

## CORRELATION BETWEEN INTENSITY MEASURES AND DAMAGE CAUSED BY THE 2023 TÜRKİYE EARTHQUAKES

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**Abstract:** *This article presents comparisons between different ground-motion intensity measures and damage frequencies observed following the Pazarcık (Mw7.8) and Elbistan (Mw7.5) earthquakes that struck Türkiye in February 2023. Various intensity measures were examined including peak ground acceleration (PGA), peak ground velocity (PGV), and spectral ordinates (e.g.,  $S_{a0.3}$ ,  $S_{a1}$ ,  $S_{d1}$ ). Two data sources were used to quantify damage frequency: a survey conducted by the team deployed by ACI 133 Reconnaissance Committee involving more than 200 reinforced concrete buildings, and surveys published by the Ministry of Environment, Urbanization, and Climate Change of Türkiye. The differences and commonalities between the two surveys are discussed, and plausible correlations between damage and intensity measures are examined. It is concluded that, relative to other intensity measures, peak ground velocity (PGV) and spectral displacement at a fundamental period of 1.0 second ( $S_{d1}$ ) had better correlations with the damage observed from Antakya to Malatya. This observation is consistent with two previously published ideas: a) in the absence of structural damage, drift demand can be expressed as a linear function of PGV, and b) seismic design ought to be focused on drift (and PGV) instead of force (and PGA).*

### 1 Introduction

On February 6, 2023, a devastating Mw7.8 earthquake at a shallow depth of 10 km struck Türkiye and northwest Syria at 04:17 local time (UTC+3). The earthquake's epicenter, as reported by USGS, was Pazarcık, Kahramanmaraş at coordinates 37.226°N and 37.014°E. Nine hours later, this earthquake was followed by the Mw7.5 Elbistan, Kahramanmaraş (38.011°N, 37.196°E) earthquake. The epicenter was approximately 90 kilometers to the north of the Mw7.8 earthquake.

This sequence of seismic events, accompanied by a substantial number of aftershocks, caused widespread devastation across the regions of southern and central Türkiye, extending into northwestern Syria. The collective loss of life within Türkiye exceeded 50,000 individuals, while the structural damage extended to over

200,000 buildings within the affected areas (Ministry of Interior of the Republic of Turkey, 2023; Presidency of Strategy and Budget, 2023). The earthquakes had a profound impact on eleven provinces in Türkiye, namely Adana, Adıyaman, Diyarbakır, Elazığ, Gaziantep, Hatay, Kahramanmaraş, Kilis, Malatya, Osmaniye, and Şanlıurfa. More than 1.5 million people were faced with housing problems, imposing a substantial financial burden on the Turkish economy.

Seismic instruments within regional networks, specifically AFAD-TADAS (2023), recorded the earthquake ground motions both near-fault ruptures and at distances over 400 km. High intensities were recorded at various stations located along the fault ruptures. A substantial portion of the buildings in the affected areas was severely damaged or collapsed. A map showing the ground motion recording stations used for this study along with the USGS Modified Mercalli Intensity contours (USGS, 2023) is presented in Figure 1.

