GROUND MOTION DIRECTIONALITY EFFECTS IN THE 2023 KAHRAMANMARAS, TÜRKIYE EARTHQUAKE SEQUENCE

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Abstract: *Earthquake ground motion intensity varies significantly with changes in orientation, in what is referred to as directionality. While differences in the level of intensity and frequency content with changes in orientation have long been identified, the horizontal intensity continues to be treated as a simple scalar, which is typically a measure of central tendency from the intensity across all horizontal orientations. This overestimates intensities in a range of orientations and underestimates it in other orientations. Prior studies on directionality have found that within 5 km from the rupture, the strike-normal component of motion tends to be the most intense, but beyond that distance, the orientation of maximum intensity is essentially random. However, a recent study indicates that the style of faulting has a significant influence on ground motion directionality. In particular, for strike-slip earthquakes, the orientation of maximum intensity tends to occur close to the transverse orientation with respect to the epicenter (i.e., perpendicular to a line segment connecting the site with the epicenter). The M_w 7.8 and M_w 7.5 February 6th, 2023 Kahramanmaras earthquakes produced the largest set of records to date from strike-slip events with magnitudes larger than 7.5. This provides a unique opportunity to study the directionality of various measures of ground motion intensity. Using strong motion records obtained from these events, we study directionality and its spatial distribution by using three intensity measures: (1) spectral pseudo-acceleration, Sa; (2) average spectral acceleration, Sa_{avg}; and (3) a recently proposed, non-spectral intensity measure which is well correlated with structural collapse, referred to as FIV3. The orientations that maximize the three intensity measures are found to occur relatively close to the transverse orientation, suggesting that the orientation of maximum ground motion shaking can be estimated a priori by only knowing the approximate location of the epicenter. This is a game changer because it means we can now anticipate the orientations where stronger intensities will occur and orientations where they will be smaller than RotD50 intensities, reducing the uncertainty of strong motion intensity estimates at specific horizontal orientations. Furthermore, ground motion intensity remains strongly linearly polarized even at large source-to-site distances such as 400 km, and the level of polarization increases with period.*

1. Introduction

It is well-documented that horizontal ground motions recorded at a given site can have significant amplitude variations with changes in the azimuth, a phenomenon known as directionality (Hong and Goda, 2007; Poulos and Miranda, 2022; Shahi and Baker, 2014). Despite its wide recognition, directionality is neglected by current ground motion models (GMMs), which predict a single scalar measure of ground motion amplitude instead of accounting for its orientation dependence. In this context, there have been many studies that have investigated the best scalars to use as measures of ground motion intensity (Abrahamson and Silva, 1997; Beyer and Bommer, 2006; Boore, 2010; Boore et al., 1997, 2006; Boore and Kishida, 2016; Joyner and Boore, 1982).

The lack of orientation-dependent GMMs may be attributed to the widely held belief that the orientation of maximum amplitude is random at most source-to-site distances. While studying rupture directivity effects, Somerville et al. (1997) observed that response spectral ordinates for single-degree-of-freedom (SDOF) oscillators with periods longer than 0.6 s have a tendency to be larger in the strike-normal orientation than in the strike-parallel orientation. Others, such as Huang et al. (2008), NEHRP Joint Consultants Venture (2011), and Shahi and Baker (2014) found that there was indeed a higher likelihood that the orientation of maximum spectral response would occur close to the strike-normal orientation but only up to a rupture distance of approximately 5 km. Beyond this distance, they found that there was no clear pattern in the angle between the fault strike and the orientation of maximum intensity, and therefore concluded that the orientation of maximum intensity is random.

While studies cited above examined directionality with respect to the fault strike, Poulos and Miranda (2023a) took a different approach by investigating the orientation of maximum spectral response with respect to the epicentral transverse orientation. The latter is defined as the orientation perpendicular to a line connecting the epicenter to the recording station and, therefore, varies with the position of each station relative to the epicenter. In their study, they used 1966 ground motion records from strike-slip earthquakes and 2226 ground motion records from reverse-faulting earthquakes with magnitudes (M_w) equal to or larger than five, all obtained from the NGA-West2 ground motion database (Ancheta et al., 2014). They found that the orientation of maximum spectral response depends on the faulting mechanism; for strike-slip earthquakes, the orientation of maximum intensity tended to be systematically close to the transverse orientation and, in general, it got even closer to the transverse orientation with increasing period. This recent finding is important since it implies that for strike-slip earthquakes the orientation of maximum intensity is primarily affected by the location of the epicenter, and therefore it can be estimated at any site by knowing the location of the epicenter.

