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Directionality of Average Spectral Acceleration, SaAvg, in the 2023 Kahramanmaras, Türkiye Earthquake Sequence

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Abstract

This study investigates the directionality of spectral accelerations averaged over a period range in 453 ground motions that were recorded in the Turkish strong-motion accelerograph network during the 2023 Kahramanmaraş earthquake sequence. This measure of ground motion intensity, referred to as *SaAvg*, is computed by using 5%-damped pseudo-acceleration spectral ordinates averaged over a period range from one-fifth to three times the period of interest. Several studies have shown that, compared to the typically used single spectral ordinate, this intensity measure is significantly better correlated with structural damage and, in particular, with structural collapse. Additionally, it is also more sufficient with respect to earthquake magnitude and distance to the source, less sensitive to record scaling, and more predictable. The variation of *SaAvg* with changes in orientation is carefully studied using two normalised parameters. It is found that, similarly to the directionality of individual spectral ordinates, the directionality of *SaAvg* also increases with increasing period of the oscillator; however, the level of directionality is smaller. Nonetheless, the dispersion on normalised parameters characterising directionality is in the order of half of that in the directionality of individual spectral ordinates, thus making the directionality of *SaAvg* significantly more predictable than that of *Sa*. Models for estimating the directionality in *SaAvg* are proposed. This study also evaluated for the first time the orientation of maximum *SaAvg*. Similarly to the orientation of maximum oscillator response in strike-slip earthquakes, it is found that the orientation of maximum *SaAvg* tends to occur close to the transverse direction from the source. In particular, this study shows that computing the transverse orientation with respect to the point of maximum slip in a finite rupture model leads to better results than doing it using the epicentre.

Keywords: Directionality, ground motion intensity, averaged spectral acceleration, orientation of maximum intensity, 2023 Türkiye sequence.

1. Introduction

A ground motion intensity measure provides the link between the probabilistic characterisation of the seismic hazard at a site and the probabilistic characterisation of structural response conditioned on the ground motion intensity level. In consequence, its selection plays an important role in seismic design and seismic risk

assessment. The most common intensity measures (IMs) currently used for characterising ground motions in earthquake-resistant structural design and seismic performance assessment are the peak ground acceleration (PGA) and the 5%-damped spectral pseudo-acceleration, $Sa(T)$, at the period of interest T . The period of interest is typically the fundamental period of the structure, T_1 . However, various studies have highlighted significant drawbacks of these IMs that result in large variabilities and potential bias in the estimation of the structural response to earthquakes (e.g., Shome and Cornell, 1998; Shome et al., 1998; Vamvatsikos and Cornell, 2005; Baker and Cornell, 2006a, 2006b; Luco and Cornell, 2007; Tothong and Luco, 2007; Haselton et al., 2011; Eads et al., 2016; Dávalos and Miranda, 2019b, 2019a, among others). In particular, these studies have shown that the correlation of $Sa(T_1)$ with peak story drift ratios reduces rapidly with increasing level of nonlinearity experienced by the structure as the number of stories increases. Furthermore, these studies have found that causal parameters of the records used in the seismic evaluation of structures and the level of scaling of each record, had a statistically significant influence, leading not only to results that vary depending on the record selection process and specific records selected, but also to possibly inadvertently biased results.

Most of the shortcomings of using $Sa(T_1)$ to characterise the intensity of the ground motion are related to only using the peak response of a single linear elastic oscillator, therefore neglecting any additional information in the ground motions. Several researchers have proposed alternative IMs based on averaging spectral ordinates at different vibration periods to include information on the intensity of the ground motion at other periods of vibration. In particular, Bianchini et al. (2009), Bojórquez and Iervolino (2011), Tsantaki et al. (2012), and De Biasio et al. (2014) explored different spectral averaging schemes focusing on ranges between T_1 and a lengthened period greater than T_1 . The upper period recommended in these studies was typically based on a very small number of structures and varied between $1.5 \cdot T_1$ and $2.5 \cdot T_1$, depending on the level of ductility experienced by the structure. These studies agreed on that including spectral ordinates longer than the fundamental period improved the correlation between the intensity measure and the peak story drift ratio in the structure, therefore reducing the record-to-record variability and consequently also increasing the efficiency of the intensity measure. This means that the seismic evaluation could be conducted using a smaller number of records and significantly smaller computational effort.

In a departure from previous studies that considered spectral ordinates averaged over a certain period range, Eads et al. (2013, 2015) proposed an IM referred to as $SaAvg$ with an unsymmetrical averaging period range that included periods both shorter and longer than T_1 . Based on a comprehensive study of a large number of structures comprising almost 700 moment-resisting and shear wall structures, they recommended that $SaAvg$ be computed as the geometric mean of 5%-damped spectral ordinates between $0.2 \cdot T_1$ and $3 \cdot T_1$. In their study, they noticed that a small number of pulses in damaging ground motions controls many features of the intensity and shape of response spectra at both sides of T_1 . Interestingly, they found that including spectral ordinates at periods shorter than T_1 was not necessarily only related to the contribution of higher modes and the consequent reduction of variability in structural responses of multi-degree-of-freedom systems, but it also led to systematic reductions of variability in seismic response and collapse intensities of single-degree-of-freedom systems, which, by definition, do not have higher modes. More recently, Adam et al. (2017) and Kazantzi and Vamvatsikos (2015) have independently confirmed that including ordinates at periods shorter than T_1 in the spectral averaging process improves the efficiency of $SaAvg$. The intensity measure $SaAvg$ has also been

88 found to be superior to S_a for predicting the structural response of structures subjected to pulse-like ground
89 motions (Kohrangi et al., 2018b).

90 As part of an evaluation of the relative merits of various recently proposed intensity measures when compared
91 to those commonly used, Dávalos and Miranda (2020) evaluated Sa_{Avg} intensities producing collapse in six
92 different moment-resisting frame buildings and found that these were much less affected by the earthquake
93 magnitude, the distance to the source, or the scaling factor of the records used in the evaluation compared to
94 S_a intensities, indicating an increased sufficiency of Sa_{Avg} . More recently, Dávalos and Miranda (2021)
95 developed a ground motion model for Sa_{Avg} and *showed that* the variability of Sa_{Avg} conditioned on a
96 magnitude and distance pair is lower than that of S_a , thus making Sa_{Avg} also more predictable than S_a .

97 Although there have been several studies on Sa_{Avg} , none of them has focused on its directionality, that is, the
98 variation in the level of Sa_{Avg} at a site with changes in orientation. Hong and Goda (2007) studied the ratio of
99 S_a at different orientations normalised by the maximum value across all orientations (referred to as the
100 RotD100 intensity). Shahi and Baker (2014) conducted a similar study on the directionality of S_a but normalised
101 spectral ordinates by the median of intensities from all non-redundant orientations (referred to as the RotD50
102 intensity). More recently, Poulos and Miranda (2022) conducted a comprehensive study of the variation of S_a
103 values for different horizontal directions during shallow crustal earthquakes. They found that, on average and
104 depending on the vibration period, the maximum S_a could be up to 30% higher than the median intensity over
105 all orientations (referred to as the RotD50 value) and up to 2.2 times the value in the perpendicular orientation.
106 Poulos and Miranda (2023a) showed that the style of faulting has an important effect on the directionality of
107 earthquake ground motion and that for strike-slip events, the orientation of maximum S_a tends to occur close
108 to the transverse orientation, defined as the direction perpendicular to a straight line segment connecting the
109 site and the epicentre. Furthermore, the authors observed that as the period of vibration of the oscillator
110 increased, the orientation of maximum oscillator response, that is of maximum S_a , became even closer to the
111 transverse orientation. These observations are particularly relevant for estimating seismic demands on groups
112 of buildings with similar orientations of their principal axes (Heresi and Miranda, 2023), as the analyst is then
113 able to predict the potential orientations of maximum intensities relative to the predominant orientations of the
114 principal axes of structures in various urban areas. However, there are no similar studies that have investigated
115 the directionality of Sa_{Avg} .

116 On February 6th, 2023, a large-magnitude strike-slip earthquake doublet (M_w 7.8 and M_w 7.5) struck the south-
117 central region of Türkiye, specifically the Kahramanmaraş province, and the north-western region of Syria
118 (Goldberg et al., 2023; Mai et al., 2023; Melgar et al., 2023). These earthquakes unfolded within a complex
119 tectonic junction involving the Arabian plate, the African plate, and the Anatolian block. The main event M_w 7.8
120 nucleated on a splay fault approximately 15 km southeast of the East Anatolian Fault (EAF), at 37.2444°N,
121 37.0234°E, with a depth of 12 km, which then propagated north and ruptured bilaterally the EAF. The second
122 earthquake M_w 7.5 originated around 95 km north of the first epicentre, at 38.0900°N, 37.2756°E, with a depth
123 of 15 km, and ruptured bilaterally the Sürgü Fault (SF) (Melgar et al., 2023). The aftermath of this seismic
124 doublet was severe, resulting in the total or partial destruction of over 35,000 buildings, and more than 650,000
125 structures, experiencing varying degrees of damage (Cetin et al., 2023). The toll on human lives was profound,

126 with almost 60,000 fatalities, over 100,000 injuries, and at least 1.5 million people displaced in Türkiye and
127 Syria. Additionally, initial estimates indicated damage losses reaching US\$34 billion (Ozkula et al., 2023).

128 The February 6th, 2023, Kahramanmaraş earthquake doublet generated one of the most extensive collections
129 of strong motion data recorded to date from strike-slip events with moment magnitudes larger than 7.4. Hence,
130 this earthquake doublet provides an excellent opportunity to study, for the first time, the characteristics and
131 spatial distribution of the directionality of ground motions from large-magnitude strike-slip earthquakes.