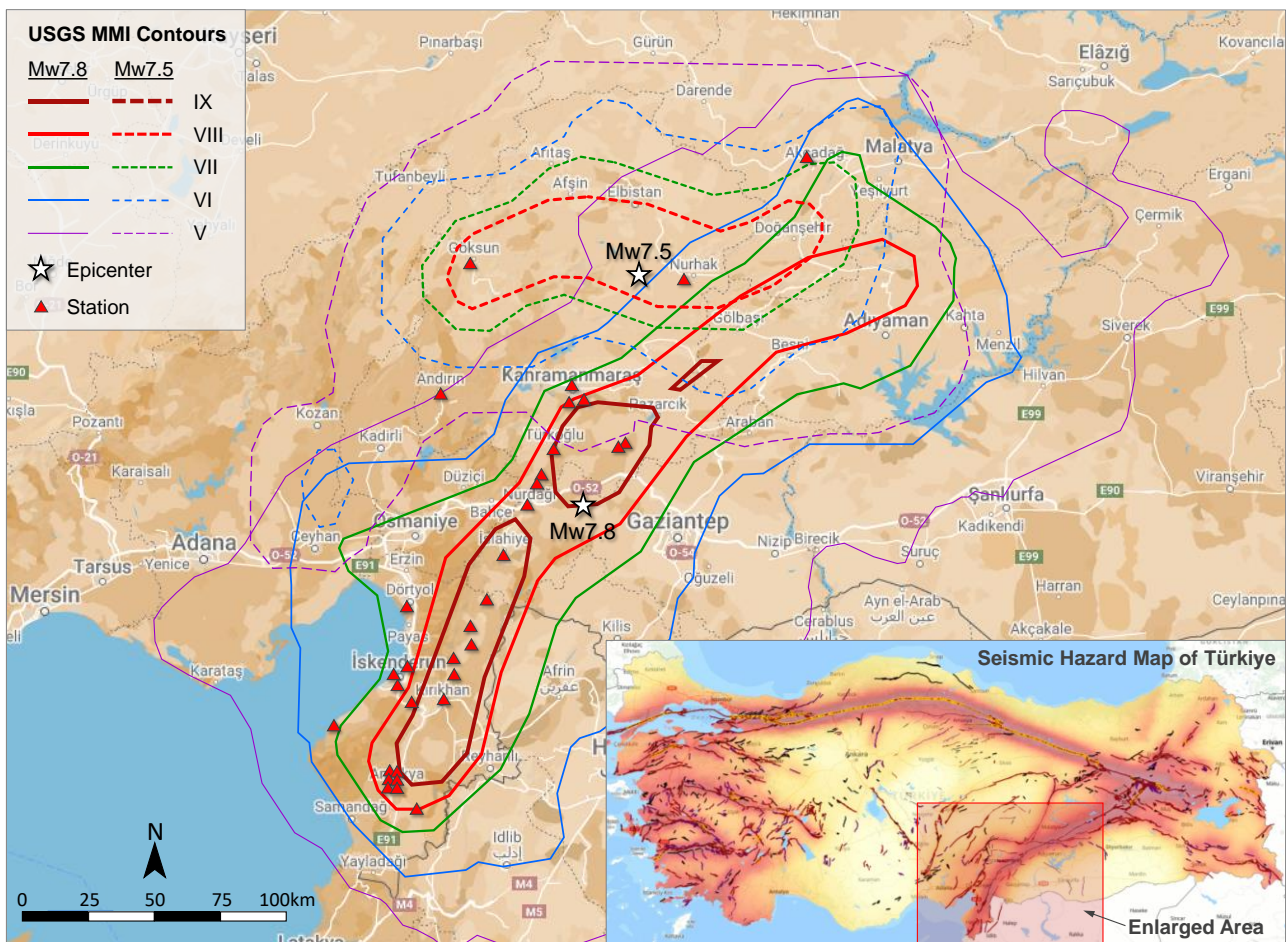


Figure 1. USGS Modified Mercalli Intensity (MMI) contours for both events, and ground motion recording stations used for this study

The authors processed the recorded ground motions and evaluated various intensity measures to compare them with the observed damage frequencies. These intensity measures included peak ground acceleration (PGA), peak ground velocity (PGV), and spectral ordinates of 2%-damped linear response spectra (e.g.,  $S_{a0.3}$ ,  $S_{a1}$ ,  $S_{d1}$ ). The damage frequencies in various locations were quantified using two data sources: (i) a survey conducted by the authors during a reconnaissance mission led by Committee 133 of the American Concrete Institute (hereinafter referred to as “ACI-133 survey”), (ii) a rapid damage assessment survey conducted by the engineers of the Ministry of Environment, Urbanization, and Climate Change of Türkiye (hereinafter referred to as “Ministry survey”). A correlation analysis was performed to identify an ideal intensity measure that appropriately correlates with observations.

## 2 Data sources

### 2.1 ACI-133 survey

A reconnaissance mission was organized by ACI 133 Disaster Reconnaissance Committee between March 25 and April 6, 2023. The mission was conducted by approximately forty people including local and international researchers, structural engineers, and civil engineering students from various universities and institutions. Nearly 250 cast-in-place multistory reinforced concrete buildings were surveyed in eight different locations: Antakya, Hassa, Kırıkhan in Hatay province; Nurdağı in Gaziantep province, Elbistan, Türkoğlu, and city center in Kahramanmaraş province, and city center (Yeşilyurt) in Malatya province. Figure 2b shows the surveyed locations and the damage frequencies in these locations.

The survey teams, each composed of three to four members, were tasked with gathering comprehensive and quantitative data regarding the inspected buildings. These teams were responsible for collecting essential information such as the building location and age (if known), number of stories, height, approximate floor plan, apparent irregularities, residual drifts, dimensions of the structural and nonstructural members, as well as capturing photographs. Additionally, other notes such as the existence of overhangs, captive columns, soft stories, and eccentricity were also recorded. After inspecting each building and sketching its floor plan, the teams rated the damage level according to the criteria given in Table 1.

Table 1. Damage classification criteria of ACI-133 survey.

