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Evaluation of Parameters Affecting Earthquake Damage Using a GIS-based Random Forests Machine Learning Model: The Case of the 6 February 2023 Kahramanmaras Earthquakes in Türkiye

Deprem Hasarını Etkileyen Parametrelerin CBS tabanlı Rastgele Ormanlar Makine Öğrenmesi Modeli Kullanılarak Değerlendirilmesi: Türkiye'de 6 Şubat 2023 Kahramanmaraş Depremleri Örneği

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ABSTRACT
Türkiye is a geographical feature with intense seismic activity due to its tectonic features. Despite such a high earthquake risk, the evaluation of parameters affecting earthquake damage is still very inadequate in Türkiye. The aim of this study was to evaluate the parameters affecting earthquake damage in the 6 February 2023 Kahramanmaras earthquake, which caused the highest number of casualties in the history of the Republic of Türkiye. Therefore, data were produced to understand the differences in the behavior of structures in the case of an earthquake hazard in different parts of Türkiye. The study used sample data from 198,634 buildings with varying types of structural damage in residential areas where the earthquake had been felt. The relationship between these data and key factors causing structural damage was analyzed using a Geographic Information Systems (GIS)-based Random Forests (RF) Machine Learning (ML) model. As a result of this study, it was understood that the 6 February 2023 Kahramanmaras earthquakes caused structural damage as a result of different combinations of building age, local soil conditions, distance to fault lines, distance to the epicenter, ground slip velocity, maximum ground velocity, and soil liquefaction effect factors.
Keywords: Earthquake, Earthquake damage, GIS

ÖZ
Türkiye, tektonik özellikleri nedeniyle sismik aktivitenin yoğun olduğu bir coğrafyada yer almaktadır. Bu kadar yüksek deprem riskine rağmen, deprem hasarını etkileyen parametrelerin değerlendirilmesi Türkiye'de hala çok yetersizdir. Bu çalışmanın amacı, Türkiye Cumhuriyeti tarihinde en fazla can kaybına neden olan 6 Şubat 2023 Kahramanmaraş depremlerinde deprem hasarını etkileyen parametreleri değerlendirmektir. Bu nedenle, Türkiye'nin farklı bölgelerinde deprem tehlikesi durumunda yapıların davranışlarındaki farklılıkları anlamak için veri üretilmiştir. Çalışmada, depremin hissedildiği yerleşim bölgelerinde farklı yapısal hasar türlerine sahip 198.634 binadan alınan örnek veriler kullanılmıştır. Bu veriler ile yapısal hasara neden olan temel faktörler arasındaki ilişki Coğrafi Bilgi Sistemleri (CBS) tabanlı Rastgele Ormanlar (RO) Makine Öğrenimi (MÖ) modeli kullanılarak analiz edilmiştir. Çalışma sonucunda, 6 Şubat 2023 Kahramanmaraş depremlerinin bina yaşı, yerel zemin koşulları, fay hatlarına uzaklık, merkez üssüne uzaklık, zemin kayma hızı, maksimum zemin hızı ve zemin sıvılaşma etkisi faktörlerinin farklı kombinasyonları sonucunda yapısal hasara neden olduğu anlaşılmıştır.
Anahtar kelimeler: Deprem, Deprem hasarı, CBS

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1. INTRODUCTION

An earthquake is a catastrophic disaster that directly or indirectly causes the loss of life and property (Kassem and Mohamed Nazri, 2023; Bektaş and Kegyes-Brassai, 2023). This natural phenomenon, which affects human life more frequently with an increase in the world population, has been discussed for a long time, especially in developing countries, because it is one of the biggest obstacles to sustainable development (Mohammadi et al., 2023). Although the time of an earthquake cannot be predicted, the risk probabilities can be estimated (Sadeghi et al., 2023). For this purpose, various assessments have been conducted to determine the factors affecting earthquake damage to existing structures (Akbulut and Ayfer, 2005; Şengezer et al., 2008). Thus, significant efforts have been made to reduce seismic risk in specific regions and estimate the seismic resistance of regional structures (Li et al., 2023).

Studies for evaluating the parameters affecting earthquake damage have recently become an important area of research for deeply examining structures' seismic fragility and vulnerability and exploring their seismic capacity (Li, 2023; Kazemi et al., 2023). This is because such studies play an essential role in the earthquake preparedness of regions at earthquake risk by mitigating the impact of earthquakes, conducting disaster and emergency management activities, and planning for the prediction and mitigation of damage and loss (Çoban and Yerel Kandemir, 2023). In the last decade, Geographic Information Systems (GIS) based methods have been used in such studies to better analyze the complex relationships between structural damage and selected parameters (Coskun and Aldemir, 2023; Fischer et al., 2023). Thus, it has been revealed that the impact of past events and the probability of future risk status can be determined more accurately in the region to be assessed for the parameters affecting earthquake damage (Pourghasemi et al., 2023).