132 The main objective of this article is to investigate the directionality and orientation of maximum intensity for
133 Sa_{Avg} during the 2023 Kahramanmaraş earthquake doublet in a similar fashion as was recently done for Sa
134 (Girmay et al., 2023) and for $FIV3$ (Bravo-Haro et al., 2024), a promising and recently proposed IM which is
135 computed as the sum of the three largest period-dependent incremental velocities having the same polarity
136 and obtained from a low-pass filtered acceleration time series (Dávalos and Miranda, 2020). Results show that
137 the directionality of Sa_{Avg} increases with increasing period of the oscillator; however, the level of directionality
138 in Sa_{Avg} is somewhat smaller than that of Sa . Nonetheless, the dispersion of normalised Sa_{Avg} ordinates that
139 characterise their directionality is, in general, in the order of half of that for the directionality of individual spectral
140 ordinates, thus making the directionality of Sa_{Avg} significantly more predictable. Furthermore, similarly to the
141 orientation of maximum oscillator response in strike-slip earthquakes, it is found that the orientation of
142 maximum Sa_{Avg} tends to occur close to the transverse direction.

143 **2. Average Spectral Acceleration as an Intensity Measure**

144 The idea of using the average of spectral ordinates within a range of periods to characterise the level of ground
145 motion intensity in a given record was first proposed by Benioff (1934), who suggested to define the seismic
146 destructiveness of a ground motion as the integral with respect to pendulum frequency of the maximum
147 displacement of an infinite series of undamped pendulums extending over a “significant range of
148 frequencies”. However, the specific range of frequencies to be used was never mentioned in his paper.
149 Following this idea, Housner (1952) introduced the spectral intensity, which he defined as the area enclosed
150 by the pseudo-velocity spectrum of viscously damped linear oscillators in a period range between 0.1 s and
151 2.5 s. Recognising the shortcomings of using PGA as an IM for design purposes, the Effective Peak
152 Acceleration (EPA) was proposed in 1978 as an alternative to characterise the intensity of ground motions in
153 the seminal ATC 3-06 recommended tentative seismic provisions (ATC, 1978) that provided the basis to
154 modern earthquake resistant design regulations worldwide. In this document, the EPA was defined as the
155 average of 5%-damped Sa ordinates between 0.1 s and 0.5 s normalised by a constant equal to 2.5. It should
156 be noted that in these three early works, the spectral ordinates averaged over a range of periods was not used
157 as a measure of ground motion intensity to specific structures, but in the first two cases it was intended as a
158 measure of intensity to groups of buildings with a wide range of heights, while in the ATC 3-06 document it
159 was intended to represent the ground motion intensity on short-period structures in the so-called acceleration-
160 sensitive region. To the best of the authors' knowledge, the first study that recommended using a structure-
161 specific period range when averaging the spectral ordinates was conducted by Kennedy et al. (1984). They

considered the average spectral value between the fundamental period of vibration of the structure (T_1) and a lengthened period. They attributed a reduction in the variability of their computed responses to the smoothing effect of averaging spectral ordinates over a period range compared to the use of a single spectral ordinate that is very sensitive to local peaks and valleys in individual lightly-damped spectra. For a more complete description and discussion of the development of intensity measures based on spectral ordinates averaged over a period range, the reader is referred to Dávalos and Miranda (2021).

This study uses the *SaAvg* definition proposed by Eads et al. (2015) who used the geometric mean of 5%-damped pseudo-acceleration spectral ordinates in a period range from one fifth to three times the period of interest. The proposed intensity measure was based on a comprehensive study of the period range that maximises the correlation with collapse intensities in nearly 700 moment-resisting frame and shear wall structures of various heights. Mathematically, their proposed intensity measure is given by:

$$SaAvg(T) = \left(\prod_{i=1}^N Sa(c_i T) \right)^{1/N} \quad (1)$$

where *Sa* corresponds to the 5%-damped pseudo-spectral acceleration and *N* is the number of spectral ordinates.

Eads et al. (2015) studied the effect of the number of spectral ordinates as well as whether using an arithmetic or logarithmic spacing leads to better results. Although they found that the optimum period range exhibits some variability from one structure to another and from one ground motion set to another, they showed that the results were not affected significantly by the number of periods, provided that at least 10 periods were considered, and that both arithmetic and logarithmic spacings produced similar results. However, they noted that the optimum period range, that is, the values of c_1 and c_N in Equation 1 were different when using arithmetic and logarithmic spacings. In this study, a constant arithmetic spacing of $dt = 0.01$ s and a period range of $c_1 = 0.2$, and $c_N = 3$ was adopted, following Eads et al. (2015) recommendation for arithmetic spacings.

Similar to spectral acceleration, *SaAvg* intensities may depend on the orientation at which they are measured, exhibiting significant levels of directionality. This can be quantified by rotating a given ground motion record around the horizontal plane across all possible orientations. Thus, the RotD100, RotD50, and RotD00 fractiles of *SaAvg* can be defined as the maximum, median, and minimum *SaAvg* intensity, respectively, as shown in Equations 2–4.

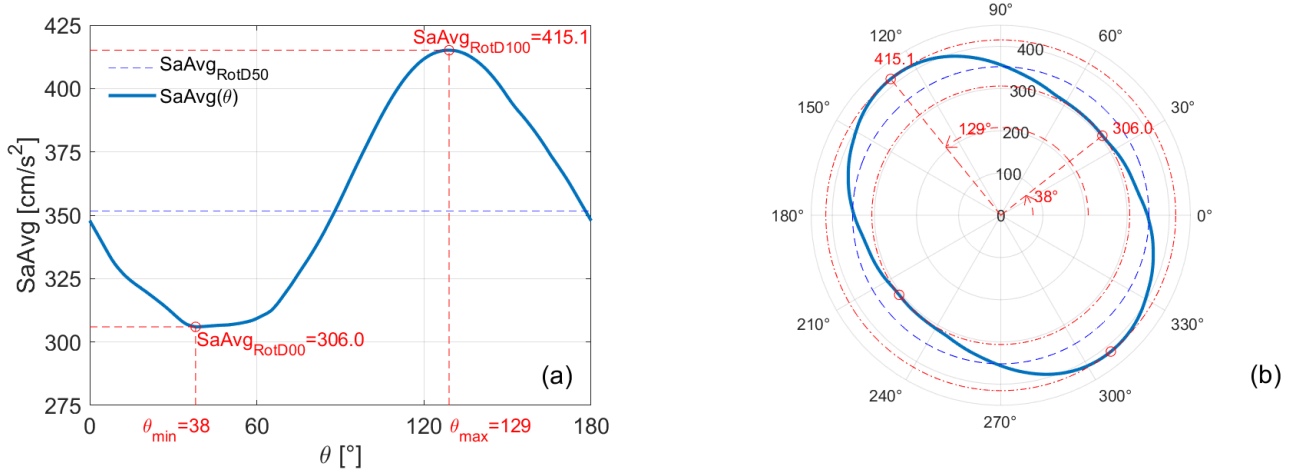
$$SaAvg_{RotD100} = \max_{\forall \theta \in [0^\circ, 180^\circ]} SaAvg(\theta) \quad (2)$$

$$SaAvg_{RotD50} = \text{Median}_{\forall \theta \in [0^\circ, 180^\circ]} SaAvg(\theta) \quad (3)$$

$$SaAvg_{RotD00} = \min_{\forall \theta \in [0^\circ, 180^\circ]} SaAvg(\theta) \quad (4)$$

where *SaAvg*(θ) is the *SaAvg* intensity at an angle of rotation θ that varies from 0 to 180°.

189 In order to illustrate the variations in Sa_{Avg} with changes in orientation, Figure 1 shows linear and polar
 190 representations of the variation of Sa_{Avg} computed for a period of 1.4 s when subjected to horizontal
 191 components of the ground motions recorded at station 3140 during the main M_w 7.8 event. For this ground
 192 motion, Sa_{Avg} exhibits relatively strong variations that can increase the ground motion intensity by more than
 193 35% at the same site by changing the orientation. Furthermore, the orientations of minimum and maximum
 194 intensity occur approximately 90° from each other. While graphs such as those shown in Figure 1 illustrate the
 195 directionality in a ground motion for a certain period, they do not provide information on the level of directionality
 196 at other periods. Spectra of Sa_{Avg} are plotted in Figures 2a and 2b for Station 3124 and 3132, respectively,
 197 both from the main M_w 7.8 event. For each station, the RotD100, RotD50, and RotD00 values of Sa_{Avg} as a
 198 function of period are shown, as well as the Sa_{Avg} in the recorded north-south (NS) and east-west (EW)
 199 orientations, and in the transverse orientation. Note that the transverse orientation refers to an orientation that
 200 is perpendicular to the radial orientation which is defined by a straight line connecting the station with the
 201 epicentre. For both stations, the average spectral acceleration exhibits significant directionality, as indicated
 202 by the variation in Sa_{Avg} ordinates in different orientations, spanning between the RotD00 and RotD100
 203 spectra, but the level of directionality is different for different periods. Interestingly, for Station 3132 (Figure
 204 2b), the transverse spectrum almost coincides with the RotD100 spectrum for all periods, indicating that the
 205 maximum average spectral acceleration occurs at or very close to the transverse orientation. On the other hand,
 206 for Station 3124 (Figure 2a), the RotD100 only occurs closer to the transverse orientation for periods
 207 longer than about 1.7 s.



208
 209 **Figure 1.** (a) Linear, and (b) polar representation of Sa_{Avg} intensities with changes in orientation for a period
 210 of vibration of 1.4 s and the strong motion recorded at station 3140 during the main M_w 7.8 event.