Damage Level	Description
None	No structural damage
Light	Hairline inclined cracks and/or flexural cracks in structural walls, columns, or beams
Moderate	Cover spalling and/or wider cracks in structural walls, columns, or beams
Severe	Disintegration of core concrete, bar buckling, bond/splitting failure in columns or shear walls
Critical	Widespread severe damage affecting a number of columns and or structural walls to the point that the building was deemed to be likely to collapse in an aftershock
Collapse	Loss of elevation in one or several floors

Table 2 summarizes the damage levels observed in the assessed buildings across these visited districts for the ACI survey, including the percentage of the buildings with critical damage. It's important to note that Islahiye was excluded from this study due to the insufficient number of assessed buildings in this district.

Table 2. Number of buildings with different damage levels in ACI survey.

District, City	Damage Level						Total	Critical, %
	None	Light	Moderate	Severe	Critical	Collapse		
Antakya, Hatay	1	9	5	17	11	0	43	26%
Central, Kahramanmaraş	12	12	2	4	19	5	54	35%
Elbistan, Kahramanmaraş	0	6	3	5	4	0	18	22%
Hassa, Hatay	2	3	2	6	6	0	19	32%
Islahiye, Gaziantep	0	3	1	2	2	0	8	25%
Kırıkhan, Hatay	0	2	2	6	2	0	12	17%
Nurdağı, Gaziantep	1	3	2	25	19	0	50	38%
Türkoğlu, Kahramanmaraş	1	1	1	10	3	0	16	19%
Yeşilyurt, Malatya	1	4	5	5	5	0	20	25%
TOTAL	18	43	23	80	71	5	240	
TOTAL (%)	8%	18%	10%	33%	30%	2%		

### 2.2 Ministry survey

The Ministry of Environment, Urbanization, and Climate Change of Türkiye (MEUCC) conducted a survey using rapid visual screening methods over a broad geographical region. The primary objective of this survey was to pinpoint priority areas requiring demolition and subsequent reconstruction. The damage classification criteria used in this survey are shown in Table 3. The survey results are accessible online but are presented

in an unstructured format, containing solely location and damage level information (MEUCC, 2023). It's important to mention that this dataset lacks specific details regarding the structural system, but more than 85% of the buildings within the affected areas are known to be reinforced concrete structures (Presidency of Strategy and Budget, 2023).

Table 3. Damage classification criteria of Ministry survey.

Damage Level	Description
None	No damage due to an earthquake. The building can be employed.
Light	Hairline cracks or spalling in the paint, plaster, and infill walls. The building can be employed.
Moderate	Wider cracks in infill walls and/or hairline cracks in structural members. Repair required.
Severe	Widespread shear cracks and/or failure in structural members. Irreparable.
Immediate demolition	Permanent displacement and/or partial or total collapse of structural members. Unsafe for entry. Personal belongings cannot be evacuated.
Collapse	Partial or complete collapse.

Following the data collection process, the authors developed a Python script to compile and categorize the Ministry survey results. Only the districts with a nearby (< 5 km) strong-motion recording station were included. This analysis encompassed results from more than 465,000 buildings, with over 90% of them undergoing assessment in 19 different districts. Table 4 provides a breakdown of the damage levels observed in the assessed building stock across these selected districts. The table also provides the percentages of buildings with severe damage, those requiring immediate demolition, and those that had collapsed, excluding the unassessed buildings. Notably, the combined percentage of buildings classified as severely damaged, requiring immediate demolition, and having collapsed within a specific district varies widely, ranging from 4% to 50%. Here, it is important to clarify that the locations with identical names in Table 2 and Table 4 (e.g., Antakya, Hatay) do not refer to the same geographical area. The Ministry survey, encompassing a larger area, assessed a greater number of buildings, while the ACI-133 survey covered a more limited number of buildings within a smaller area within each district. Figure 2a shows the selected districts from the Ministry survey and the corresponding damage frequencies.