The 2023 Kahramanmaras earthquake sequence produced one of the largest sets of records to date from strike-slip earthquakes with moment magnitudes greater than 7.5. This earthquake sequence provides a unique opportunity to independently evaluate the recent findings of Poulos and Miranda (2023a) for 5%-damped response spectral ordinates and to study the directionality for other intensity measures (IMs) that are better correlated with structural damage and, in particular, with structural collapse. Using the recordings from the M_w 7.8 and M_w 7.5 February 6th Türkiye doublet, this study investigates the orientation of maximum horizontal intensity, and its geographic distribution, for the following three intensity measures: (1) 5%-damped pseudo-acceleration response spectral ordinates, Sa; (2) average spectral acceleration, Sa_{avg}; and (3) FIV3, which is a recently proposed non-spectral intensity measure that is particularly well correlated with structural collapse. Additionally, for each IM, the extent of linear polarization of ground motions, which reflects the extent of directionality, is quantified and its geographic distribution is studied.

2. Ground motion records

The ground motion records for the M_w 7.8 and M_w 7.5 events used in this study were 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. In order 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 (Boore, 2004), computed as 1/1.25 times the low-pass frequency as done by Abramson and Silva (1997). 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.

3. Orientation of maximum ground motion intensity

There are many possible ground motion parameters, typically referred to as intensity measures (IMs), that can be used to provide a quantitative measure of the intensity of an earthquake waveform. Currently, the most widely used IM in earthquake engineering is the 5%-damped response spectral ordinate (Sa), which represents the peak response for a linear elastic SDOF with a given vibration period. A much better descriptor of the intensity of a ground motion, and in particular one that is a better predictor of structural collapse, is the average spectral acceleration (Sa_{avg}), which is also based on the peak response of linear elastic oscillators. However, instead of relying on a single period, Sa_{avg} is computed as the geometric mean of spectral acceleration ordinates between $0.2T_1$ and $3T_1$, where T_1 is the fundamental period of the structure being evaluated (Eads et al., 2015). This IM is usually computed considering a uniform spacing of 0.01s within this period range. Another recently developed IM that is particularly well correlated with structural collapse is FIV3 (Dávalos and Miranda. 2019). Unlike the two other IMs discussed previously, FIV3 does not require the computation of linear elastic oscillator response and determines the ground motion intensity directly by using the recorded ground acceleration waveform. The reader is referred to Dávalos and Miranda (2019) for details on the calculation of FIV3 for a given waveform.

The maximum intensity (i.e., RotD100) for the spectral-based IMs can be computed by combining two orthogonal relative displacement histories at a given period, $\mathrm{u_x}(t)$ and $\mathrm{u_y}(t)$, into a single time series, $\mathrm{u}(t,\varphi)$, associated with an azimuth (φ) and rotating over all non-redundant orientations as shown by Equations 1 and 2. The orientation of maximum intensity would then be that associated with the maximum of all orientations (Boore, 2010). A similar combination and rotation of the ground acceleration histories is used to obtain the FIV3 time series in a specific orientation for a given oscillator period.

$$u(t,\varphi) = u_x(t)\cos(\varphi) + u_y \sin(\varphi) \tag{1}$$

$$RotD100 = \max_{t,\varphi} |u(t,\varphi)| \tag{2}$$

Figure 1 uses short black lines to indicate the orientation of maximum intensity for the three IMs at each recording station for a 3 s oscillator when subjected to ground motions recorded during the M_w 7.8 and M_w 7.5 earthquakes. In Poulos and Miranda (2023a), the angular difference between the epicentral transverse orientation (i.e., orientation perpendicular to a line connecting the station to the epicenter) and the orientation of maximum intensity is defined as the parameter α. This parameter ranges between [-90°,90°], with the sign describing whether RotD100 is clockwise or counterclockwise from the transverse orientation, respectively. This study focuses on the angular distance, $|\alpha|$, which does not differentiate between clockwise or anticlockwise directions. In Figure 1, the color in the circles indicate the angular distance at each station, with blue tones indicating that the orientation of maximum intensity is close to the transverse orientation and red tones indicating the maximum intensity is closer to the radial orientation. From this figure, it is apparent that the orientations of maximum intensity for all three IMs tend to be similar for stations that are close to each other and tend to form a circular pattern around the epicenter over the geographic region considered. Furthermore, the color of most circles is blue for all three IMs, suggesting low values of $|\alpha|$, which implies that the orientation of maximum ground motion intensity tends to occur close to the transverse orientation for all three IMs and both seismic events. A visual comparison shows that the number of blue stations appears to be the greatest for FIV3 followed by Sa_{avg}, suggesting that the transverse orientation may be a better estimator for the orientation of maximum intensity for these two IMs when compared to Sa. This is further validated by comparing the absolute mean value of $|\alpha|$ among the three IMs.