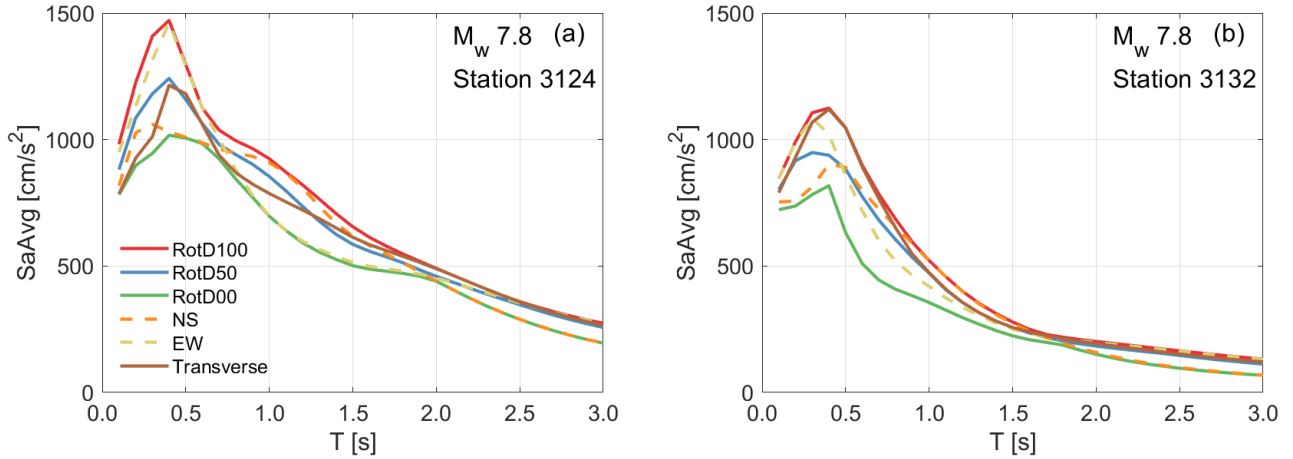


Figure 2. SaAvg response spectra for ground motions from the main M_w 7.8 event, recorded at (a) Station 3124, and (b) Station 3132.

3. Selected Ground Motion Records

Strong-motion accelerometer data used in this investigation were obtained from the Turkish Accelerometric Database and Analysis System (TADAS) operated by Turkish Department of Earthquake, Disaster, and Emergency Management Authority (AFAD, 2023a, 2023b). This accelerograph network has been operating since 1973 but has been significantly expanded in the last 25 years following the 1999 earthquake in Northern Türkiye (Gulkan et al., 2007; Alver et al., 2019) and to date comprises 762 individual recording stations countrywide, generating almost 20,000 strong motion records every year (FDSN, 2023).

The database of strong motion records selected in this study comprises 231 and 221 pairs of records obtained from the main M_w 7.8 and second M_w 7.5 events, respectively, during the 2023 Kahramanmaraş, Türkiye Earthquake Doublet. These records were retrieved from the AFAD online platform, based on a set of criteria to ensure that an adequate study of their directionality is feasible (Girmay et al., 2023). More specifically, only stations that recorded both horizontal components and included information on their azimuths were considered. In addition, a minimum value of 1 cm/s was imposed on the peak ground velocity (PGV) of at least one of the two horizontal components of each ground motion record, to ensure a strong signal-to-noise ratio across a broad period range. Finally, a careful visual inspection of the waveforms on both recorded horizontal components of each record allowed identification and elimination of records with problems such as delayed start or premature termination.

In Figures 3a and 3b, the average spectral acceleration at a period of 1 s, $SaAvg(T=1\text{ s})$, for each selected record from the M_w 7.8 and M_w 7.5 events, respectively, is plotted against the Joyner-Boore distance, R_{JB} . The definition and details on the computation of average spectral acceleration are given in Section 2. The median, 16th, and 84th percentiles of predicted average spectral acceleration using the DM21 ground motion model (GMM) (Dávalos and Miranda, 2021) are also plotted in the same figures. Similarly, event-specific median and 16th and 84th percentiles are also shown in these figures. The event-specific median is computed by shifting the median by the maximum likelihood estimator of the between-event residual (Abrahamson and Youngs,

1992), whereas the event-specific 16th and 84th percentiles are calculated only considering the within-event standard deviation of the model. This model is applicable for moment magnitude, Joyner-Boore distance, and mean shear wave velocity in the upper 30 m in the following ranges: $5 < M_w < 8$, $0 \text{ km} < R_{JB} < 150 \text{ km}$, and $180 \text{ m/s} < V_{s30} < 360 \text{ m/s}$. The earthquake events and most records selected in this paper exhibit parameters within these limits, and hence, the DM21 model can be employed for Sa_{Avg} predictions. However, its accuracy is expected to deteriorate at stations with Joyner-Boore distance longer than 150 km or shear wave velocity lower than 180 m/s or higher than 360 m/s, as they fall outside of the recommended ranges of this GMM.

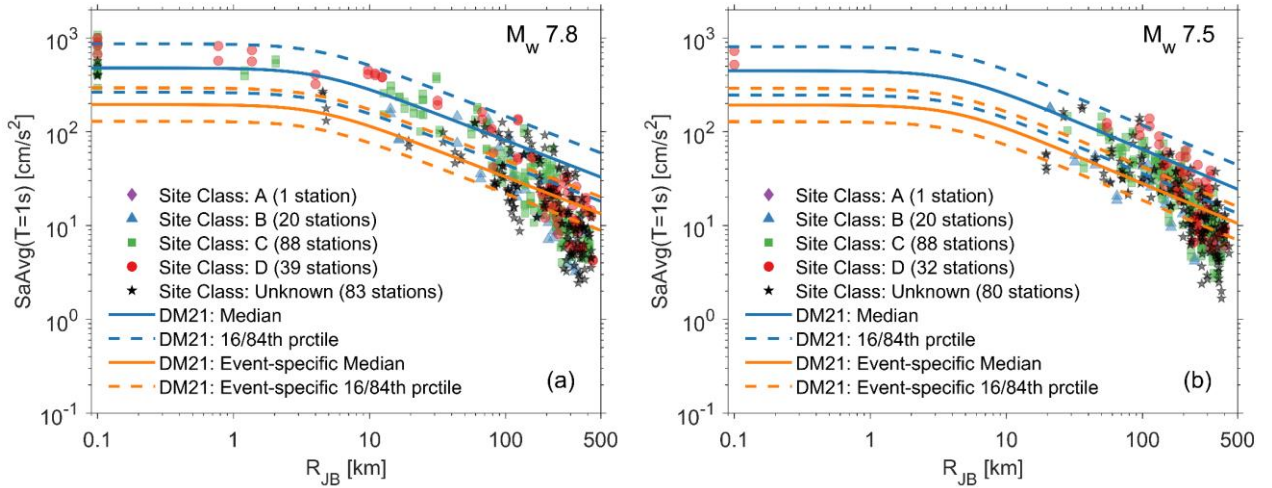


Figure 3. Comparison of Sa_{Avg} from records and predicted Sa_{Avg} using the DM21 model for (a) the main M_w 7.8 event, and (b) the second M_w 7.5 event. Sa_{Avg} values at $R_{JB}=0$ are shown in this figure at 0.1 km.

In general, the DM21 prediction equation captures the median and scatter of data relatively accurately for stations with $R_{JB} < 100 \text{ km}$, for both events. The accuracy deteriorates for the M_w 7.5 event, as only 32 out of the 221 stations exhibited shear wave velocity within the range used for the calibration of the model. At longer Joyner-Boore distances, the model overpredicts the average spectral acceleration, as it was developed exclusively for $R_{JB} < 150 \text{ km}$ and its lack of an anelastic attenuation term. This tendency of overestimating the intensity measure at long distances is consistent with the overestimation of response spectral ordinates observed in recent studies of these events (Cetin et al., 2023; Hu et al., 2024)

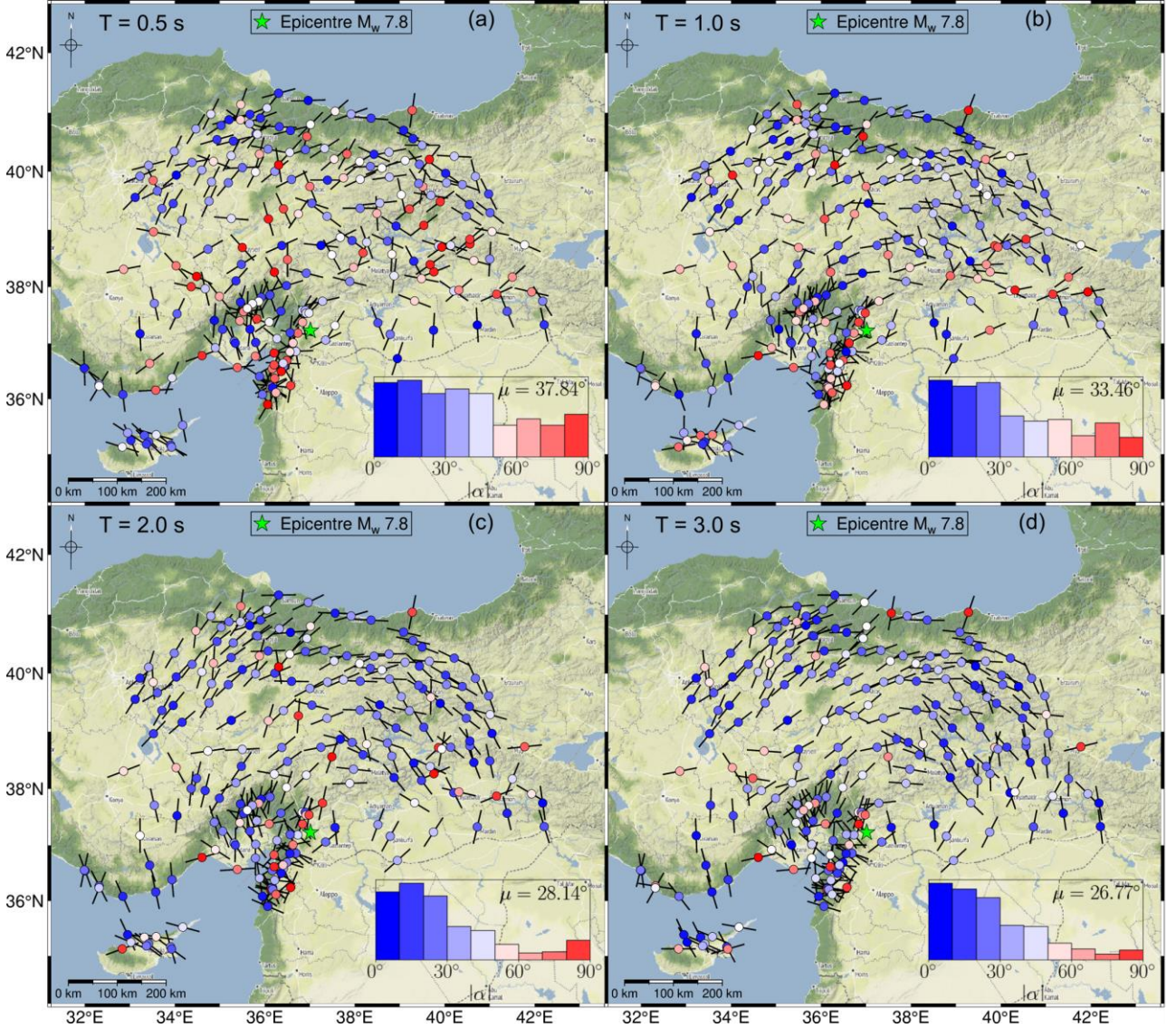
4. Orientation of Maximum Sa_{Avg} Intensity