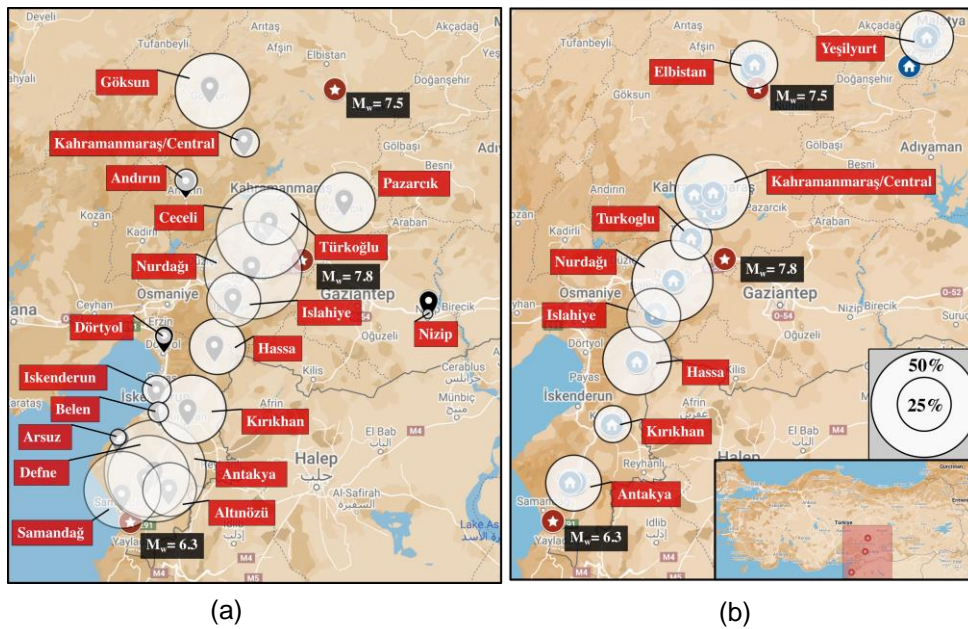


Figure 2. (a) Selected districts and damage frequencies for the Ministry survey, (b) Surveyed building locations and damage frequencies in each district for the ACI Survey

Table 4. Number of buildings with different damage levels in Ministry survey.

District, City	Damage Level							Total	S+ID+C-NA %
	N	L	M	S	ID	C	NA		
Hassa, Hatay	6439	3940	601	2608	554	1016	936	16094	28%
Nurdağı, Gaziantep	2308	2793	360	3169	609	1686	958	11883	50%
Kırıkhan, Hatay	5949	8490	992	5723	537	1615	932	24238	34%
Türkoğlu, Kahramanmaraş	6818	5745	452	3087	737	1117	1234	19190	28%
İskenderun, Hatay	13084	16098	1672	4274	320	466	2554	38468	14%
Belen, Hatay	6287	2176	256	684	70	132	500	10105	9%
Arsuz, Hatay	17715	8128	1068	1773	174	173	1720	30751	7%
Dörtyol, Hatay	15164	7184	954	1686	66	108	1215	26377	7%
Ceceli, Kahramanmaraş	150	109	0	162	2	37	12	472	44%
Defne, Hatay	4694	6594	1373	6958	756	810	924	22109	40%
İslahiye, Gaziantep	6157	5082	937	3011	521	1041	1577	18326	27%
Pazarcık, Kahramanmaraş	6370	5780	427	3982	640	1075	2350	20624	31%
Nizip, Gaziantep	15536	6915	855	839	90	85	4085	28405	4%
Andırın, Kahramanmaraş	8798	4112	520	1624	38	116	2513	17721	12%
Antakya, Hatay	9557	18151	3045	21323	3604	6246	3464	65390	50%
Samandağ, Hatay	7720	6912	1463	8548	548	658	1008	26857	38%
Göksun, Kahramanmaraş	4212	4152	652	4886	309	644	1980	16835	39%
Altınözü, Hatay	8997	5112	551	3778	622	820	978	20858	26%
Onikişubat, Kahramanmaraş	20082	17483	1589	5457	464	728	5310	51113	15%
TOTAL	166037	134956	17767	83572	10661	18573	34250	465816	
TOTAL (% , excluding NA)	38%	31%	4%	19%	2%	4%	8%		

(N: None, L: Light, M: Moderate, S: Severe, ID: Immediate demolition, C: Collapse, NA: Not assessed)

### 2.3 Strong-motion records

Acceleration records were obtained from the cited AFAD-TADAS database to compute ground motion intensity measures. A plausible correlation was investigated between the calculated ground motion intensities and the observed damage in both surveys. To determine the selected intensity measures, the maximum values were extracted from stations located within close proximity (< 5 km) to the surveyed areas. An exception was made for central Malatya, where none of the stations was capable of recording the seismic events. In this instance, the nearest reliable recording station, station 4406, situated 25 km away from the city center, was used to derive intensity measures for Malatya. For the areas that have more than one nearby station, the averages of maxima were used. Figure 1 shows the locations of the selected stations for both surveys.

For Göksun, Elbistan, and Malatya, the records from the Mw7.5 earthquake were employed since the associated intensity levels were higher in these areas relative to the Mw7.8 earthquake. For all other locations, the records from the Mw7.8 earthquake were used. In total, 14 stations were selected for the ACI survey, while 29 stations were chosen for the Ministry survey. The acceleration and velocity time histories for six records with relatively high intensities are presented in Figure 3. Additionally, Figure 4 displays the linear acceleration and displacement response spectra for 2% damping for the aforementioned stations. A summary of the selected stations and the calculated intensity measures is presented in Table 5.