Although each panel in Figure 1 presents the spatial distribution for $|\alpha|$ using colors, Figure 2 quantifies this range of angular distances by presenting it in the form of empirical probability distributions. In particular, Figure 2 shows histograms of the angular distance between the transverse orientation and the orientation of maximum intensity for oscillators with a period of 3 s. From this figure, it is immediately apparent that the histograms for both earthquakes in the doublet are heavily skewed towards small values of $|\alpha|$ for all three IMs. If the orientations of maximum intensity were to be equally likely in all orientations with respect to the transverse orientation, then the resulting distribution would be uniform and would have a mean $|\alpha|$ of 45° like that shown by the dashed red line in the figure. However, the mean $|\alpha|$ for all three IMs and the two magnitudes (provided in each panel of the figure) show values that are significantly below 45°, indicating that the orientation of maximum intensity, indeed, tends to be closer to the transverse orientation regardless of the IM considered. Additionally, of the three IMs considered, the mean $|\alpha|$ for FIV3 is the lowest, followed by Sa_{avg}, and then Sa, whilst the skewness for FIV3 is the greatest followed by Sa_{avg} and then Sa. This suggests that FIV3 and Sa_{avg}

may both have an orientation of maximum intensity that is closer to the transverse orientation when compared to Sa, and thus may have an orientation of maximum intensity that is more predictable.