It is of interest to investigate the orientation of maximum Sa_{Avg} intensities at each recording station to study its spatial distribution and identify general trends. The orientation of the maximum Sa_{Avg} intensity at each station during the M_w 7.8 event of the Kahramanmaraş earthquake doublet is shown in Figure 4, computed for periods of 0.5 s, 1.0 s, 2.0 s, and 3.0 s in subplots a, b, c, and d, respectively. On each panel, every small circle represents the location of a recording station and the short black lines crossing each circle indicate the orientation of maximum Sa_{Avg} intensity at the station. The colour inside each circle indicates the absolute values of the angular difference between the orientation of maximum Sa_{Avg} intensity and the transverse

orientation, $|\alpha|$, which ranges between 0° and 90° . In these figures, for all four periods, the transverse orientation is computed with respect to the epicentre of the M_w 7.8 main event. Each subplot includes an empirical probability distribution (i.e., observed distribution) of $|\alpha|$ in the lower right corner. This figure reveals several interesting characteristics. The first general observation, is the progression of identifiable patterns in the spatial distribution of the orientation of maximum $SaAvg$ as the period increases, reaching gradually a concentric array around the epicentre. In turn, the mean $|\alpha|$, shown above each empirical distribution, decreases with increasing period, and the empirical density function (a normalised histogram) of $|\alpha|$ becomes more concentrated towards low values of $|\alpha|$, indicating that the direction of maximum $SaAvg$ intensity occurs closer to the transverse orientation for longer periods. A second interesting observation is that even for lower periods, where the orientation of maximum intensity does not show as clear trends as for long periods, there is a tendency for the orientation of maximum $SaAvg$ to be similar to each other in neighbouring stations. A third observation from this figure is that this approximately concentric pattern of the short line segments that indicate the orientations of maximum $SaAvg$ intensity exists not only for stations that are near the epicentre but holds even for long distances from the epicentre, such as 400 km, visible for all four periods, but particularly clear for periods of 2.0 s and 3.0 s. A fourth observation is that the mean $|\alpha|$ is significantly lower than 45° for all periods; hence, for most stations, on average, the orientation of the maximum intensity is closer to the transverse component, even for short periods. This can also be appreciated by the spatial prevalence of various tones of blue across the maps. These observations are consistent with those made by Poulos and Miranda (2023b) for the orientation of maximum 5%-damped spectral ordinates in various strike-slip earthquakes in the NGA west ground motion database. Furthermore, similar results have been recently published by Girmay et al. (2023) and Bravo-Haro et al. (2024) for the orientation of maximum 5%-damped spectral ordinates and $FIV3$, respectively, for the same Kahramanmaraş earthquake doublet studied herein.

A characteristic of the Kahramanmaraş earthquake doublet is that for the Elbistan M_w 7.5 (second event), the epicentre practically coincides with the surface projection of the point of maximum slip, as per the USGS finite fault model (USGS, 2023a), with the separation between the two points being only ~ 4.8 km. However, in the Pazarcik M_w 7.8 (main event) the point of maximum slip in the USGS finite fault model (USGS, 2023b) is located approximately 55 km to the northeast of the epicentre. Such feature enables to study if the surface projection of the point of maximum slip provides a better reference from which to compute the transverse orientation to estimate the orientations of maximum intensity. To this end, in Figure 5, the transverse orientation is now computed with respect to the surface projection of the point of maximum slip, following the same style of Figure 4, only for the Pazarcik M_w 7.8 earthquake. In this case, an oscillator with a period of 2.5 s is considered and the main observation that can be drawn is that the mean $|\alpha|$ shifts from 27.69° to 24.66° when the epicentre and the surface projection of point of maximum slip are considered to compute the transverse orientation, respectively. Hence, there is a reduction of 10.9% in the mean value of $|\alpha|$, and this can also be seen in the slight shift to the left of the histogram in Figure 5b with respect to that shown in Figure 5a. This means that the orientation of maximum response is closer to the transverse orientation defined by the point of maximum slip than to the transverse orientation defined by the epicentre. Furthermore, the reduction in the mean value of $|\alpha|$ is also accompanied by a small reduction in the standard deviation of $|\alpha|$ of 4%, which implies that the predictability of the direction of maximum $SaAvg$ intensity increases slightly when the surface

304 projection of the maximum slip point is considered as the seismic source instead of the epicentre when
 305 computing the transverse orientations. In other words, the predictability of the direction of maximum *SaAvg*
 306 intensity increases if the surface projection of the maximum slip point is considered as the seismic source
 307 instead of the epicentre. These results are consistent with those found by Girmay et al. (2023), who also
 308 explored the use of the surface projection of the point of maximum slip for estimating the direction of maximum
 309 5%-damped response spectral ordinates and with those found by Bravo-Haro et al. (2024) for *FIV3* also during
 310 the 2023 Türkiye earthquake doublet.



311 **Figure 4.** Orientation of maximum *SaAvg* intensities for periods of vibration of (a) 0.5 s, (b) 1.0 s, (c) 2.0 s,
 312 and (d) 3.0 s during the $M_w 7.8$ event and their angular difference with respect to the transverse orientation.
 313 Black crossing lines correspond to the orientation of the maximum *SaAvg* intensity and the colour inside the
 314 small circles indicates the absolute angular difference to the transverse orientation $|\alpha|$. The bottom right
 315 insert on each map corresponds to the histogram and the mean $|\alpha|$ along with the colour-based intensity. For
 316 all stations and periods, the computation of $|\alpha|$ is done with respect to the epicentre.
 317

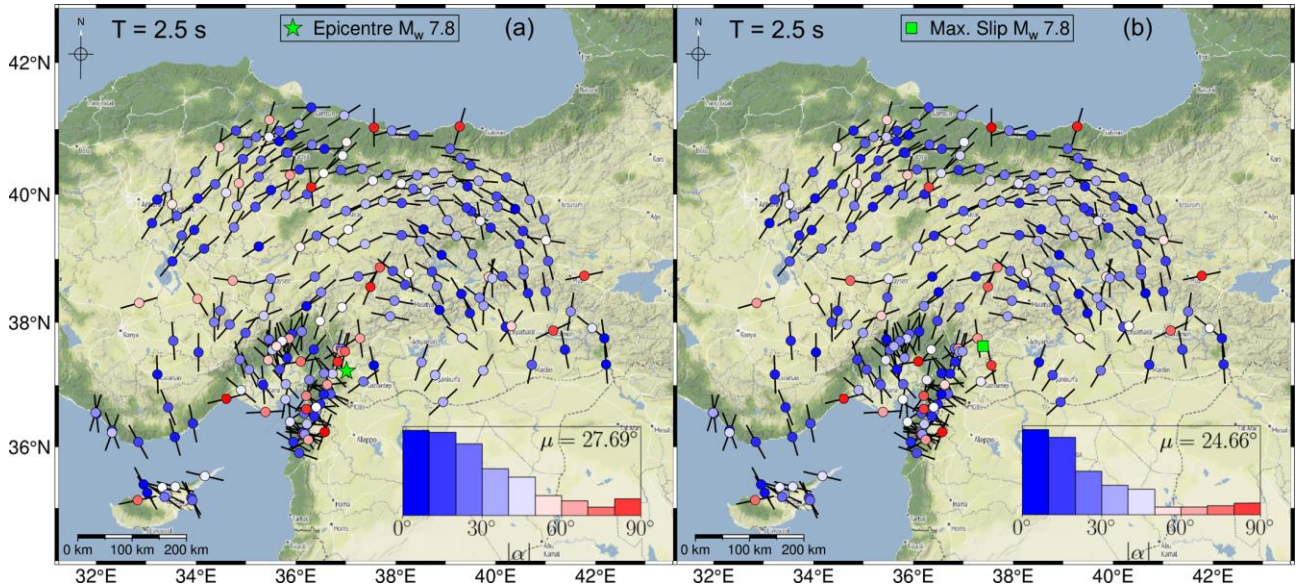


Figure 5. Orientation of maximum *SaAvg* intensities for a period of vibration of 2.5 s during the M_w 7.8 main event and their angular difference with respect to the transverse orientation. Black crossing lines correspond to the orientation of the maximum intensity and the colour indicates the absolute angular difference to the transverse orientation $|\alpha|$. The bottom right insert on each map corresponds to the histogram and the mean $|\alpha|$ along with the colour-based intensity. The computation of $|\alpha|$ is shown with respect to the epicentre (panel a) and with respect to the surface projection point of maximum slip (panel b), respectively.