## 3 Comparison

In this section, the selected intensity measures were compared against the observed damage frequencies in both surveys. It's important to emphasize that the number of assessed buildings, assessment methods, coverage areas, and damage classification criteria differ between the two surveys. Therefore, instead of expecting agreement between two data sets, the objective is to assess whether they exhibit the strongest relationship with the observed damage when considering the same intensity measure(s). Furthermore, it should also be noted that the buildings that were rated "Critical" were used to quantify the damage frequencies in the visited locations for the ACI-133 survey, while those that were rated "Severe", "Immediate Demolition", and "Collapse" were used for the Ministry survey.

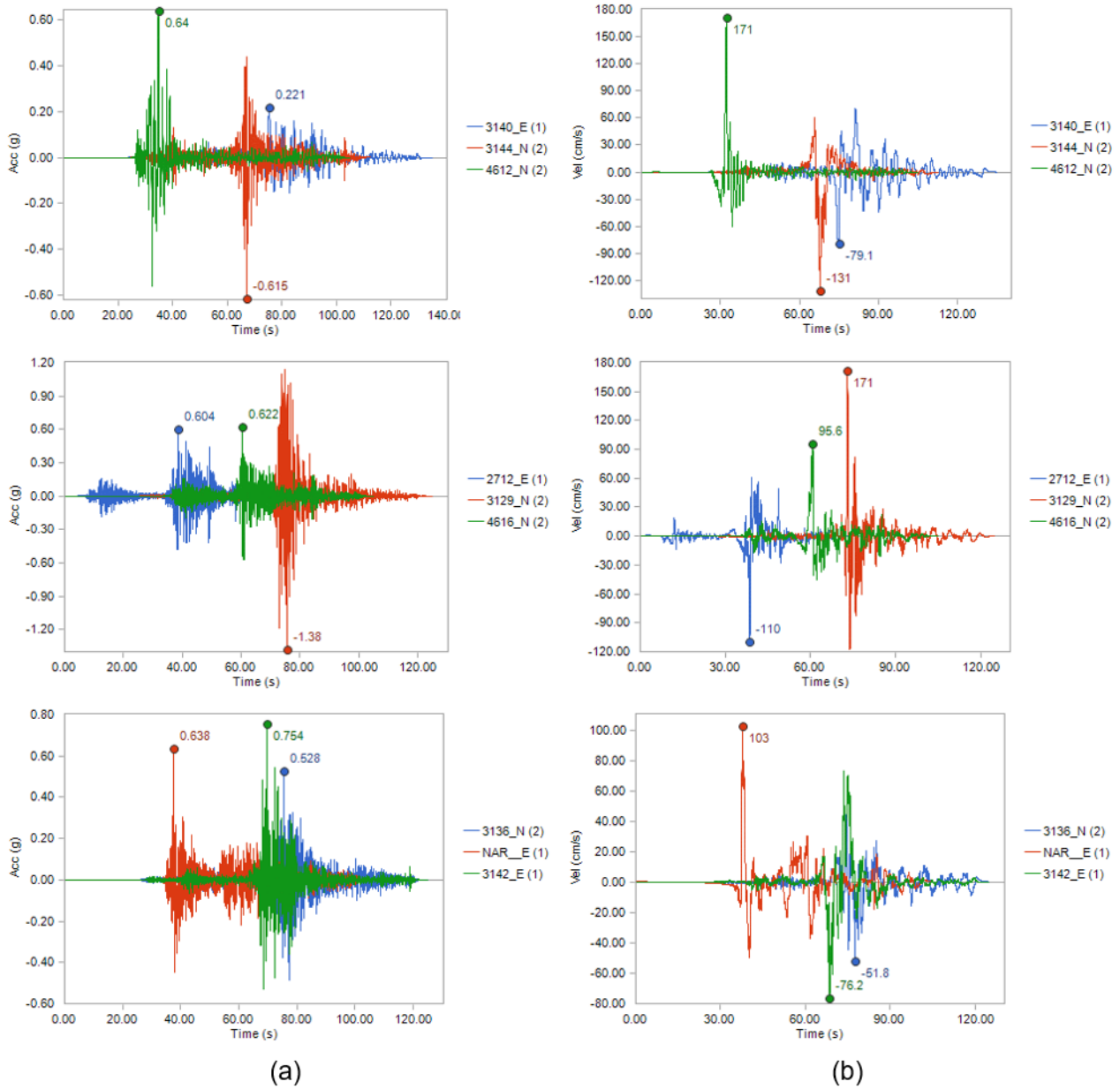


Figure 3. (a) Acceleration and (b) velocity time histories for some of the selected stations