Türkiye is located in a geographical area where intense seismic activity is experienced due to its tectonic characteristics. Today, earthquakes in Türkiye are supported by scientific data (Gündüz et al., 2013). This reality is occasionally painfully remembered, with major earthquakes having serious material and moral consequences (Utkucu et al., 2023). However, despite the high earthquake risk in Türkiye, the studies for the evaluation of parameters affecting earthquake damage are quite insufficient (Akbulut and Ayfer, 2005; Şengezer et al., 2008). However, since disaster culture is not widespread in Türkiye, and there is not enough awareness among all segments of society about being prepared for disasters, it has been painfully experienced in the past that the loss of life and property as a result of earthquakes, especially in densely populated areas, is higher (Yılmaz, 2012; Özşahin and Kaymaz, 2013; Karasözen et al., 2023). Therefore, to prevent such losses in the future, it is important to assess the structural damage caused by earthquakes in a specific area and the factors that contribute to their occurrence (Li et al., 2023). In addition, it is recommended that such assessments should not be performed directly for each building, as it is not economically feasible, but rather in the form of regional studies (Aggarwal and Saha, 2023) and generally based on inferences from experienced earthquakes (Akbulut and Ayfer, 2005). Thus, useful results can be produced to reduce risks and minimize the losses caused by earthquakes (Taştan and Aydınoğlu, 2015).

The highest loss of life and worst damage in the history of Türkiye was experienced on 6 February 2023 with the Kahramanmaras earthquakes with an instrumental magnitude (Mw) of more than 7, both of which affected the same region on the same day (Çoban and Yerel Kandemir, 2023). In the immediate aftermath of these earthquakes, which left deep traces in the geography of Türkiye and the collective memory of Turkish society, assessment reports were prepared by both the national and international scientific communities (AFAD, 2023a, 2023b; SBB, 2023; DEU, 2023; ITU, 2023; METU DMAM, 2023; ESTU, 2023; GTU/MARTEST, 2023; Dinçer et al, 2023; U.S. Geological Survey, 2023a, 2023b) and different types of academic studies (Şen, 2023; Taftsoglou et al., 2023a; Abdelmeguid et al., 2023; Papazafeiropoulos and Plevris, 2023; Chadha, 2023; Mavrouli et al., 2023; Karabacak et al., 2023; Kurcer et al., 2023; Mai et al, 2023; Okuwaki et al, 2023; Stein et al, 2023; Melgar et al, 2023). However, although many topics on the general characteristics and effects of earthquakes have been addressed in these studies, an evaluation of parameters affecting earthquake damage is lacking. Therefore, filling this gap in the literature is important for a better understanding of the related earthquakes and their effects, which are called the catastrophes of the century.

This study aimed to evaluate parameters affecting earthquake damage during the Kahramanmaras earthquakes (6 February 2023). This study, which was carried out using sample data on structural damage, aimed to determine the causes and consequences of structural damage in the regions affected by the earthquakes. For this purpose, the spatial distribution of structural damage in the region affected by the earthquakes was determined according to the sample data, and the relationship between this distribution and factors causing structural damage was analyzed.