To obtain further insight into the variation of the angular distance between the orientation of RotD100 and the transverse orientation, $|\alpha|$, its mean value across all stations from each event is plotted against the period in Figure 6. For the two events in the doublet (M_w 7.8 and M_w 7.5), the angular distance was computed using the transverse orientation with respect to both the epicentre and the surface projection of the point of maximum slip. The curves computed with the epicentre and the maximum slip point are almost identical for the M_w 7.5 event; hence, the angular distances remain nearly unchanged regardless of the definition of transverse orientation. On the other hand, for the M_w 7.8 event, the mean angular distances reduce when the transverse orientations are computed based on the maximum slip rather than the epicentre; hence, using the maximum slip point to determine the transverse orientation could provide a better prediction for the orientation of maximum *SaAvg* in this case. In general, a descending trend is observed for the mean $|\alpha|$ with increasing period. This implies that maximum *SaAvg* occurs closer to the transverse orientation as the period increases, exhibiting mean angular differences as low as 25° at 3 s. Comparing the angular distances for the two events, it is evident that lower mean $|\alpha|$ values are obtained for the main M_w 7.8 event. The distribution of $|\alpha|$ for the main M_w 7.8 event is also characterized by 4% lower standard deviation. Therefore, the maximum *SaAvg* orientation is expected to be more predictable for the main event than for the second event.

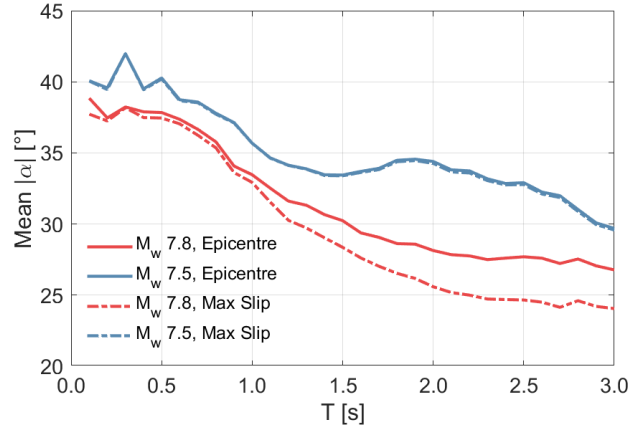


Figure 6. Mean absolute angular distance between the orientation of maximum *SaAvg* intensity and the transverse orientation as a function of period. Results are shown for the transverse orientation with respect to both the epicentre and the surface projection of the point of maximum slip and for the main M_w 7.8 and second M_w 7.5 events.

5. Level of Polarisation of *SaAvg* Intensities

The ratio of the maximum *SaAvg* intensity across all orientations (i.e., RotD100) to the *SaAvg* median intensity across all orientations (i.e., RotD50) provides a simple metric to evaluate the level of polarisation in this intensity measure. The larger this ratio is, the larger the level of polarisation in the ground motion. Figure 7 shows the spatial distribution of the RotD100/RotD50 ratio of the *SaAvg* intensities for a period of 3 s for both the M_w 7.8 Pazarcık (panel a) and M_w 7.5 Elbistan (panel b) events. The ratio displays a similar average behaviour for both events in terms of their spatial distribution as well as their mean ratio averaged over all stations in each event, which is virtually identical and equal to 1.18 and 1.17 in the two events in the doublet, respectively. As before, the circles indicate the location of each recording station and the colour inside them indicates the RotD100/RotD50 ratio of *SaAvg* intensities at each site. Contrary to the belief that stations closer to the source tend to be more polarised, these figures show that there is no clear pattern in the level of polarisation across stations and that values much larger than the mean can occur at stations close to the source as well as at stations that are up to ~400 km away from the source. This is consistent with Boore et al. (2002), who first noticed the ground displacement waveforms at two closely spaced stations located at a distance of approximately 120 km from the epicenter of the 1999 Hector Mine, California earthquake were both strongly linearly polarized despite being located at a distance from the rupture of approximately three times the total rupture length. Also noticeable is that the histograms of the ratio (shown at the bottom right corner of each subpanel), present very similar distributions, significantly departing from a uniform distribution, and are skewed towards higher ratios. Like in the case of response spectral ordinates, and as first pointed out by Boore (2010) for that measure of intensity, the upper limit of this ratio is also $\sqrt{2}$, which corresponds to the ratio of a fully linearly polarised ground motion, in which motion occurs only within a vertical plane. A similar spatial distribution of the level of polarisation was also reported by Bravo-Haro et al. (2024) when computing the RotD100/RotD50 ratios of *FIV3* intensities.

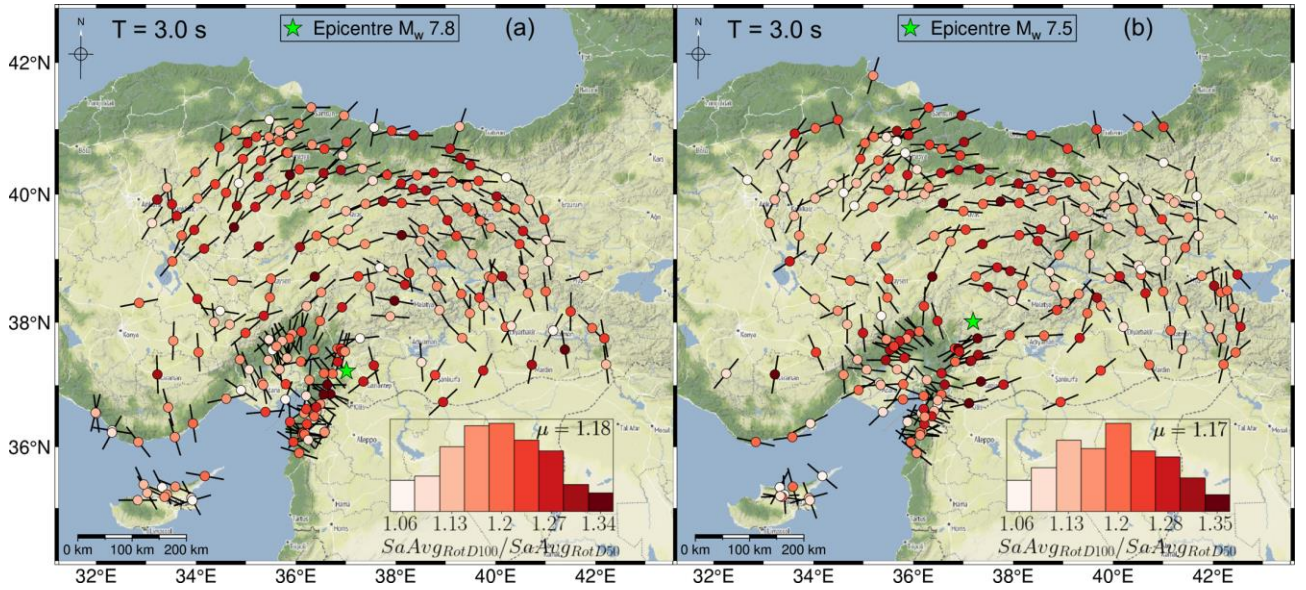


Figure 7. Spatial distribution and empirical probability distribution of the level of polarisation in the ground motions as measured by RotD100 to RotD50 SaAvg ratios computed for a period of 3.0 s and for (a) the main M_w 7.8 event, and (b) the second M_w 7.5 event.

To evaluate possible trends in the level of polarisation of ground motions with changes in distance to the source, Figure 8 shows RotD00/RotD100 ratios of SaAvg intensities for a 3 s period as a function of the Joyner-Boore distance, considering all stations from both events. The locally weighted scatterplot smoothing (LOWESS) fit line, along with the 95% confidence intervals, are also shown in the same figure. In general, the mean level of polarisation of SaAvg($T=3$ s) does not exhibit a strong departure from the mean value across all distances (which is approximately 0.66) with changes in the distance from the station to the horizontal projection of the rupture. Specifically, the mean RotD00/RotD100 values increase from about 0.60 for stations on top of the rupture ($R_{JB}=0$ km) to a value of about 0.69 for stations at 400 km from the rupture. These results are consistent with those found for the polarization of individual spectral ordinates in prior strike-slip earthquakes (e.g., Poulos and Miranda, 2023a, 2024; Girmay et al., 2023, 2024). However, across all distances, significant variations in the level of polarisation occur, with maximum SaAvg intensities being anywhere from 5% to 300% larger than the minimum SaAvg across all orientations. Although not presented here due to space limitations, similar observations occur for other periods.