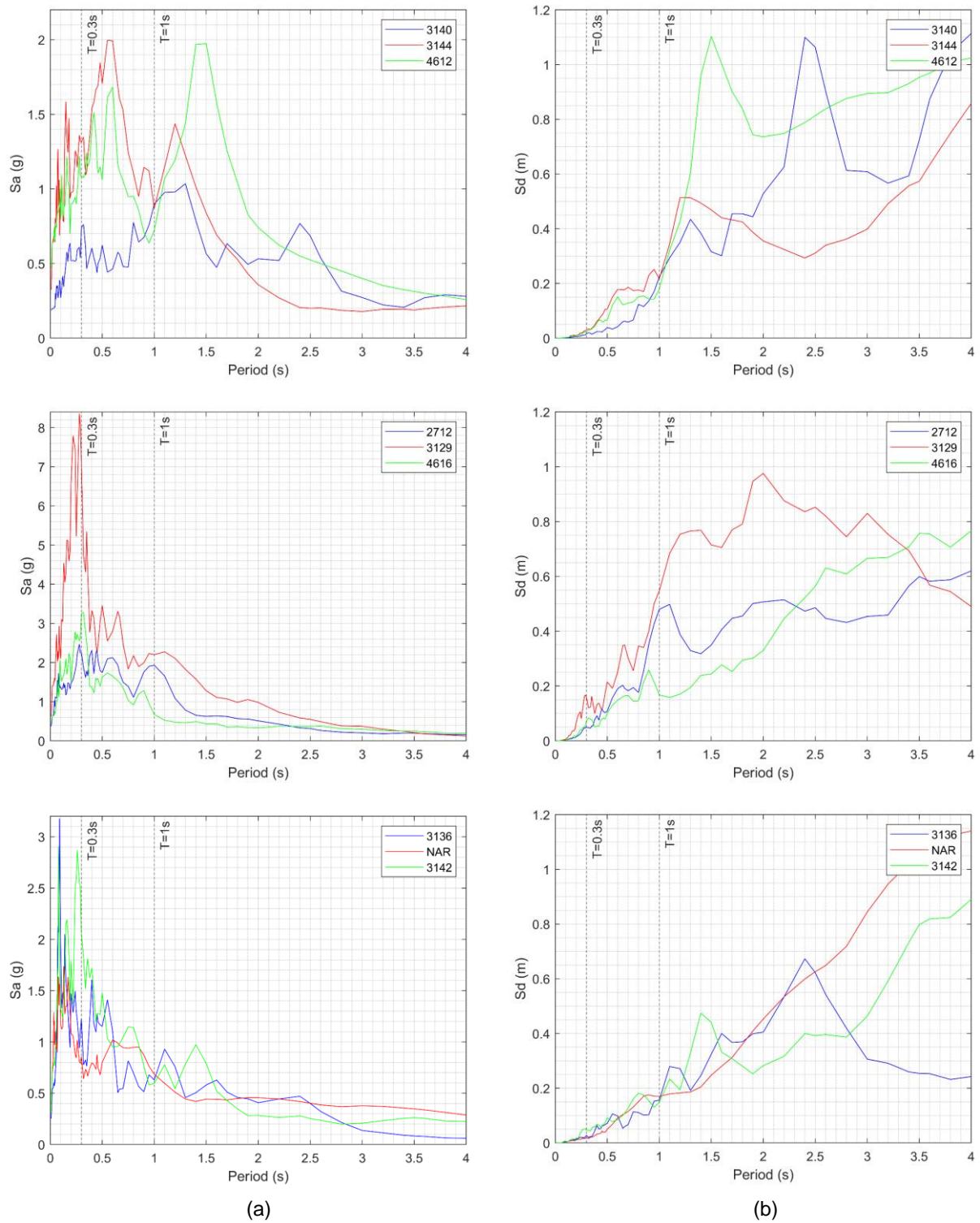


Figure 4. Linear (a) acceleration and (b) displacement response for 2% damping for some of the selected stations

