connecting the recording station and the earthquake epicenter. Contrary to what occurs with respect to the previously studied strike-normal orientation, we found that the orientation of maximum spectral response remains close to the transverse orientation regardless of source-to-site distance and up to distances longer than 300 km. Furthermore, our recent study concluded that, on average, the orientations of maximum spectral response tend to become even closer to the transverse orientation as the period increases. On the other hand, our study found that ground motions recorded during reverse earthquakes do not show any trend in the orientation of maximum spectral response relative to the transverse orientation and the probability distribution of the angle between the orientation of maximum response spectral intensity and the transverse orientation at each recording station has an approximately uniform probability distribution.

An example of the orientation of maximum response spectral ordinates for oscillators with 5% damping and periods of 10 s subjected to the horizontal components of ground motions recorded during the 1999 M_w 7.1 Hector Mine earthquake in the state California in the U.S. in shown in figure 8. At each recording station there are two short lines shown, one in black indicating the orientation of maximum spectral response and another in grey the transverse orientation. The colour of the circle at each recording station indicated the angular difference between these orientations. In can be seen that for the large majority of the recording stations the absolute value of this angular difference referred to as $|\alpha|$, is smaller than 30º. Referring back to figure 3 and 5, it can be seen that rotations within this range from the orientation of the maximum spectral reduction produce only small reduction in the ground motion response spectral intensity relative to the maximum intensity of all orientations, therefore there is a significant probability that ground motion intensity estimated with current GMM based on RotD50 will be exceeded in the transverse orientation and that they will significantly overestimate the ground motion intensity in the radial orientation.

A second example of the orientation of maximum response spectral ordinates is shown in Figure 9 for oscillators with 5% damping and periods of 10 s subjected to the horizontal components of ground motions recorded during the July 5th, 2019 M_w 7.1 Ridgecrest earthquake in the state California in the U.S. Also shown in the figure is the histogram of angular differences between the orientation of maximum spectral response and the transverse orientation, $|\alpha|$, where it is shown that for most recording stations, whether they are close to the epicentre or far away, the orientation of maximum spectral response occurs relatively close to the transverse orientation with a mean angular difference for this earthquake and period of 22º.

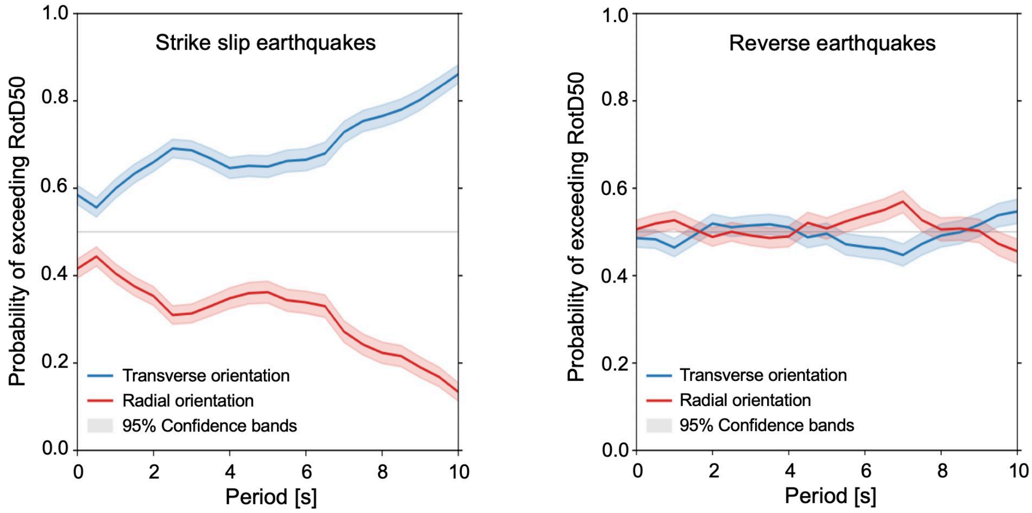

Figure 10. Probability that response spectral ordinates in the transverse and radial directions exceed the RotD50 intensity for ground motions recorded during strike-slip earthquakes (left) and during reverse faulting earthquakes (modified from Poulos and Miranda, 2023b).