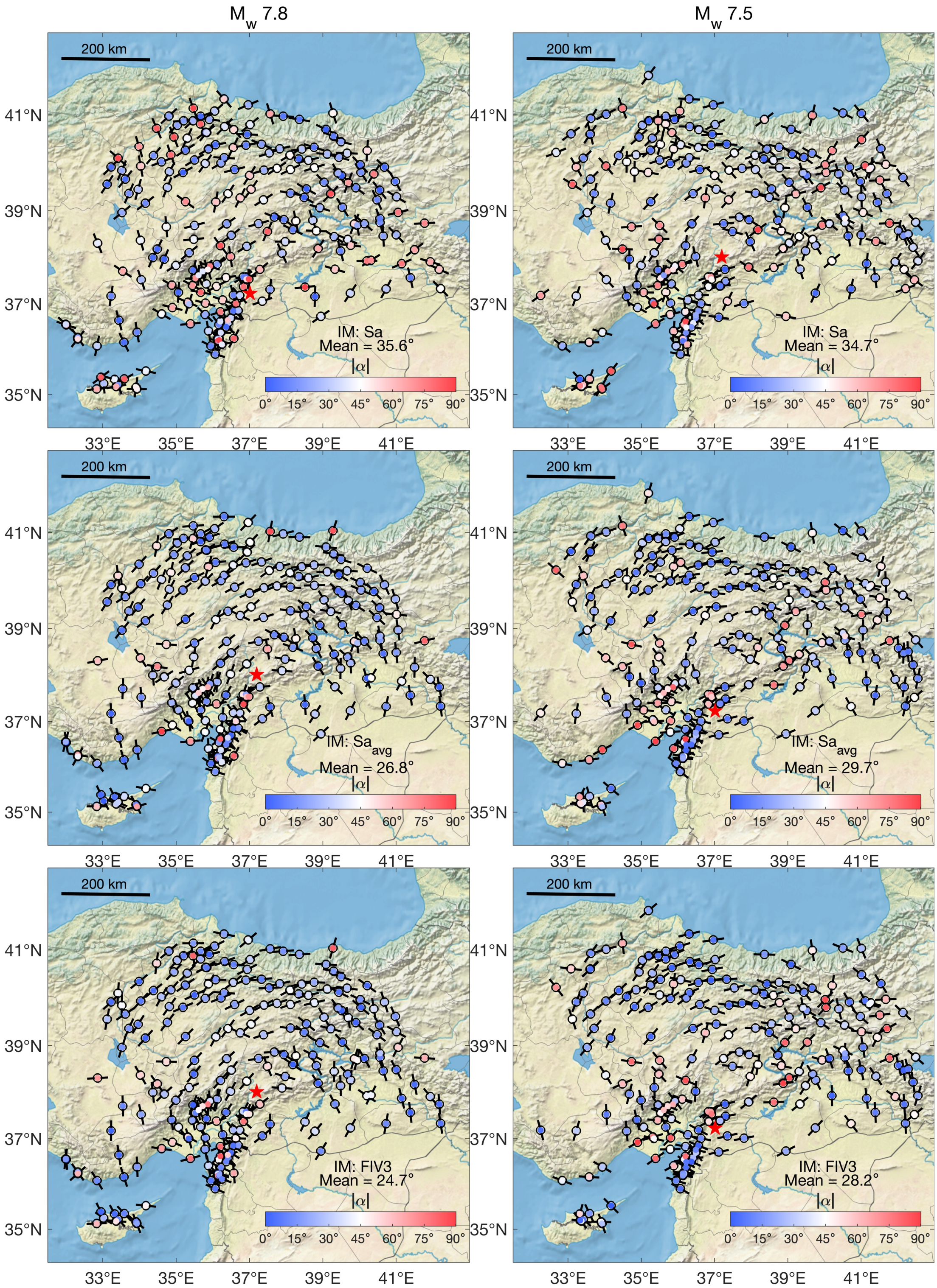

Figure 1: Orientation of maximum intensity of oscillators with T = 3 s subjected to ground motions recorded in the M_w 7.8 and M_w 7.5 events of the 2023 Türkiye sequence and their angular distance with respect to the epicentral transverse orientation. The orientation of maximum intensity is shown by the short black lines and the angular distance is shown by the color in each circle. The lower right corner of each panel shows the IM considered and the corresponding mean $|\alpha|$.

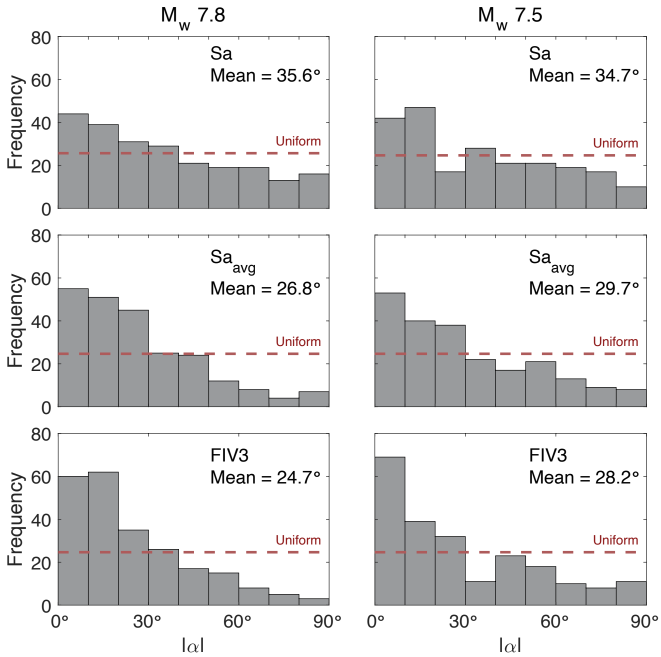

Figure 2. Histograms of the angular distance between the transverse and RotD100 orientation for 3 s oscillators subjected to recordings from the M_w 7.8 and M_w 7.5 events (231 and 222 records, respectively). The dashed red lines show the histograms should the orientation of RotD100 be equally likely to occur in any orientation.

Previous figures presented the directionality for 3 s oscillators. To get a better understanding of whether the trend regarding the orientation of maximum intensity observed above is period dependent, Figure 3 plots the variation of mean $|\alpha|$ (when using Sa as the IM) with oscillator period for both events. The shaded bands around the mean lines represent the interquartile range of $|\alpha|$ at each period. From this figure, it is apparent that the mean $|\alpha|$ for both events is notably below 45°, implying that the orientation of maximum intensity is systematically close to the transverse orientation at all periods. Mean $|\alpha|$ also tends to decrease with increasing period, meaning that the orientation of maximum intensity gets even closer to the transverse orientation as oscillator period increases, consistent with the findings of Poulos and Miranda (2023a) for the NGA-West2 database. For a more detailed analysis of the directionality of Sa, Sa_{avg}, and FIV3, the reader is referred to Girmay et al. (2023), Liapopoulou et al. (2023), and Bravo-Haro et al. (2023), respectively.