Table 5. Selected stations and the calculated intensity measures for each survey

District, City	Damage Frequency	Stations	PGA [g]	PGV [m/s]	S <sub>d0.3</sub> [m]	S <sub>v0.3</sub> [m/s]	S <sub>a0.3</sub> [g]	S <sub>d1</sub> [m]	S <sub>v1</sub> [m/s]	S <sub>a1</sub> [g]
<b>Ministry Survey</b>										
Altınözü, Hatay	26%	3136	0.53	0.54	0.04	0.74	1.57	0.18	1.12	0.72
Andırın, Kahramanmaraş	12%	4613	0.16	0.15	0.01	0.19	0.40	0.03	0.16	0.10
Antakya, Hatay	50%	3123-3124-3131-3132	0.54	1.04	0.04	0.81	1.73	0.45	2.84	1.82
Arsuz, Hatay	7%	3135	1.34	0.65	0.07	1.37	2.93	0.21	1.31	0.84
Belen, Hatay	9%	3115-3146	0.38	0.51	0.03	0.59	1.27	0.13	0.79	0.50
Ceceli, Kahramanmaraş	44%	4616	0.68	0.96	0.07	1.54	3.29	0.19	1.22	0.78
Defne, Hatay	40%	3129	1.37	1.70	0.16	3.30	7.05	0.55	3.43	2.20
Dört Yol, Hatay	7%	3134	0.25	0.40	0.02	0.33	0.71	0.16	1.02	0.66
Göksun, Kahramanmaraş	39%	4612	0.64	1.71	0.02	0.51	1.09	0.18	1.13	0.72
Hassa, Hatay	28%	3137-3143-3144	0.65	1.12	0.04	0.85	1.82	0.23	1.41	0.91
İskenderun, Hatay	14%	3112-3116	0.13	0.28	0.01	0.16	0.34	0.09	0.54	0.34
İslihiye, Gaziantep	27%	2718	0.66	1.13	0.05	1.11	2.37	0.31	1.93	1.23
Kırıkhan, Hatay	34%	3139-3142-3145	0.73	1.20	0.05	1.07	2.28	0.31	1.92	1.23
Nizip, Gaziantep	4%	2704	0.17	0.13	0.01	0.18	0.39	0.07	0.45	0.29
Nurdağı, Gaziantep	50%	2712	0.60	1.09	0.05	1.03	2.21	0.48	3.01	1.93
Pazarcık, Kahramanmaraş	31%	4615-NAR	0.63	1.22	0.03	0.68	1.46	0.24	1.52	0.97
Samandağ, Hatay	38%	3140	0.22	0.79	0.02	0.35	0.74	0.22	1.40	0.90
Türkoğlu, Kahramanmaraş	28%	4616-4629-4632	0.46	0.56	0.04	0.87	1.85	0.16	1.02	0.65
<b>ACI-133 Survey</b>										
Antakya, Hatay	26%	3123-3125-3126	0.99	1.33	0.06	1.29	2.75	0.35	2.20	1.41
Elbistan, Kahramanmaraş	22%	4631	0.40	0.93	0.03	0.57	1.21	0.21	1.29	0.83
Hassa, Hatay	32%	3143-3144	0.59	1.29	0.04	0.75	1.60	0.23	1.45	0.93
Kahramanmaraş (central)	35%	4621-4624-4625	0.41	0.61	0.03	0.56	1.19	0.22	1.36	0.87
Kırıkhan, Hatay	17%	3142	0.75	0.86	0.05	1.07	2.29	0.19	1.21	0.77
Malatya (central)	25%	4406	0.45	0.35	0.02	0.46	0.98	0.14	0.86	0.55
Nurdağı, Gaziantep	38%	2712	0.60	1.09	0.05	1.03	2.21	0.48	3.01	1.93
Türkoğlu, Kahramanmaraş	19%	4616	0.68	0.96	0.07	1.54	3.29	0.19	1.22	0.78

Figure 5 shows the damage frequencies at selected locations for both surveys in relation to the selected intensity measures. Additionally, linear trendlines intercepting the origin were included, along with the  $R^2$  values for both data sets. While the spectral velocities and displacements were obtained by integrating the spectral accelerations, their correlations with the damage mirror those of the spectral accelerations. Nonetheless, they are presented here to provide an understanding of velocity and drift demands.

In Figure 5, it becomes evident that, for both surveys, PGV and spectral intensities at  $T = 1.0$  s demonstrate the strongest correlation with the observed damage. On the other hand, PGA and spectral intensities at  $T = 0.3$  s do not exhibit better correlations with the damage frequencies, and they display some outliers. Among the examined intensity measures, PGV has the advantage of simplicity and independence from the period. Moreover, it has been shown in the literature that PGV correlates well with drift demands, and consequently, with structural and nonstructural damage (Sozen, 2003; Westergaard, 1933). Additionally, PGV is known to show strong correlations with earthquake magnitude, effective duration, and frequency content of the ground motion (Akkar and Özen, 2005; Wald et al., 1999; Wu et al., 2003).