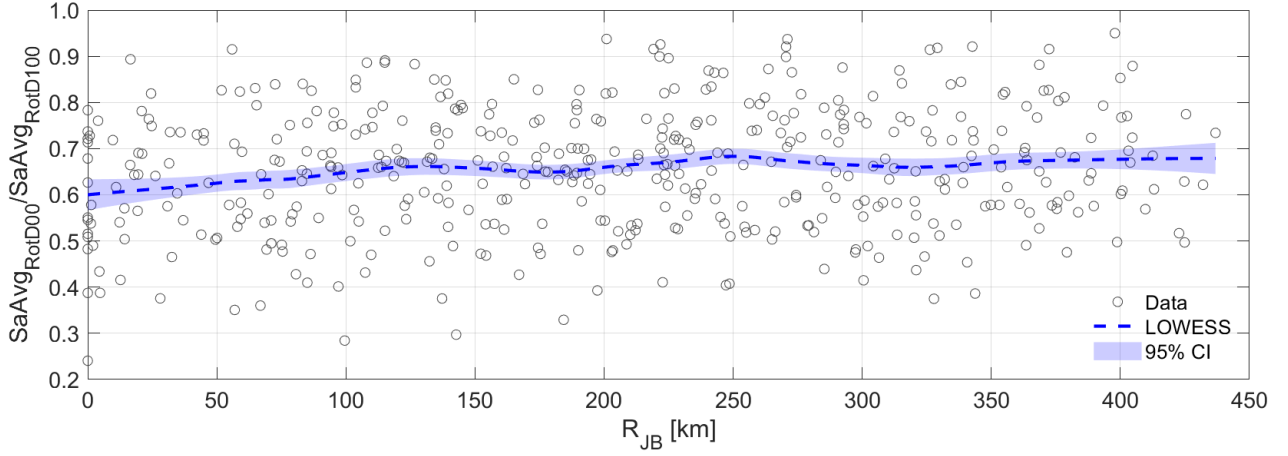


Figure 8. Ratios of RotD00 to RotD100 SaAvg intensities for a period of 3 s as a function of Joyner-Boore distance, considering all ground motions from both the M_w 7.8 and M_w 7.5 events. The LOWESS fit and 95% confidence interval are also shown.

6. Normalised SaAvg Demands

In their comprehensive study of the directionality of spectral ordinates, Poulos and Miranda (2022) used two nondimensional ratios to characterise the variation of spectral ordinates as the motion is rotated away from the orientation of maximum intensity. The first parameter that they used was the spectral ordinate at different orientations (i.e., for different rotation angles about a vertical axis) normalised by the maximum spectral ordinate across all orientations. In this investigation the same normalisation was done for SaAvg as shown in Equation 5:

$$\eta(\phi) = \frac{SaAvg(\phi)}{SaAvg_{RotD100}} \quad (5)$$

where $SaAvg(\phi)$ is the SaAvg intensity at an angle of rotation ϕ measured from the angle at which the maximum SaAvg intensity occurs, and $SaAvg_{RotD100}$ is the maximum SaAvg intensity across all orientations, given from Equation 2. Note that the parameter $\eta(\phi)$ is dimensionless and was first proposed by Hong and Goda (2007) to study the variation of spectral ordinates as one rotates away from the orientation of maximum intensity.

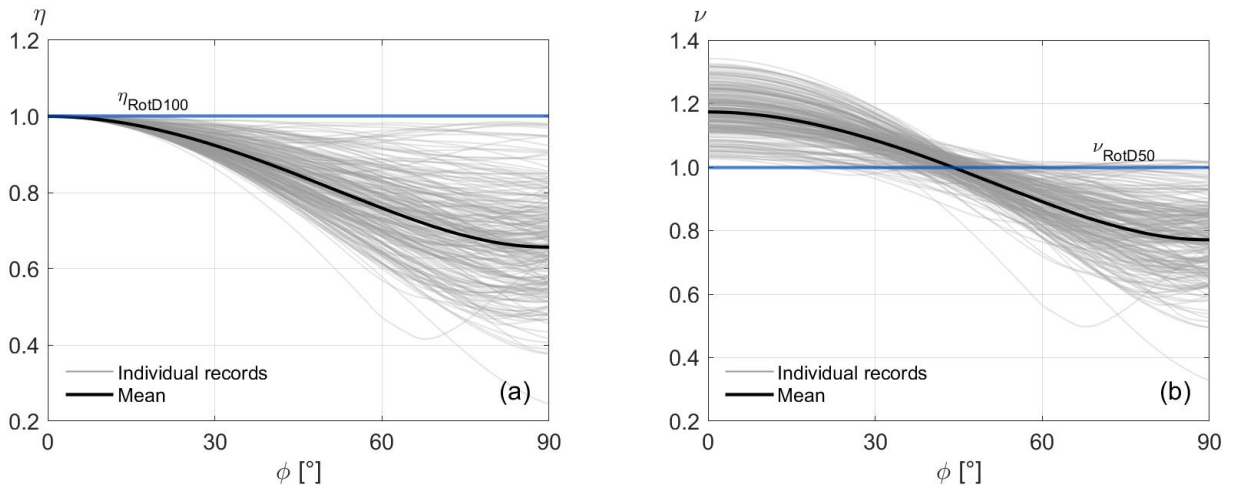
The second parameter that was studied in this work as a measure of directionality was the SaAvg intensity for different orientations normalised by the median of all SaAvg intensities of the record between 0 and 180°, as shown in Equation 6.

$$\nu(\phi) = \frac{SaAvg(\phi)}{SaAvg_{RotD50}} \quad (6)$$

where $SaAvg_{RotD50}$ is the median SaAvg intensity across all orientations, given from Equation 3.

The parameter $\nu(\phi)$ is also dimensionless and is analogous to the one studied by Shahi and Baker (2014) and Poulos and Miranda (2022) for spectral ordinates but is modified herein for SaAvg.

410 Figures 9a and 9b, show individual values of η and ν , respectively, of all records from the main M_w 7.8 event
 411 for an oscillator with a 3 s period as a function of the rotation angle ϕ , which is measured from the orientation
 412 in which the $SaAvg_{RotD100}$ occurs. The mean curves, averaged over the results for all individual records, are
 413 also presented in each figure in thick black lines, along with horizontal blue lines indicating the RotD100
 414 (corresponding to $\eta = 1$ in Figure 9a) and the RotD50 level (corresponding to $\nu = 1$ in Figure 9b). Although a
 415 large scatter in the level of polarity is evident, the mean lines indicate a decreasing trend in $SaAvg(T=3.0\text{ s})$
 416 as the orientation angle shifts away from the orientation in which the $SaAvg_{RotD100}$ intensity occurs. At an angle
 417 ϕ of 45° , the $SaAvg$ intensity is, on average, approximately equal to the RotD50 intensity, which is
 418 approximately 85% of the RotD100 intensity. At orientations perpendicular to the orientation of RotD100, the
 419 average $SaAvg(T=3\text{ s})$ reaches its minimum value, which for a period of 3 s is approximately 65% of its
 420 maximum RotD100 value, and approximately 78% of its median RotD50 intensity level.



421
 422 **Figure 9.** Normalised $SaAvg$ intensities (a) η and (b) ν of individual records (in grey thin lines) and mean
 423 values (in black thick lines) computed for a period of 3 s for ground motions recorded in the main M_w 7.8
 424 event. The blue lines correspond to the RotD100 and RotD50 intensities in panels a and b, respectively.

425 It was previously mentioned that the orientation of maximum intensity varies from one station to another, but
 426 that for most stations, it tends to nearly coincide with the transverse orientation. Since the transverse
 427 orientation can be determined from the relative position of each station with respect to the epicentre, and given
 428 that current GMMs typically estimate RotD50 intensities, it is of interest to study how much larger the $SaAvg$
 429 intensity at the transverse orientation is relative to the RotD50 intensity, and to also investigate the spatial
 430 distribution of this ratio. Figure 10 shows the spatial distribution of the ratio between the $SaAvg$ intensity in the
 431 transverse orientation, $SaAvg_T$, and the RotD50 $SaAvg$ intensity, $SaAvg_{RotD50}$, for the same period of 3 s during
 432 the M_w 7.8 and M_w 7.5 events. Similarly, as was done in Figures 4, 5, and 7, this figure present results for
 433 individual stations, empirical distribution across all stations in each event, and the mean across all stations for
 434 each of the two events. For the sake of brevity, results are shown only for the transverse orientation with
 435 respect to the epicentre of both events. The first observation is that since for most stations the maximum
 436 intensity tends to occur close to the transverse orientation (see Figures 4 and 5), the $SaAvg$ intensity at the

transverse orientation is, for most stations, well above the RotD50 ($SaAvg_T/SaAvg_{RotD50} > 1.0$). Secondly, the empirical probability distribution and mean value of the $SaAvg_T/SaAvg_{RotD50}$ ratios are similar for both events, with mean values of 1.10 and 1.08 for the M_w 7.8 and M_w 7.5 events, respectively. Thirdly, both empirical distributions are strongly skewed towards values higher than ~ 1.08 , with only a small percentage of stations exhibiting $SaAvg$ intensity in the transverse orientation smaller than the RotD50 $SaAvg$ intensity, and with no stations approaching the upper theoretical limit (i.e., $\sqrt{2}$) that corresponds to fully linearly polarised ground motions. Furthermore, in some regions, such as in the subset of 25 almost in-line red-coloured stations located south-west of the epicentre of the M_w 7.5 event near the Amanos segment of the EAF, the mean ratio between the transverse intensity and RotD50 intensity reaches a value of 1.20. Hence, in these regions close to the fault, $SaAvg$ intensities in the transverse orientation were, on average, 20% larger than the median intensity from all orientations.