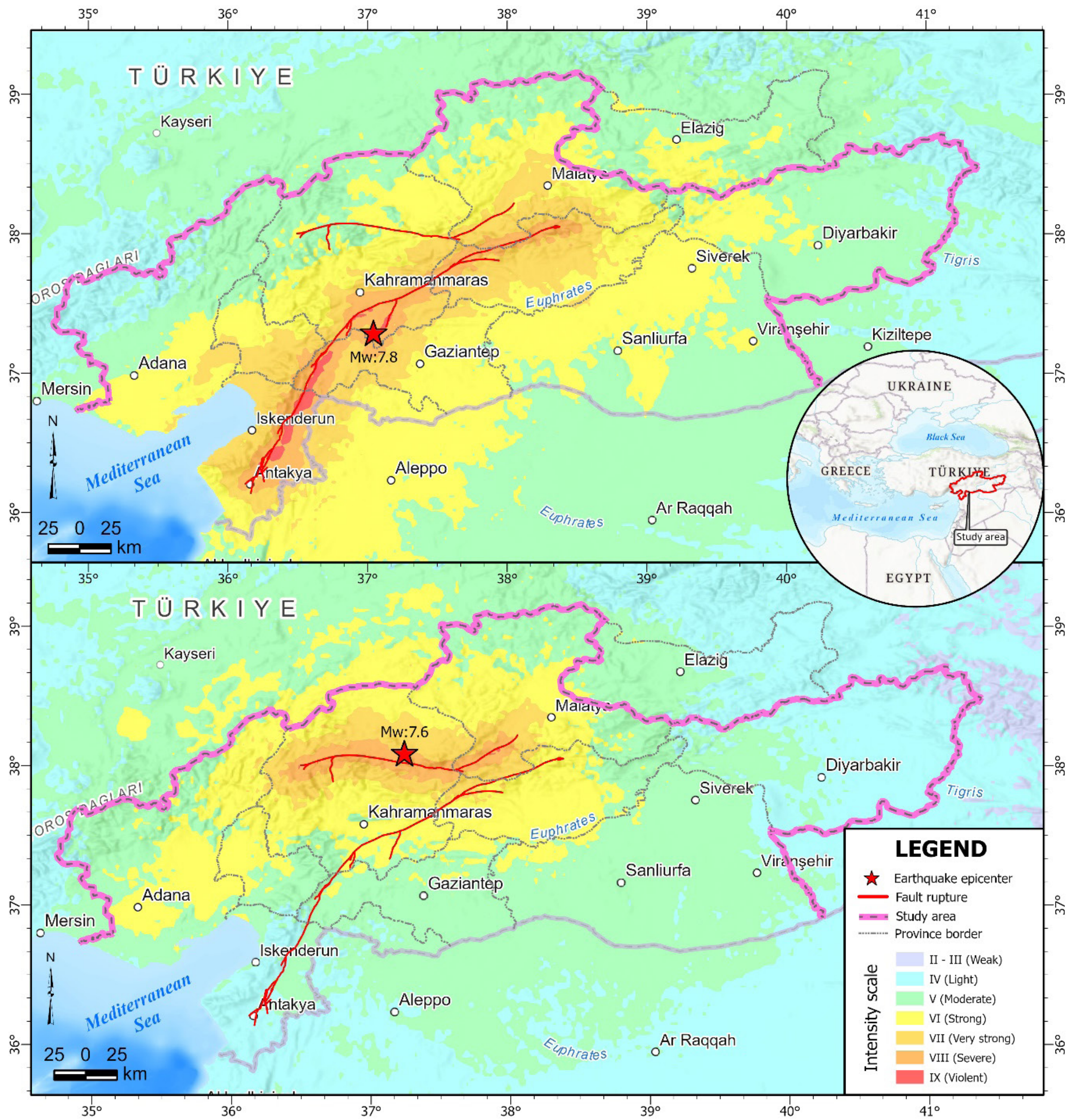

Figure 1. Location map of the study area. The maps show the intensity distributions of the Mw 7.8 (top) and Mw 7.6 (bottom) earthquakes. The red stars are the epicenters of the earthquakes. The red lines indicate rupture scars on the fault surface. Earthquake intensity and epicenter (Goldberg et al., 2023) and fault rupture (Reitman et al., 2023) data were obtained from relevant sources. The base map, accessible using ArcGIS Pro, was provided by ESRI (ESRI, 2023a).

Thus, important information was obtained to provide a better understanding of the earthquakes that have occurred and to provide information for predicting the effects of possible earthquakes on structural damage. In addition, data were also produced to understand the differences in the behavior of structures in different parts of Türkiye in the event of an earthquake.

2. METHOD

2.1. Study Area

The study area was the region affected by the February 6, 2023, Kahramanmaras earthquakes that occurred at 04:17 and 13:24 local time (Figure 1). After these two large earthquakes with instrumental magnitudes (Mw) of 7.8 (Pazarcık / First earthquake) and 7.6 (Elbistan / Second earthquake), numerous aftershocks of different magnitudes occurred in the region (AFAD, 2023a). The intensity of the earthquakes was calculated as MMI XI and MMI X near the epicenter, respectively (AFAD, 2023b; Figure 1). As a result of these earthquakes, which directly affected 11 provinces in different geographical regions of Türkiye, a state of emergency was declared in 10 provinces, and national mourning was declared for seven days (Maden, 2023). The cost of these earthquakes is estimated to be close to 10% of the gross domestic product (GDP), while the total cost to the Türkiye economy is estimated to be 70 billion dollars (Şen, 2023).

The study area is located at the collision boundary between the Arabian Plate and Eurasian Plate in the Eastern Mediterranean basin, one of the most active plate tectonic areas of the world (Sengör et al., 1985; Bozkurt, 2001; Şengör and Yazıcı, 2020; Lee et al., 2024). This tectonic boundary, which extends for approximately 700 km along the eastern edge of the Anatolian Plateau, corresponds to a large left-lateral strike-slip fault called the Eastern Anatolian Fault Zone (EAFZ) (Liu et al., 2023). The EAFZ has a complex geometry and is characterized by multiple fault segments with fault folds and tributaries with strike directions ranging from east-west to N 75° E (Zhang et al., 2023). The slip rate along the main segment of the EAFZ was estimated to range from 10 mm/y in the northeast to 4 mm/y in the southwest, a feature associated with frequent shallow seismicity in the uppermost ~20-25 km of the crust (Liu et al., 2023). As documented in historical records, the EAFZ has caused a series of devastating earthquakes in Turkey and northwestern Syria (Ambraseys and Jackson, 1998; Tan and Taymaz, 2006; Taymaz et al., 2021).

On February 6, 2023, a pair of earthquakes with magnitudes of Mw 7.8 and Mw 7.6 occurred in the EAFZ, approximately 9 hours apart. These two earthquakes occurred within the borders of the Kahramanmaraş Province; thus, they were named the Kahramanmaraş earthquake sequence (Görüm et al., 2023). This earthquake sequence was also the largest seismic event in Turkey since 1939 (Barbot et al., 2023). The main shock, which developed on a short and previously unmapped fault extending southward from the main branch of the EAFZ, caused ruptures of approximately 270 km ± 10 km (Karabacak et al., 2023), and the aftershock, which developed on the Sürgü Fault, caused ruptures of approximately 167 km ± 12 km (Kurcer et al., 2023). The maximum rupture velocity for the first earthquake was 3,2 km/s, while for the second earthquake, rupture velocities of 4,8 km/s were higher toward the west and 2,8 km/s were lower toward the east. In addition, the maximum displacements for this pair of earthquakes, which produce extremely complex rupture dynamics (Abdelmeguid et al, 2023; Mai et al, 2023; Okuwaki et