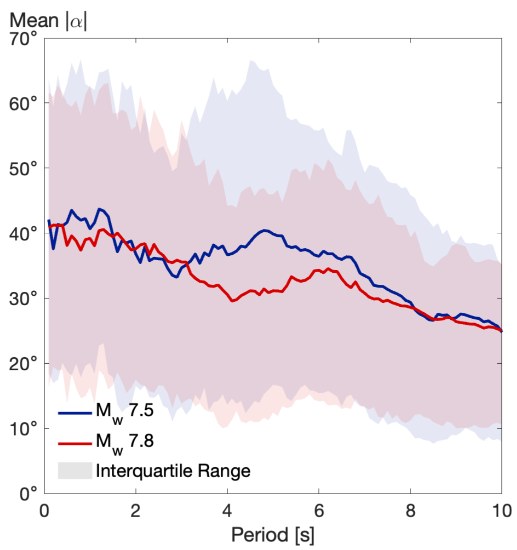

Figure 3. Influence of period on the mean angular distance between the orientation of RotD100 of Sa and the transverse orientation for oscillators subjected to records from the M_w 7.8 and M_w 7.5 events (total of 453 records).

4. Level of polarization in recorded ground motions

The bidirectional response of an oscillator subjected to two horizontal components of ground motion can be traced within the plane. This response in the horizontal plane is considered polarized if the intensity in a specific orientation is markedly larger than in other orientations. In other words, a highly polarized ground motion would result in a highly elliptical bidirectional response of the oscillator.

Several past studies have quantified the level of polarization using the ratio of two scalar intensities within the horizontal plane. Perhaps the most widely known measure of polarization is the ratio between the maximum intensity (i.e., RotD100) and the median intensity of all orientations (i.e., RotD50), which ranges between 1 (for an unpolarized response) and $\sqrt{2}$ (for a fully linearly polarized response) (Shahi and Baker, 2014). Another similar method of quantifying the level of polarization is Hong and Goda's $\eta(90°)$ (2007), which corresponds to the ratio between the maximum intensity and the intensity in the perpendicular orientation. This parameter is bounded between [0, 1] and captures the variation in intensity within the horizontal plane better than Shahi and Baker's RotD100/RotD50. However, it still does not capture the total variation (i.e., from the minimum to the maximum) within the horizontal plane as the minimum intensity does not necessarily occur in an orientation that is perpendicular to the orientation where the maximum occurs. Therefore, a similar but improved measure of polarization is obtained by using the ratio between the minimum response (i.e., RotD00) and maximum response (RotD100), which ranges from 0 for a fully polarized motion and 1 for an unpolarized motion.

The geographic distribution and magnitude dependence of the level of polarization for a 3 s oscillator subjected to ground motions recorded during the M_w 7.8 and 7.5 events, as quantified by the RotD00/RotD100 ratio, is shown in Figure 4. In this figure, the color of the small circle at each recording station represents the level of linear polarization, with red tones indicating a large polarization (i.e., low RotD00/RotD100) and yellow tones indicating a low polarization (i.e., high RotD00/RotD100). Several observations can be made from this figure. First, most stations are orange colored for all three IMs, suggesting that the ground motions from the Türkiye sequence are fairly polarized, with maximum intensities being around two times larger than the minimum intensities. Second, for spectral-based IMs (Sa and Sa_{avg}), the frequency of red-orange stations appears to be greater for the smaller magnitude event, which suggests that lower magnitudes result in slightly more polarized motions. This is also partially true for FIV3, although there appears to be more strongly polarized records in the larger magnitude event.