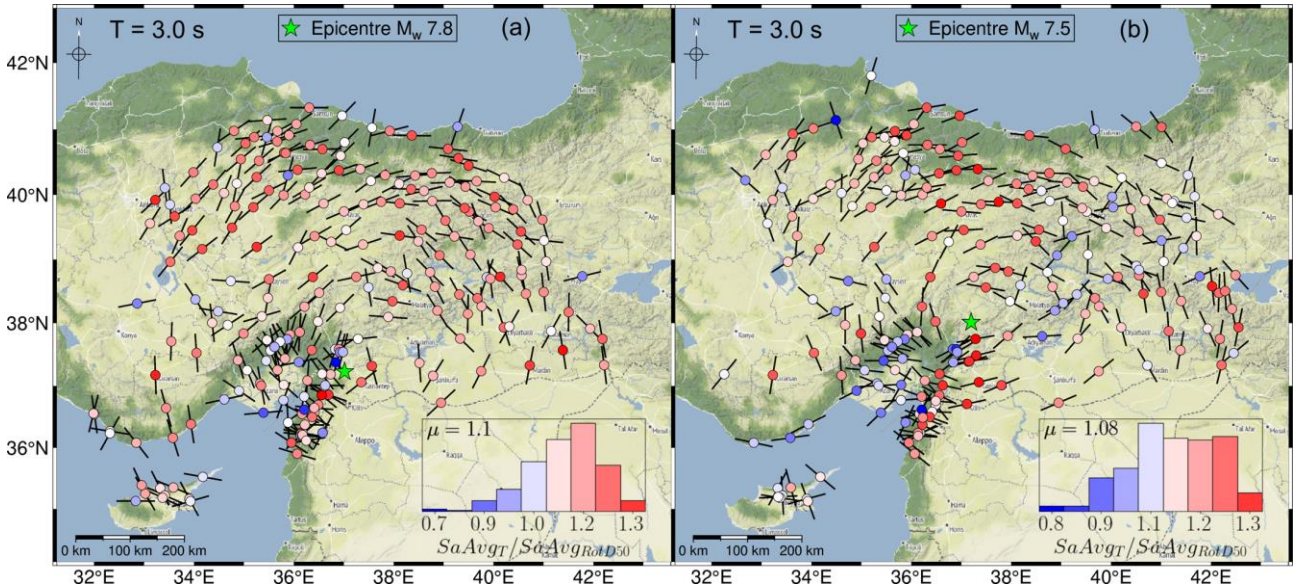


Figure 10. Spatial distribution and empirical probability distribution of $SaAvg_T$ to $SaAvg_{RotD50}$ ratios computed for a period of 3.0 s, for (a) the main M_w 7.8 event, and (b) the second M_w 7.5 event. The transverse orientation is computed with respect to the epicentre for both panels.

Figure 10 provided valuable information on the spatial distribution of $SaAvg_T/SaAvg_{RotD50}$ ratios for a period of 3 s. However, it is of interest to also examine the $SaAvg$ intensity in transverse and radial directions relative to the RotD100 and relative to each other across a wide range of periods. Figures 11a and 11b present the median variation of four different $SaAvg$ ratios for the M_w 7.8 and M_w 7.5 events, respectively, as a function of the period of vibration. For both events, the Transverse/RotD100 ratio is approximately constant across periods and only slightly smaller than one, meaning that a multiple of the intensity in the transverse component could be used as a proxy for the maximum $SaAvg$ intensities (e.g., $SaAvg_{RotD100} \approx 1.05SaAvg_T$). In general, the ratio Radial/RotD100 is close to the Transverse/RotD100 ratio for periods of vibration between 0.1 and 0.6 s and it then starts decreasing as the period of vibration increases, reaching an average value of about 0.75 at 3 s for both events. For short periods, the ratio Transverse/Radial, is slightly larger than 1, and then it starts increasing

with increasing period, reaching an average value of about 1.3 at a period of 3 s. These results compare with previous observations from Girmay et al. (2023) for response spectral ordinates. Finally, the RotD100/RotD50 ratio, which can be used to convert from the orientation-independent median to the maximum response, seems to be fairly constant across the period range, with an average value of about 1.15, unlike for S_a , where an increment is observed with increasing period.

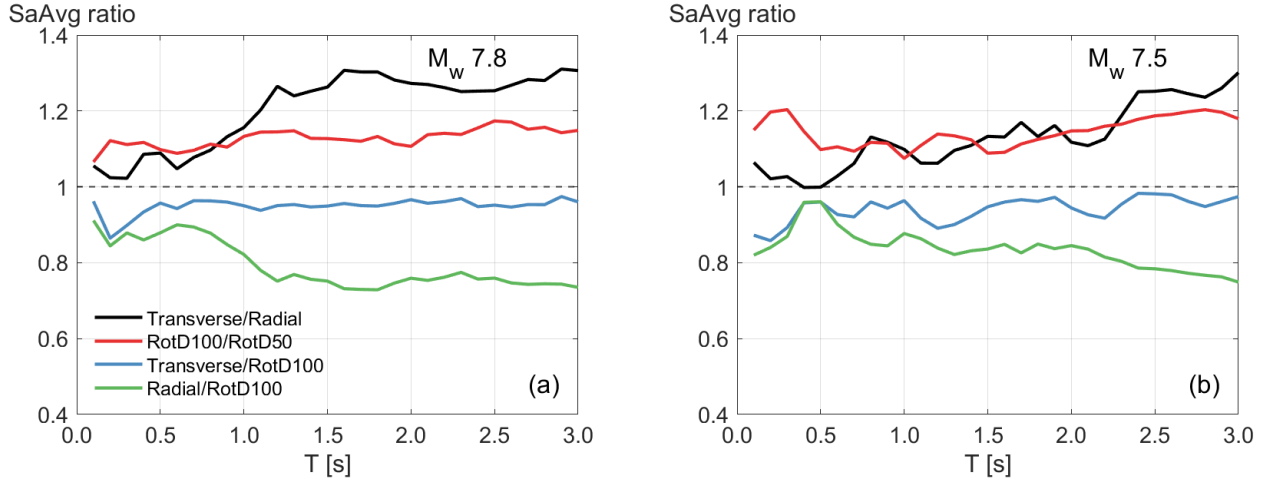


Figure 11. Median of normalised $SaAvg$ intensities as a function of period for (a) the main M_w 7.8 event, and (b) the second M_w 7.5 event.

7. Directionality Models for the Probabilistic Characterisation of $SaAvg$

Models to estimate median nondimensional ratios η and ν as a function of the rotation angle θ and the period of vibration T are developed in this section, using empirical results from the two Kahramanmaraş events. Both models employ the same functional form, adapted from the model proposed by Poulos and Miranda (2023b) for response spectral ordinates. The proposed models for the median η and ν are presented in Equations 7–8.

$$\bar{\eta}(\theta) = a_1 + a_2(1 - \cos(2\theta)) + a_3(1 - \cos(4\theta)) \quad (7)$$

$$\bar{\nu}(\theta) = a_4 + a_5(1 - \cos(2\theta)) + a_6(1 - \cos(4\theta)) \quad (8)$$

where $\theta \in (0^\circ, 90^\circ)$ is the rotation angle, measured from the orientation where $SaAvg_{RotD100}$ occurs, and a_1 – a_6 are regression coefficients that were determined as functions of the period using nonlinear regression analysis, aiming to minimise the differences between empirical and estimated η and ν results. They can be evaluated from Equations 9–14.

$$a_1 = 1 \quad (9)$$

$$a_2 = -0.0059 T^4 + 0.0392 T^3 - 0.0905 T^2 + 0.0623 T - 0.1216 \quad (10)$$

$$a_3 = -0.0018 T^4 + 0.0137 T^3 - 0.0351 T^2 + 0.0391 T - 0.0178 \quad (11)$$

$$a_4 = 0.0084 T^4 - 0.0584 T^3 + 0.1411 T^2 - 0.1179 T + 1.1543 \quad (12)$$

$$a_5 = -0.0079 T^4 + 0.0527 T^3 - 0.1219 T^2 + 0.0866 T - 0.1409 \quad (13)$$

$$a_6 = -0.0024 T^4 + 0.0179 T^3 - 0.0451 T^2 + 0.0486 T - 0.0205 \quad (14)$$

Figure 12a compares the median η values obtained from the empirical data and the proposed models as a function of the rotation angle θ and the period of vibration T . The rotation angle varies between 0° and 90° , while a set of four periods of vibration (0.5, 1.0, 2.0, and 3.0 s) is considered. Figure 12b presents an analogous comparison between the empirical results and the proposed model for ν . In both cases, and for the four periods of vibration shown, the models developed in this section are in good agreement with the observed data.

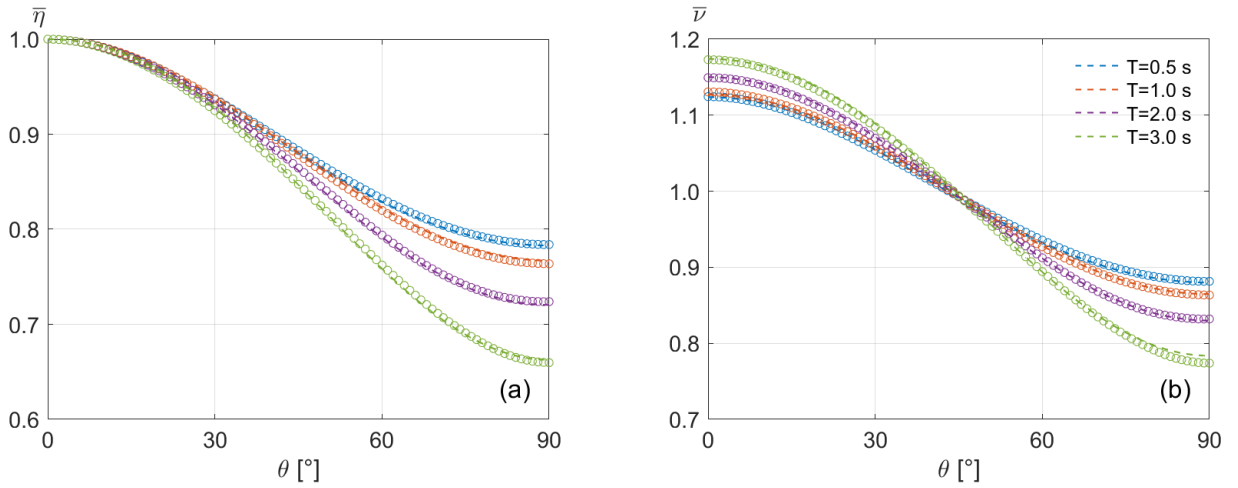


Figure 12. Geometric mean of (a) η and (b) ν as a function of the rotation angle for oscillators with varying periods considering both events. The dashed lines refer to the fitted model, while the circles show the observed data.