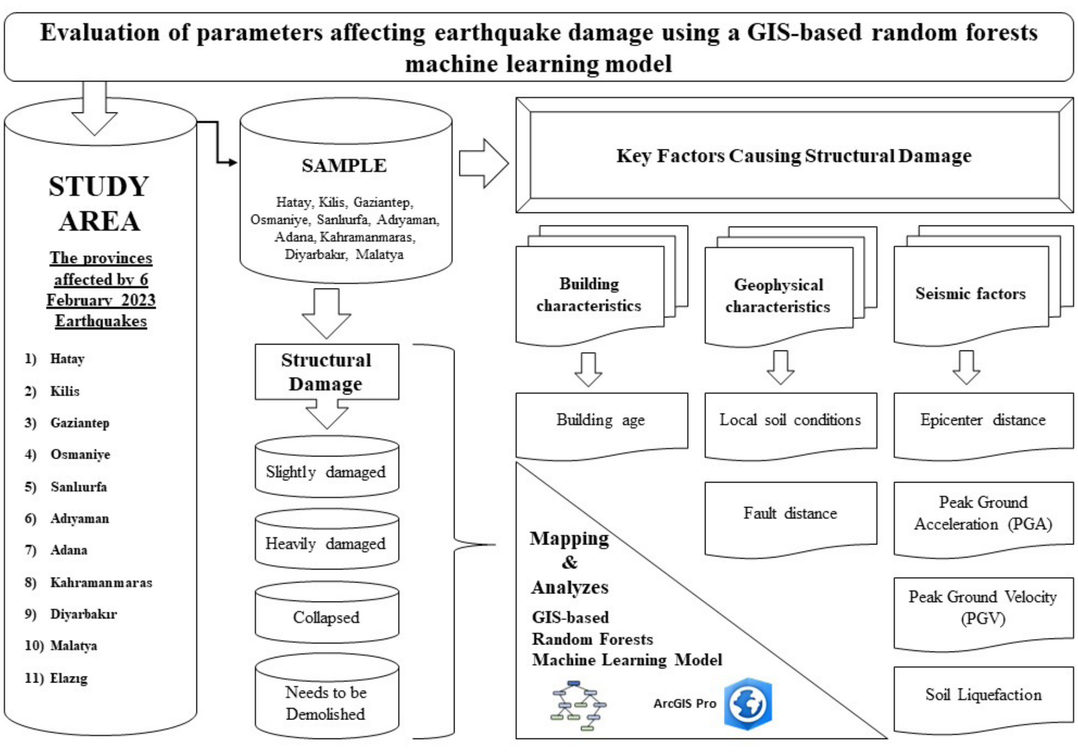

Figure 2. Flowchart of methodology.

al, 2023; Stein et al, 2023), were determined to be 8 and 6 m, respectively (Melgar et al, 2023).

2.2. Method

This study was carried out using sample data corresponding to 30% of the building stock in the entire study area. The sample size was determined by considering the basic approaches accepted in natural and earth sciences (Özel et al., 2022). In this context, the point data of 198.634 buildings with different levels of structural damage in the residential areas where the earthquake was felt, collected by a simple random sampling method and made available through one of the voluntary geographic information (VGI) platforms, were utilized. Geospatial and descriptive data collected by millions of participants about more than 500 million buildings worldwide through VGI platforms are widely used in scientific studies (Biljecki et al., 2023). Therefore, in this study, the sample data collected using the same method were used with permission. The sample data were collected by a corporate company (Gece Software) using Remote Sensing (RS) methods and visualized by the NGO Earth Drawers and Needs Map. The relevant data can also be viewed on a map developed by Mapbox, one of the VGI platforms (2023 Türkiye Earthquakes, 2023).

In the study area, sample data covering all settlements in all other provinces affected by the earthquake except Elazıg Province were associated with building age and local soil conditions according to structural damage categories. Thus, the impact of factors that directly affect the seismic performance of buildings was revealed (Sajan et al., 2023). Structural damage was categorized according to damage assessment results conducted by the Ministry of Environment, Urbanization, and Climate Change (MEUCC, 2023a). The categories are as follows: slightly damaged, heavily damaged, collapsed, and need to be demolished (Alptekin, 2020). The data organized by the purpose of the study were associated with key factors that cause structural damage in earthquakes. In this context, only the key factors for which data were available were evaluated (Figure 2). Other factors affecting earthquake damage (construction type and quality, number of stories, soft storey, short column problems, building geometry and direction etc.) were excluded due to insufficient information or the complexity of seismic, geological, site conditions, and structural features (Şengezer et al., 2008).

Building age was categorized as pre- and post-2000 due to the lack of sufficient data or because it is very difficult to determine the age of each building individually (GTU/MARTEST, 2023). The pre-2000 building age was determined using CORINE land cover data from 2000 (European Environment Agency Corine Land Cover, 2000). Buildings other than pre-2000 are considered post-2000 buildings. Other important parameters related to the seismic performance of buildings, such as the structural system, number of stories, structural material, etc., were excluded from the evaluation due to the large size of the region affected and the lack of reliable data.