A third observation from Figure 4 is that strongly polarized motions occur at all distances from the rupture even for stations as far as 400km from the epicenter, which suggests that highly linearly polarized ground motions are not exclusive to the near field region as some previous studies have suggested. This observation holds true for all three IMs. To evaluate if there are specific trends in the level of polarization with respect to the site-to-source distance, Figure 5 shows the level of polarization for the three IMs as a function of the Joyner-Boore distance, R_{JB} (i.e., distance from the station to surface projection of the rupture). For consistency, the oscillator period used in the figure is the same as that used in Figures 1, 2, and 4. Each point in these graphs represents a recording station from either magnitude event, and the dashed red line represents the locally weighted scatterplot smoothing (LOWESS) with a 95% confidence band. From this figure, it is seen that the level of polarization does not change significantly with distance, except for the first 25 km where Sa and Sa_{avg} are more polarized as R_{JB} decreases. The relatively constant level of polarization beyond 25 km shows that polarization is not necessarily the result of forward directivity effects in the near-fault region. Similar results have been observed by Girmay et al. (2023) and Liapopoulou et al. (2023) for Sa and Sa_{avg}, respectively, for oscillators with different fundamental periods. It is important to also note that the LOWESS curves for Sa are relatively lower than those corresponding to the two other IMs across all distances, suggesting that Sa is the most polarized IM.

Combining the observation made above and in the previous section, it is interesting to note that while both Sa_{avg} and FIV3 exhibit lower polarization when compared to Sa, both tend to have orientations of RotD100 that are, on average, closer to the transverse orientation relative to those of Sa. An important implication of this is that Sa_{avg} and FIV3 are IMs that tend to have smaller variations in the level of intensity with changes in orientation, which makes them slightly more predictable than Sa within the context of directionality. However, this requires further investigation using a larger database of records.