Similarly, nonlinear regressions were conducted to propose models for the logarithmic standard deviation of nondimensional parameters η and ν . In particular, $\sigma_{\ln\eta}$ can be estimated using Equation 15, while $\sigma_{\ln\nu}$ can be estimated from Equation 16.

$$\sigma_{\ln\eta} = b_1 \sin(b_2 \theta) [1 - \cos(2\theta)] \quad (15)$$

$$\sigma_{\ln\nu} = b_3 + b_4 \exp \left[-\frac{1}{2} \left(\frac{\theta - 1.617}{0.4} \right)^2 \right] + 0.034 \exp \left[-\frac{1}{2} \left(\frac{\theta - 0.775}{0.25} \right)^2 \right] \quad (16)$$

where $b_1 - b_4$ are regression coefficients that depend on the period of vibration and are given by Equations 17–20.

$$b_1 = 0.00035 T^3 + 0.00723 T^2 - 0.0123 T + 0.08156 \quad (17)$$

$$b_2 = -0.0479 T^2 + 0.0078 T + 1.1532 \quad (18)$$

$$b_3 = -0.0005 T^2 + 0.0031 T + 0.0561 \quad (19)$$

$$b_4 = 0.0081 T^2 - 0.0080 T + 0.0557 \quad (20)$$

Figures 13a and 13b present a comparison of the empirical results and proposed models for $\sigma_{\ln\eta}$ and $\sigma_{\ln\nu}$, respectively, for the same four different periods of vibration used in Figure 12. Evidently, the proposed variability models capture accurately the observed trends across all orientation angles and vibration periods examined.

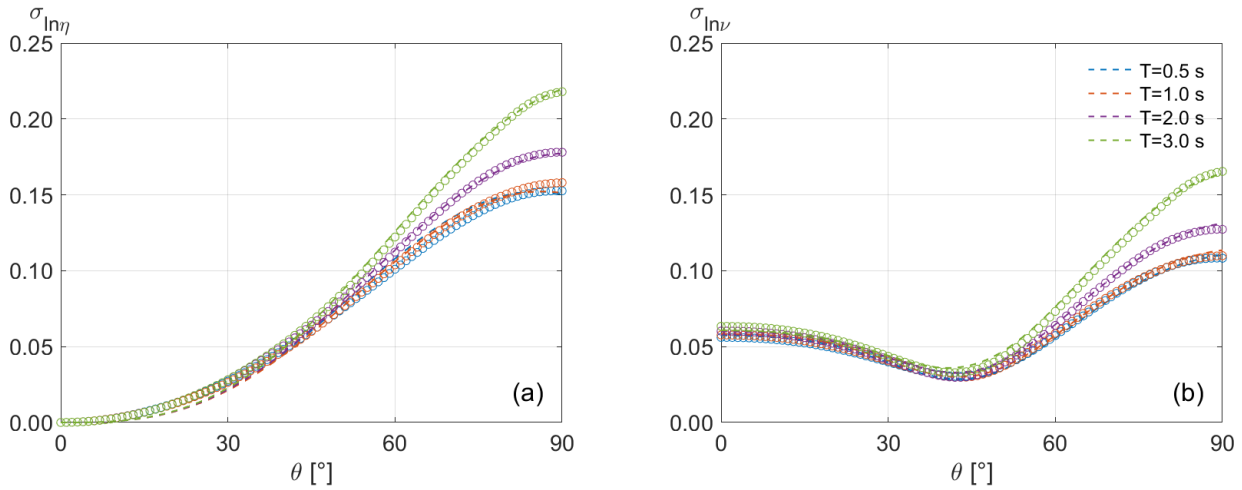


Figure 13. Logarithmic standard deviation of (a) η and (b) ν as a function of the rotation angle for oscillators with varying periods, considering both events. The dashed lines refer to the fitted model, while the circles show the observed data.

The models proposed for the median and standard deviation of η and ν can be used to adjust $SaAvg_{RotD100}$ and $SaAvg_{RotD50}$ intensities from Sa GMMs, respectively. These adjusted intensities will therefore be orientation specific, being higher for transverse orientations and lower for radial ones. In other words, these models will aid in accounting for directionality in strike-slip earthquakes. It should also be noted that, in general, estimation of $SaAvg$ through a GMM directly developed for this IM, referred to as direct method, provides a more accurate procedure compared to estimating it through GMMs of the median, variability, and correlation of individual spectral ordinates, which is often referred to as indirect method (Kohrangi et al., 2018a; Davalos and Miranda, 2021).

512 8. Summary and Conclusions

513 This study investigated the changes in the average spectral acceleration with changes in orientation. This
514 relatively new measure of ground motion intensity, referred to as *SaAvg*, is computed by using 5%-damped
515 pseudo-acceleration spectral ordinates averaged over a period range defined from one-fifth to three times the
516 period of interest. Several previous studies have shown that, compared to individual spectral ordinates (*Sa*),
517 this ground motion intensity measure captures more information about the ground motion and therefore offers
518 several advantages for the characterisation of ground motion intensities. Those previous studies have
519 concluded that *SaAvg* is better correlated with structural damage and, in particular, with collapse of structures,
520 thus making it more efficient. Additionally, they also concluded it is also more sufficient with respect to
521 earthquake magnitude, distance to the source, and that structural response parameters are less sensitive to
522 record scaling, greatly facilitating record selection when conducting nonlinear response history analyses.
523 Furthermore, residuals of *SaAvg* with respect to recently developed ground motion models show that its
524 variability is smaller than that of individual spectral ordinates, hence also making this intensity measure more
525 predictable.

526 The 2023 Kahramanmaraş earthquake sequence in Türkiye produced one of the best sets of ground motion
527 records available to date from large magnitude strike-slip earthquakes, offering a unique opportunity to study
528 the directionality of horizontal components of ground motions. A ground motion set of 453 records was
529 assembled from the two largest events in the sequence: the M_w 7.8 Pazarcık and M_w 7.5 Elbistan earthquakes.
530 Records were selected such that the maximum usable period is longer than 10 s in both recorded horizontal
531 components and a strong signal-to-noise ratio at low frequencies is attained, to obtain *SaAvg* ordinates up to
532 3 s, which requires reliable spectral ordinates up to 9 s.

533 Results from this investigation show that *SaAvg* ordinates exhibit a strong directionality, that is, they exhibit a
534 significant anisotropy in their amplitude with changes in azimuth/orientation. For example, at a period of 2 s
535 the maximum *SaAvg* intensity is, on average, approximately 39% larger than that in the perpendicular
536 orientation. Similar to the directionality of individual spectral ordinates, the level of directionality of *SaAvg* is
537 found to depend on the period of vibration and tends to be larger with increasing periods. On average, the
538 maximum *SaAvg* intensity is nearly 28% larger than the intensity in the perpendicular direction for a period of
539 0.2 s and increases to approximately 51% larger for a period of 3 s.

540 The reduction in *SaAvg* intensity as one rotates away from the orientation/azimuth in which the maximum
541 intensity occurs exhibits a very similar variation as that of individual spectral ordinates. However, for a given
542 rotation angle, the level of reduction is smaller in *SaAvg* than that for individual spectral ordinates. For example,
543 for a period of 0.1 s, a rotation of 90° away from the orientation of maximum intensity produces an average
544 reduction of about 27% in individual spectral ordinates but only about 24% for *SaAvg*. For a period of 3.0 s,
545 the corresponding average reductions in intensity are 46% for *Sa* and 34% for *SaAvg*. The variability in
546 directionality is also smaller for *SaAvg* than it is for *Sa*, indicating that the directionality of *SaAvg* is more
547 predictable than that of *Sa*.

548 This study also investigated the spatial distribution of the level of polarisation in *SaAvg* and of the orientation
549 of maximum *SaAvg* intensity. Results indicate that the ground motions remain strongly polarised even at long
550 distances such as 400 km from the epicentre. There is only a very slight reduction in the level of polarisation
551 of about 10% from the near field to distances of about 250 km and then it remains approximately constant up
552 to distances of 400 km. The orientation of maximum *SaAvg* intensity tends to occur close to the transverse
553 orientation. Slightly better results were obtained when the transverse orientations were computed with respect
554 to the surface projection of the point of maximum slip in finite fault models of the rupture than when computed
555 with respect to the epicentre. These results are consistent to those found in empirical studies on the
556 directionality of *Sa* or of another recently proposed measure of ground motion intensity referred to as *FIV3*.
557 Larger intensities in the transverse direction are also consistent with the amplitude of SH body waves whose
558 maximum intensity occurs perpendicular to the direction of propagation.

559 Finally, models were developed to estimate the geometric mean and variability of normalised *SaAvg* intensities
560 as a function of the angle of rotation and period of vibration. The proposed models provide excellent estimates
561 of the statistical results. At present time, ground motion models typically provide isotropic estimates of ground
562 motion intensity, as they only evaluate the median intensity across all orientations, therefore neglecting the
563 large variations that occur with changes in orientation. Results from this investigation suggest that in the case
564 of strike-slip earthquakes, one may approximately estimate the orientations where the maximum intensity will
565 occur. Therefore, the models developed herein can be used to develop improved ground motions models to
566 predict ground motion intensities at specific orientations with information on the site of interest relative to the
567 seismic source.

568

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580

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585

586 **Conflict of interest**

587 The authors have no relevant financial or non-financial interests to disclose.

588

589 **Authorship contributions**

590 Conceptualisation: EM; Investigation: ML, HD, MBH, PH, EM; Methodology: EM; Formal analysis: ML, HD,
591 MBH, PH, EM; Writing—original draft: ML; Writing—review and editing: ML, HD, MBH, PH, EM

592

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