Local soil conditions were categorized 1:500,000 geological maps of Türkiye (MTA, 2002). These conditions were evaluated by dividing them into five categories: (1) Quaternary, (2) Neogene, (3) Paleogene, (4) Mesozoic, and (5) Paleozoic/Precambrian formations because the effect of the former on earthquake damage is more significant. The fault distances were

Table 1. Data, produced data, and data sources used in the study

Data	Produced data	Data source
Map data were developed using Mapbox (Night Software & Plotters and Needs Map)	Sampling Data (1: Hatay, 2: Kilis, 3: Gaziantep, 4: Osmaniye, 5: Sanlıurfa, 6: Adıyaman, 7: Adana, 8: Kahramanmaras, 9: Diyarbakır, 10: Malatya)	2023 Turkey Earthquakes, 2023
Structural damage	(1) Slightly damaged, (2) Heavily damaged, (3) Collapsed, (4) Needs to be Demolished	MEUCC, 2023a
CORINE land use data (2000)	Building age (1: Pre-2000, 2: Post-2000)	European Environment Agency Corine Land Cover, 2000
Geological maps of Türkiye (Scale: 1:500,000)	Local soil conditions (1: Quaternary, 2: Neogene, 3: Paleogene, 4: Mesozoic and 5: Paleozoic/Precambrian)	MTA, 2002
Active Fault Map Series of Türkiye (Scale: 1:250,000)	Fault distance	Emre et al., 2013
6 February 2023 Pazarcık-Elbistan Kahramanmaras (Mw: 7.7 - Mw: 7.6) earthquakes	PGA Epicenter distance	AFAD, 2023c
Mw 7.8 - Pazarcık earthquake, Kahramanmaras earthquake sequence Mw 7.6: Elbistan earthquake, Kahramanmaras earthquake sequence	PGV Soil liquefaction	U.S. Geological Survey, 2023a; 2023b

obtained from the Active Fault Map Series of Türkiye (Scale: 1:250,000) sheets made available by the General Directorate of Mineral Research and Exploration (Emre et al., 2013). The fault and epicenter distances were determined using GIS-based near-analysis (ESRI, 2023b). Faults were evaluated only according to their distance from the main fault lines, and other fault parameters were not considered due to the large size of the affected region and the presence of many different fault features.

Peak ground acceleration (PGA) and epicenter distance were mapped using AFAD data (AFAD, 2023c). Peak ground velocity (PGV) and soil liquefaction were obtained from data available from the United States. Geological Survey (U.S. Geological Survey, 2023a, 2023b). However, the fact that the earthquakes in the study area occurred relatively recently and at similar magnitudes made it very difficult to determine which earthquake caused particular structural damage. Therefore, the PGA, epicenter distance, and PGV were separately considered for both earthquakes (Table 1). Soil liquefaction was estimated using the global geographic soil liquefaction model, which was used because it better shows spatial effects (Zhu et al., 2017).

The study data were processed using GIS-based approaches. First, the spatial data processed using GIS techniques were interpreted using various descriptive statistics in Microsoft Excel. In the next stage, the Random Forest (RF) technique, one of the most advanced Machine Learning (ML) methods, was used to analyze high-dimensional complex data (Hu and Szymczak, 2023). The RF algorithm has been used to evaluate parameters affecting earthquake damage and has been proven to achieve favorable results (Mangalathu et al., 2020). The RF algorithm was selected as the classifier to evaluate the importance of the seven factors affecting earthquake damage in the study area, and the Classification and Regression Tree (CART) algorithm was applied to classify the data. CART, a decision tree model, and a nonparametric data mining method are techniques used in supervised learning to solve classification and regression tasks (Jia et al., 2020). This technique has several advantages, including ease of processing numerical and categorical data and multiple output states (Jia et al., 2019). The RF model was applied using forest-based classification and regression tools in the ArcGIS Pro Spatial Analyst extension. According to the conducted tests, the number of trees was classified as 100. The model works by following the steps of finding the contributions of each attribute in each RF tree, averaging them, and comparing the contributions among the attributes (ESRI, 2023c). The contribution also indicates the importance of the factor (Jia et al., 2020). Thus, an algorithm with high accuracy and representativeness for the dataset (Breiman, 2001) was used to analyze the effects of parameters affecting earthquake damage in the study area. The analyses and thematic maps in this study were created using ArcGIS Pro (Version 3.0.1), a GIS software.

3. RESULTS

The most important impact of the Kahramanmaras earthquakes, which occurred in one of the most densely populated regions of Türkiye, was that they caused massive structural damage (Mavrouli et al., 2023). The earthquakes that occurred in the study area directly affected 2,618,697 buildings, depending on their intended use and province. As a result of damage assessment studies conducted on 1,712,182 buildings after the earthquake, it was determined that 35,355 had collapsed, 1,491 needed to be demolished, 179,786 were heavily damaged, and 431,421 were slightly damaged (SBB, 2023). When the sample data in the study were considered, it was understood that a total of 198,634 buildings were affected, depending on the purpose of use and province (Table 2).

Three key factors cause structural damage in an earthquake: building characteristics (building age), geophysical characteristics (local soil conditions, fault distance), and seismic factors (epicenter distance, PGA, PGV, soil liquefaction) (Peek-Asa et al., 2003; Yön et al., 2017). The earthquakes that affected the study area caused structural damage mainly due to these factors (ITU, 2023). Structural damage in the study area and an explanation of the relationship between these factors are important for an optimal earthquake vulnerability assessment. Thus, the effects of parameters affecting earthquake damage during the Kahramanmaras earthquakes can be better understood.