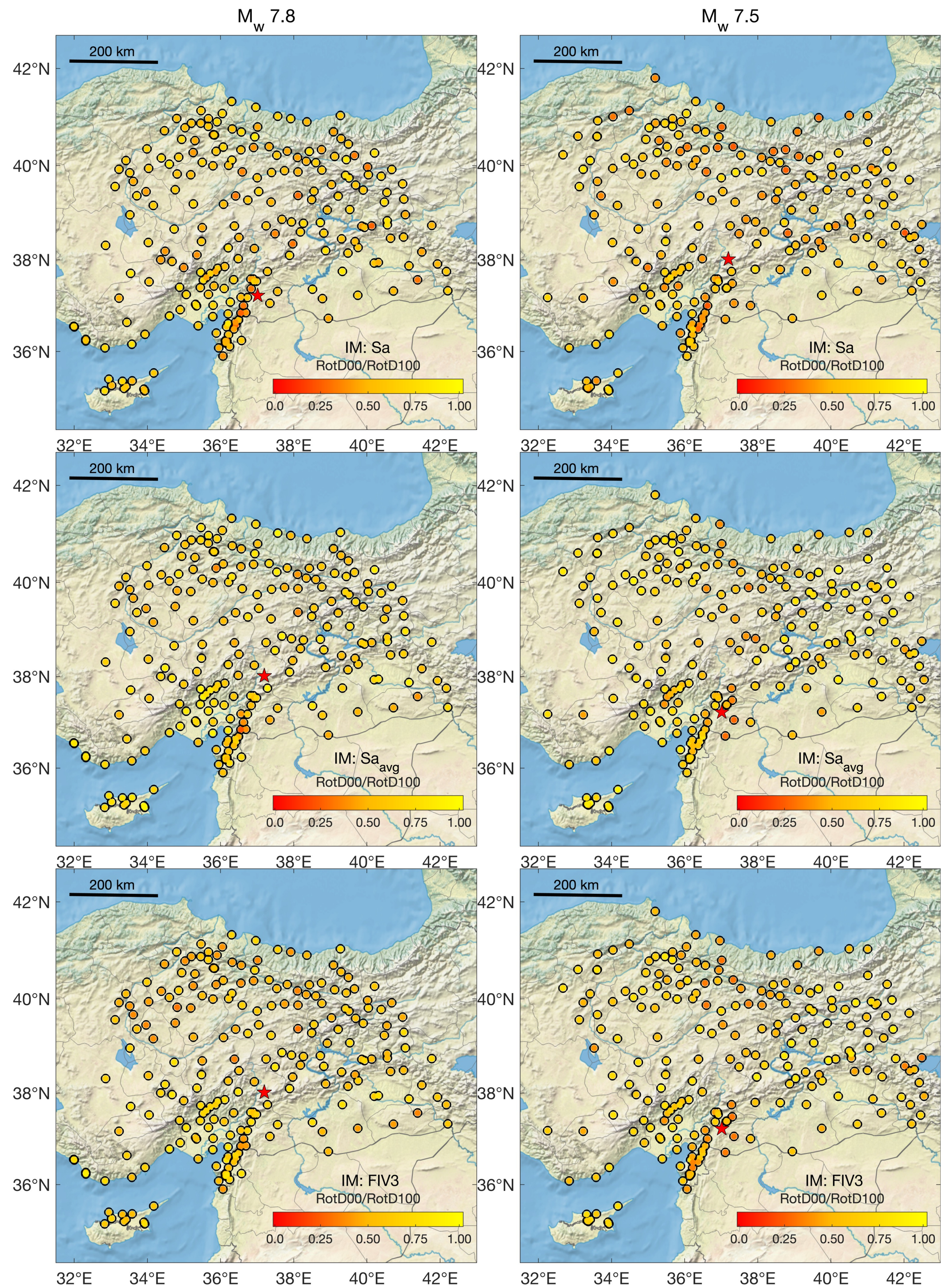

Figure 4. Spatial distribution of polarization as measured by RotD00/RotD100 for 3 s oscillators subjected to ground motions recorded during the Mw 7.8 and Mw 7.5 events. A fully unpolarized motion would have a bright yellow circle and a fully linearly polarized motion would have a bright red circle.

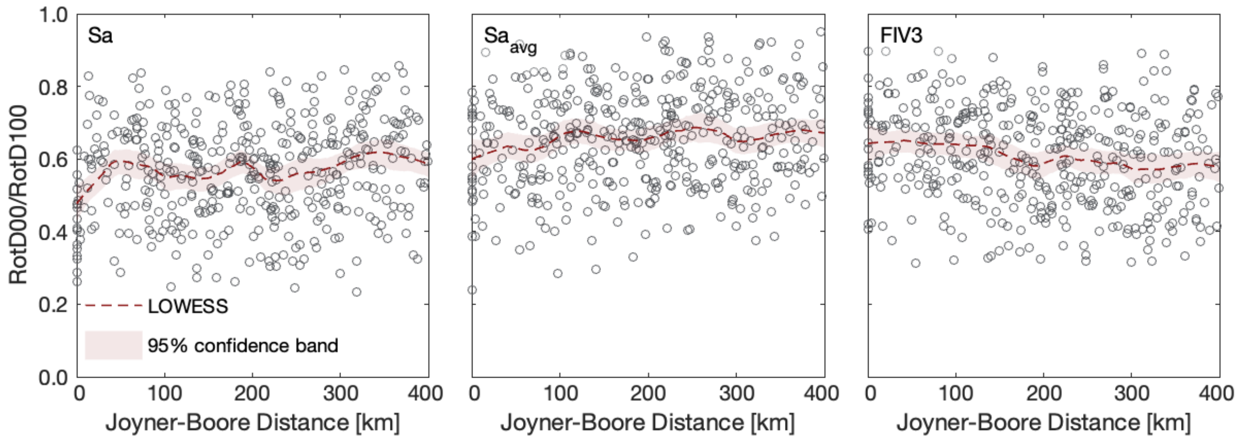

Figure 5. Influence of Joyner-Boore distance on the level of polarization of the three IMs, as measured by the RotD00/RotD100 ratio, for a 3 s oscillator subjected to ground motions recorded during the M_w 7.8 and M_w 7.5 doublet (total of 453 records). The red line represents a locally weighted scatterplot smoothing (LOWESS).

The period dependence of the level of polarity can be understood from Figure 6. This figure shows the geometric mean of spectral responses at all non-redundant orientations relative to the transverse orientation normalized by the RotD50 intensities for four representative oscillator periods, subjected to all ground motions from both events. Normalization by RotD50 is performed so that the intensity at any orientation of interest can be compared to the intensity that is often predicted by GMMs (i.e., RotD50). It is apparent that the intensity at the transverse orientation is on average significantly greater than the RotD50 intensity for all oscillator periods. This implies that current GMMs significantly underestimate the intensity at some orientations (especially orientations close to the transverse orientation). As the orientation of interest departs from the transverse orientation, the average intensity decreases following an approximate cosine-shaped trend at all periods. The level of polarization can be inferred from this figure by comparing the geometric mean ratio of Sa(θ)/RotD50 at $\theta = 90°$ to that at $\theta = 0°$. As the oscillator period increases, the ratio of Sa(0°)/RotD50 to Sa(90°)/RotD50 increases, indicating that the response of the oscillator becomes more linearly polarized with increasing period. The plot also includes the geometric mean of Sa(θ)/RotD50 computed by Poulos and Miranda (2023b) using the NGA-West2 database, which shows that the motions recorded in the Türkiye events are on average less polarized than those in the NGA-West2 database. This is probably due to the larger magnitude of these events relative to the mean magnitude in that subset of 5,096 motions from NGA-West2, but further evaluation is necessary.