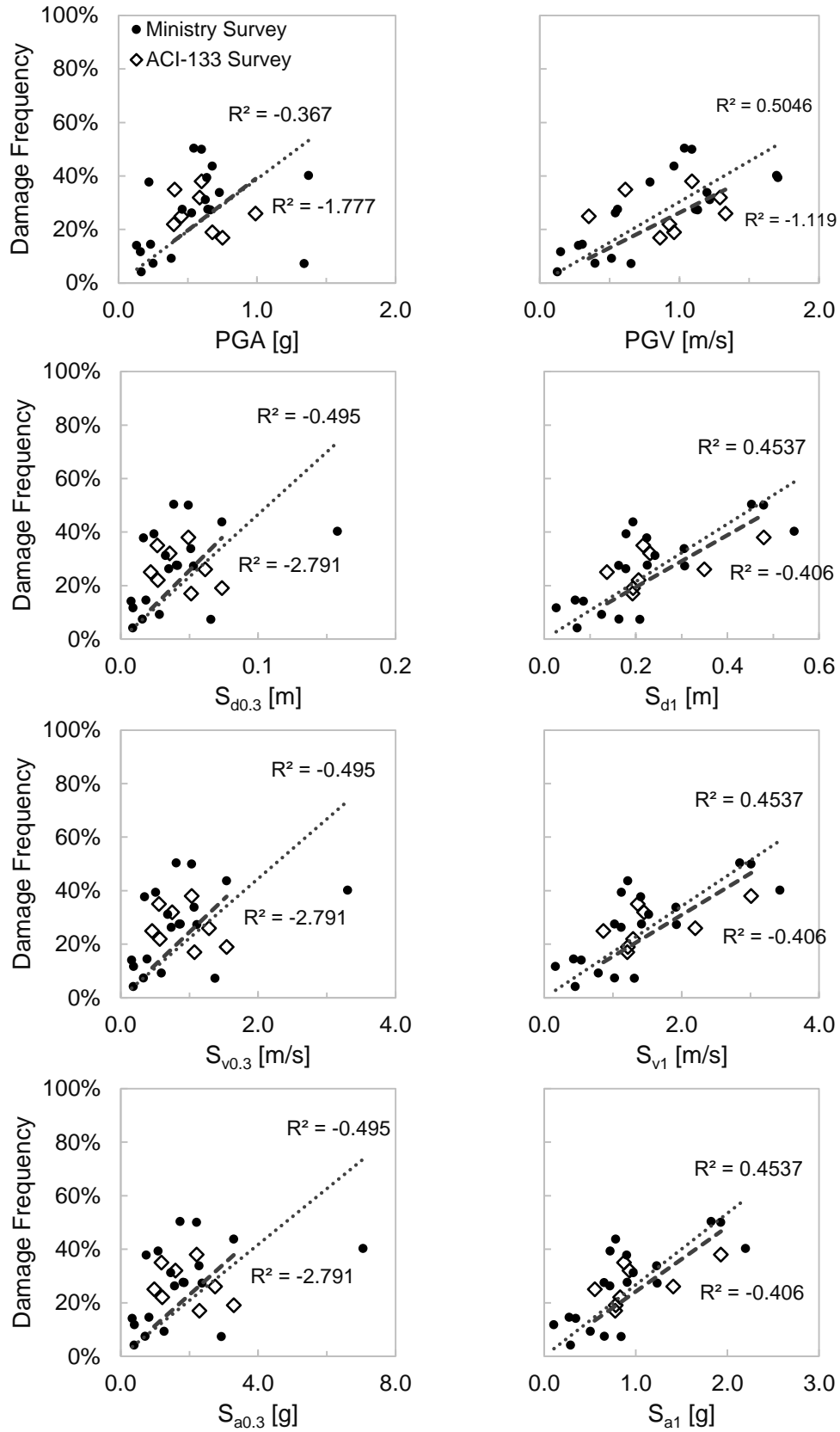


Figure 5. Comparison of the observed damage frequencies and intensity measures

## 4 Conclusions

This study aims to investigate the correlation between seismic intensity measures and damage resulting from the 2023 Türkiye earthquake sequence. Accelerograms recorded by ground motion stations located along and around fault ruptures were used to obtain intensity estimates. The selected intensity measures included PGA, PGV, and spectral displacements, velocities, and accelerations at periods of 0.3 and 1.0 seconds.

Two data sources were employed for damage assessment: the ACI-133 Survey and the Ministry Survey. The ACI-133 Survey involved comprehensive data collection from approximately 250 buildings in eight different locations, while the Ministry Survey conducted rapid visual screening over a broader region, covering more than 465,000 buildings.

A comparison of intensity measures against observed damage frequencies revealed that PGV and spectral intensities at  $T = 1.0$  s exhibited the strongest correlation with damage frequencies estimated through two independent surveys. In contrast, PGA and spectral intensities at  $T = 0.3$  s did not exhibit better correlations with damage frequencies. PGV, known for its simplicity and independence from the period, has consistently demonstrated strong correlations with drift demands, structural and nonstructural damage, earthquake magnitude, effective duration, and ground motion frequency content in prior research. This study's findings suggest that PGV is a robust intensity measure for assessing earthquake damage, offering valuable insights for future seismic risk mitigation strategies. These observations align with two previously published concepts:

- a) Drift demand in structures without damage can be expressed as a linear function of PGV,
- b) Seismic design ought to be focused on drift (and PGV) instead of force (and PGA).

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