Table 2. Number of structurally damaged buildings in the study area

Structural Damage	Number of Buildings		Ratio difference (%)
	Study area (SBB, 2023)	Sample (This study)	
1	431,421	140,200	32
2	179,786	42,482	24
3	35,355	10,237	29
4	17,491	5,715	33
Mean			**30**

Building age is the most prominent characteristic affecting earthquake damage (Taştan and Aydınoğlu, 2015; Çoban and Yerel Kandemir, 2023). Building age, which reflects the design conditions and material quality of earthquake regulations and construction techniques in force at the time of construction, plays a decisive role in structural damage (Güler and Canbaz, 2017). In the study area, 53% of the total buildings were constructed pre-2000, and the remaining 47% were constructed post-2000; a significant portion of the pre-2000 buildings were demolished (MEUCC, 2023b). According to the sample data, 70% of the total buildings in the study area were constructed pre-2000 and 30% post-2000, and these buildings were subjected to various types of serious damage (Table 3). Therefore, structural damage in the study area was higher in pre-2000 buildings than in those constructed post-2000 (Table 3). Notably, pre-2000 buildings had problems caused by the use of plain (unribbed) reinforcement, soft/weak local soil characteristics, inappropriate adjacent construction techniques, poor concrete quality, and insufficient reinforcement (GTU/MARTEST, 2023).

Local soil conditions are among the most important geotechnical factors affecting earthquake damage (Özşahin and Eroğlu, 2019). These conditions, which reflect the bearing capacity of the soil on which the building foundation is built, significantly affect the increase or decrease in earthquake intensity (Şen, 2011). One of the leading causes of structural damage in earthquakes in the study area was the low bearing capacity of the local soil conditions on which the building foundations sit (ITU, 2023). In the study area, heavily damaged, collapsed, and needs to be demolished structures were concentrated in Quaternary formations, while slightly damaged structures were concentrated in other formations (Figure 3). The higher number of slightly damaged structures in the other formations must have been because the sample data did not show a homogeneous distribution according to soil type. Therefore, this result, which shows that structural damage is mostly experienced in Quaternary formations in the study area, is important in terms of revealing the relationship between soil properties and structural damage.

Table 3. Number of buildings built before and after 2000 in the study area

Province	Study area (SBB, 2023)		
	Number of Buildings (Total)	Number of Buildings (Pre-2000)	Number of Buildings (Post-2000)
1	351,029	200,749	150,280
2	245,205	132,590	112,615
3	307,841	176,966	130,875
4	37,501	15,531	21,970
5	144,452	77,176	67,276
6	119,307	58,396	60,911
7	430,827	291,459	139,368
8	172,581	96,231	76,350
9	222,463	101,099	121,364
10	381,746	130,963	250,783
Total	**2,412,952**	**1,281,160**	**1,131,792**
%	**100**	**53**	**47**
	Sample (This study)		
Province	**Number of Buildings (Total)**	**Number of Buildings (Pre-2000)**	**Number of Buildings (Post-2000)**
1	37,057	26,465	10,592
2	2,402	1,752	650
3	42,772	25,683	17,089
4	10,565	7,735	2,830
5	18,748	15,240	3,508
6	20,226	16,511	3,715
7	2,269	2,088	181
8	36,387	22,060	14,327
9	8,551	7,127	1,424
10	19,656	13,825	5,831
Total	**198,633**	**138,486**	**60,147**
%	**100**	**70**	**30**

In the study area, previous studies in different provinces have reported that local soil conditions consisting of Quaternary formations are the most vulnerable to structural damage in affecting earthquake damage (Korkmaz, 2006). Structural damage such as settlement, collapse, and collapse due to soil liquefaction may occur during earthquakes under local soil conditions consisting of Quaternary formations (Özşahin, 2010; Bulut Üstün et al., 2023) because the bearing capacity of Quaternary formations in the study area was suggested to be lower than that of other formations (Dinçer et al., 2023). For example, Hu et al. (2024) hypothesized that the energy released during the main shock may have been mainly influenced by topography and geomorphology, which rapidly weakened as it spread across the mountains and converged across the plain toward the valley zone, causing severe damage in Antakya. For this reason, in the study area, it has been reported that the high acceleration values observed during earthquakes cause more destruction in Quaternary formations than other formations due to the resonance effect (GTU/MARTEST, 2023).

Fault distance is another geophysical feature that affects earthquake damage (Özşahin and Eroğlu, 2019; Çoban and Yerel Kandemir, 2023). Active faults should be known and mapped to determine earthquake activity levels more safely and accurately (Yalçın et al., 2013). In this respect, structural damage may increase indirectly, if not directly, with increasing active fault distance (Sönmez, 2014). In the study area, based on the ground behavior estimates of earthquakes, ground motion was observed to weaken with distance from active faults (Abdelmeguid et al., 2023). Accordingly, it was found that heavily damaged buildings