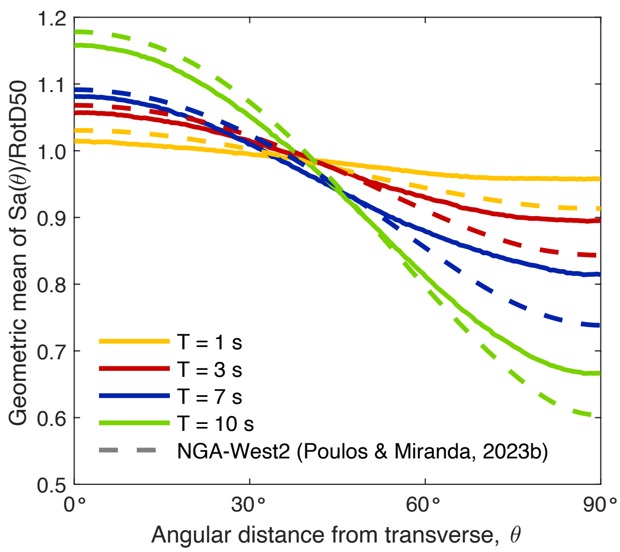

Figure 6. Geometric mean of the ratio between the response spectral ordinate at a given angle (θ) measured from the transverse orientation and the RotD50 intensity as a function of θ.

5. Summary and conclusions

This work evaluated the directionality of three ground motion intensities using records from the M_w 7.8 and M_w 7.5 earthquake doublet of the 2023 Türkiye earthquake sequence. The orientation of maximum intensity and its geographic distribution was studied for response spectral acceleration (Sa), average spectral acceleration (Sa_{avg}), and FIV3. It was found that the orientation of maximum intensity for all three IMs tends to occur close to the epicentral transverse orientation (i.e., orientation perpendicular to a line connecting the station to the epicenter). This observation was found to be true for both events in the doublet and at all distances from the rupture (from 0 to 400 km). The orientation of maximum intensity for the three IMs was compared, and it was found that FIV3 and Sa_{avg} have an orientation of maximum intensity that is closer to the transverse orientation when compared to Sa. In addition, it was found that the orientation of maximum response gets closer to the transverse orientation as the oscillator period increases, consistent with prior observations by Poulos and Miranda (2023a). These results indicate that for strike-slip earthquakes, there is a predominant orientation of maximum intensity for all three types of IMs.

Oscillators subjected to recordings from both M_w 7.8 and M_w 7.5 earthquakes had responses that were fairly polarized for all three IMs. The level of polarization does not change significantly with distance after approximately 25 km, suggesting that the fairly strong polarization observed in these IMs is not related to forward directivity effects in the near-fault region. It was found that the level of polarization tends to increase with oscillator period and that the ground motions from the Türkiye sequence were on average less polarized than those in the NGA-West2 database. Out of the three IMs considered, Sa exhibited the largest polarization, on average, followed by FIV3, and then Sa_{avg}.

While both Sa_{avg} and FIV3 exhibit lower linear polarization when compared to Sa, both also tend to have intensities at the transverse orientation that are closer to RotD100 relative to those of Sa. An important implication of this is that Sa_{avg} and FIV3 tend to have smaller variations of intensity in the horizontal plane, making them slightly more predictable than Sa within the context of directionality. However, further investigation using a larger database of ground motions is warranted.

Knowing that the orientation of maximum response occurs close to the transverse orientation for strike-slip earthquakes has two important practical implications: (1) it is possible to determine the orientations where RotD50 intensities estimated using current GMMs either underestimate or overestimate ground motion intensities; and (2) it is possible to develop correction factors to current RotD50 GMMs to provide improved/unbiased estimates of ground motion intensity at specific horizontal orientations (e.g., Poulos and Miranda, 2023b).

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