Figure 10 shows the probability that a spectral acceleration in the transverse orientation of a site exceeds the RotD50 intensity and the probability that a spectral acceleration in the radial orientation exceeds the RotD50 intensity. These probabilities were computed as the proportion of records where RotD50 is exceeded and are computed for strike-slip and reverse records separately. Records from normal faulting earthquakes were not considered due to their very low number in the ground motion database. If spectral accelerations in the transverse or radial directions were on average equal to the RotD50 intensity, their exceedance probability would be approximately 0.5, which is what occurs for records from reverse earthquakes. However, as shown in the figure on the left, ground motion records from strike-slip earthquakes have a probability significantly higher than 0.5 of exceeding RotD50 in the transverse direction and significantly lower than 0.5 of exceeding RotD50 in the radial direction. Furthermore, these differences in probabilities of exceeding RotD50 tend to become more important as the period increases. For example, the exceedance probability for the transverse direction is approximately 0.6 for periods of 1 s and increases to be as high as 0.86 at 10 s. This figure also presents 95% pointwise confidence bands of these exceedance probability estimations, computed using Bootstrapping showing that these differences in probabilities of exceeding RotD50 for strike-slip earthquakes are statistically significant. Based on these results, the authors have recently developed a model to estimate 5%-damped response spectral ordinates at specific orientations in strike slip earthquakes. The proposed orientation-dependent model explicitly accounts for the directionality of ground motions by modifying means and standard deviations computed with existing GMM that estimate RotD50 spectral ordinates for strike-slip events to obtain probability distributions of response spectral ordinates at specific orientations. For more information on this new GMM the reader is referred to Poulos and Miranda (2023b).

Summary and Conclusions

The amplitude of response spectral ordinates at a site changes significantly with changes in orientation. This characteristic is what we refer to as ground motion directionality. Strong directionality is present not only at sites located to the source and affected by forward directivity effects, but occurs in any earthquake and is present even at recording stations very far from the rupture. A probabilistic model to characterize the directionality present in ground motions records from shallow crustal earthquakes has been summarized. The model includes simplified equations to estimate the geometric mean and logarithmic standard deviations of two different directionality parameters. Both parameters are normalized response spectral ordinates. In the first parameter, referred to as $\eta(\phi)$, spectral ordinates are normalized by the maximum intensity of all orientations RotD100, while in the second directionality parameter referred to as $\nu(\phi)$, spectral ordinates are normalized by the median intensity of all orientations RotD50. Both parameters provide information of the amplitude of spectral ordinates as a function of the angle of rotation ϕ measured from the azimuth in which the maximum spectral ordinate occurs.

Statistical results conducted with 5,065 ground motion records indicate that the level of directionality in ground motions records is significant and cannot be neglected and therefore using RotD50 intensities which provide a measure of central tendency of the intensity in different orientations a site may underestimate significantly seismic intensities in certain orientations and overestimate seismic intensities in other orientations. In particular, the average fraction of rotation angles where the RotD50 intensities are exceeded in one of two orthogonal orientations, such as those corresponding to the longitudinal and transverse principal directions of a structure is very high and varies from 92% for periods of vibration of 0.01 s to 98% for periods of vibration of 10 s.

A new measure of ground motion intensity in the horizontal direction is proposed. This new measure of horizontal intensity, referred to as MaxRotD50, is particularly well suited for earthquake-resistant design where a major concern of structural engineers is the probability that the design ground motion intensity is exceeded in at least one of the two principal horizontal components of the structure, which for most structures are orthogonal to each other. MaxRotD50 is defined using the maximum 5%-damped response spectral ordinate of two orthogonal horizontal directions and then computing the 50th percentile for all non-redundant rotation angles, that is, the median of the set of spectral ordinates in a range of 90º. This proposed measure of intensity is always between the median and maximum spectral ordinate for all non-redundant orientations, commonly referred to as RotD50 and RotD100, respectively. A set of 5,065 ground motion records was used to show that MaxRotD50 is, on average, approximately 13% to 16% higher than Rot50 that is used in most current GMM and forms the basis to establish design spectral ordinates in the new Eurocode and in many other seismic codes around the world and is approximately 6% lower than RotD100 adopted in the United States as basis for design spectral ordinates.

Recent studies on the orientation of maximum response spectral ordinates have been summarized. We found that style of faulting has a significant effect on the orientation of maximum spectral intensity. In particular, our studies found that for strike-slip earthquakes, the orientations of maximum response spectral intensity tend to occur close to the transverse orientation, i.e., an orientation that is perpendicular to the line segment connecting the recording station and the earthquake epicenter. Contrary to what occurs with respect to the previously studied strike-normal orientation, we found that the orientation of maximum spectral response remains close to the transverse orientation regardless of source-to-site distance and up to distances longer than 300 km. Furthermore, our recent study concluded that, on average, the orientations of maximum spectral response tend to become even closer to the transverse orientation as the period increases. On the other hand, our research found that ground motions recorded during reverse earthquakes do not show any clear trend in the orientation of maximum spectral response relative to the transverse orientation.

We recommend that directionality effects be explicitly considered when estimating ground motion intensity. In particular, since the orientation of maximum response spectral intensity tends to occur close to the transverse orientation in the case of strike-slip earthquakes, we recommend that ground motion horizontal intensity from strike-slip earthquakes be estimated at specific orientations as a function of the angular difference between the orientation of interest (e.g., the longitudinal or transverse direction of a structures) to the transverse orientation computed for the seismic scenarios that control the seismic hazard at the site. A first of such models has recently been developed by the authors, which we believe provides a significant improvement relative to current orientation-independent approaches to estimate ground motion intensity in regions such as California where strike-slip events typically represent the largest seismic hazard to most locations.

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