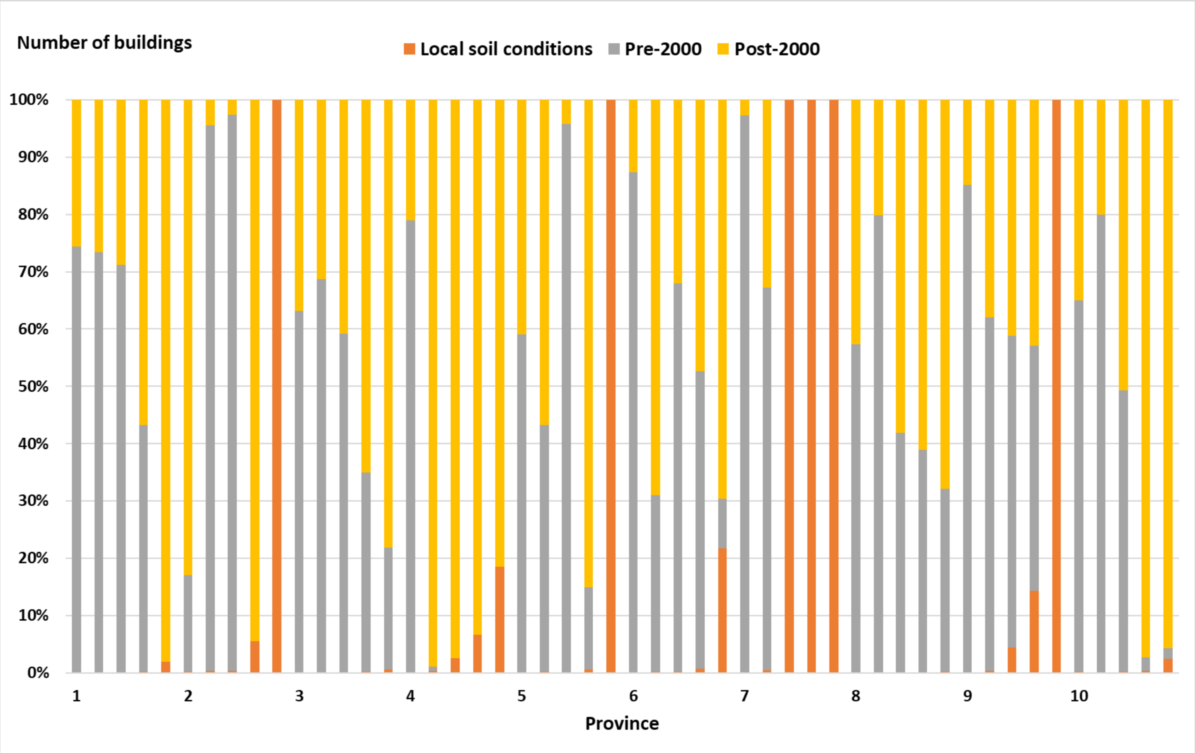

Figure 3. The effect of local soil conditions on structural damage according to building age in the study area (numbers referring to provinces in the study area start from the first column showing local soil conditions. Accordingly, although it varies by province, the number of pre-2000 buildings is higher in the study area. In addition, in some provinces, there are no building records of local soil conditions, so local soil conditions fill the entire column.

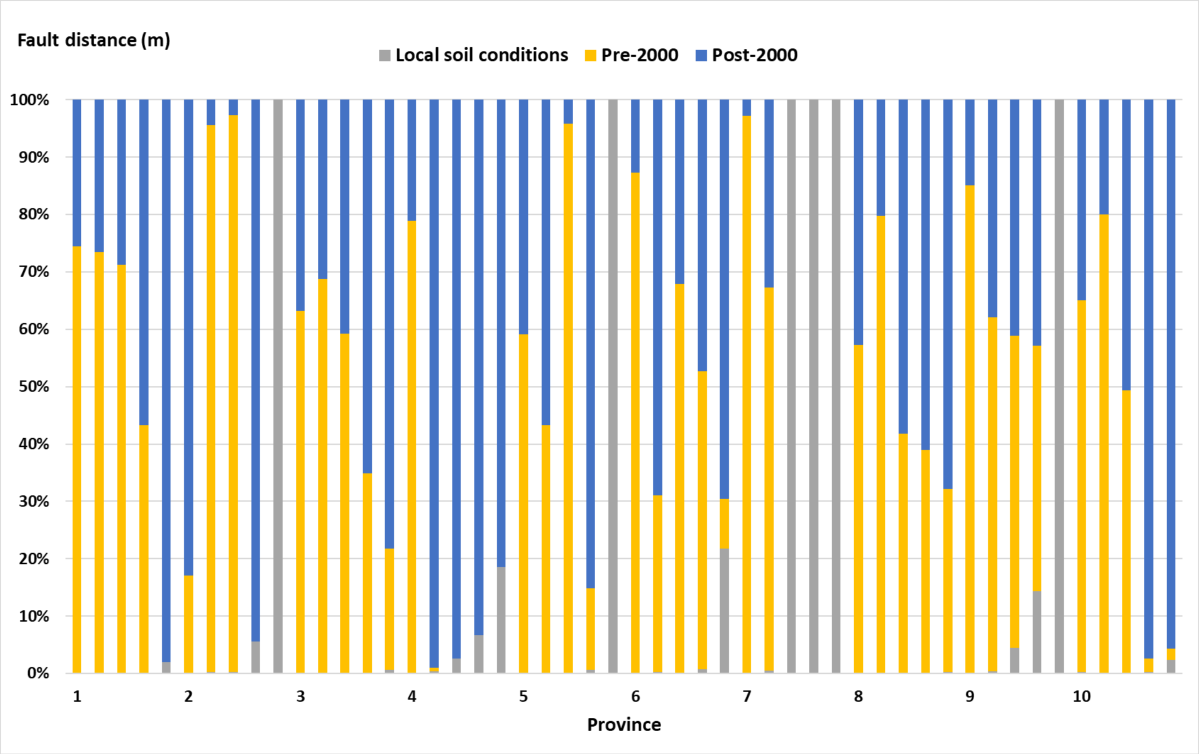

Figure 4. The effect of fault distance on structural damage according to building age in the study area (numbers referring to provinces in the study area start from the first column showing local soil conditions. According to this, the average distance to the fault in the study area varies significantly between provinces. In addition, in some provinces, there are no building records of local soil conditions, so local soil conditions fill the entire column.

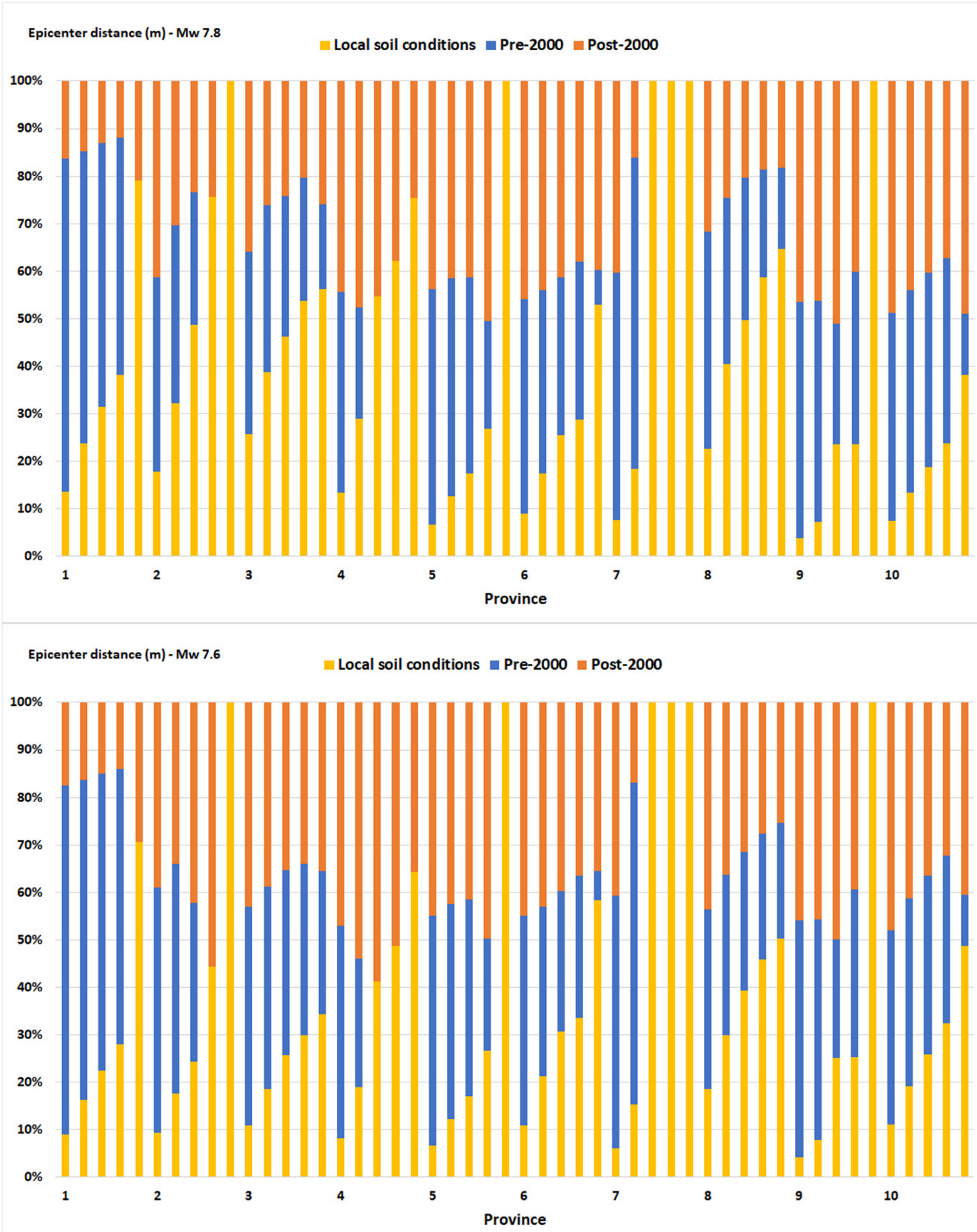

Figure 5. The effect of epicenter distance on structural damage according to building age in the study area (numbers referring to provinces in the study area start from the first column showing local soil conditions. For earthquake doublets, the average epicenter distance in the study area varied by province in terms of local soil conditions and building age. However, the graphic pattern of the earthquake doublet was very similar. In addition, in some provinces, there are no building records of local soil conditions, so local soil conditions fill the entire column.

were concentrated in provinces where the fault distance was smaller (GTU/MARTEST, 2023). On the other hand, it is also understood that fault distance had a more pronounced effect on pre-2000 buildings (Figure 4). It was also reported that proximity to the fault distance was one of the main reasons for greater damage in Hatay, Kahramanmaras, and Adıyaman compared to

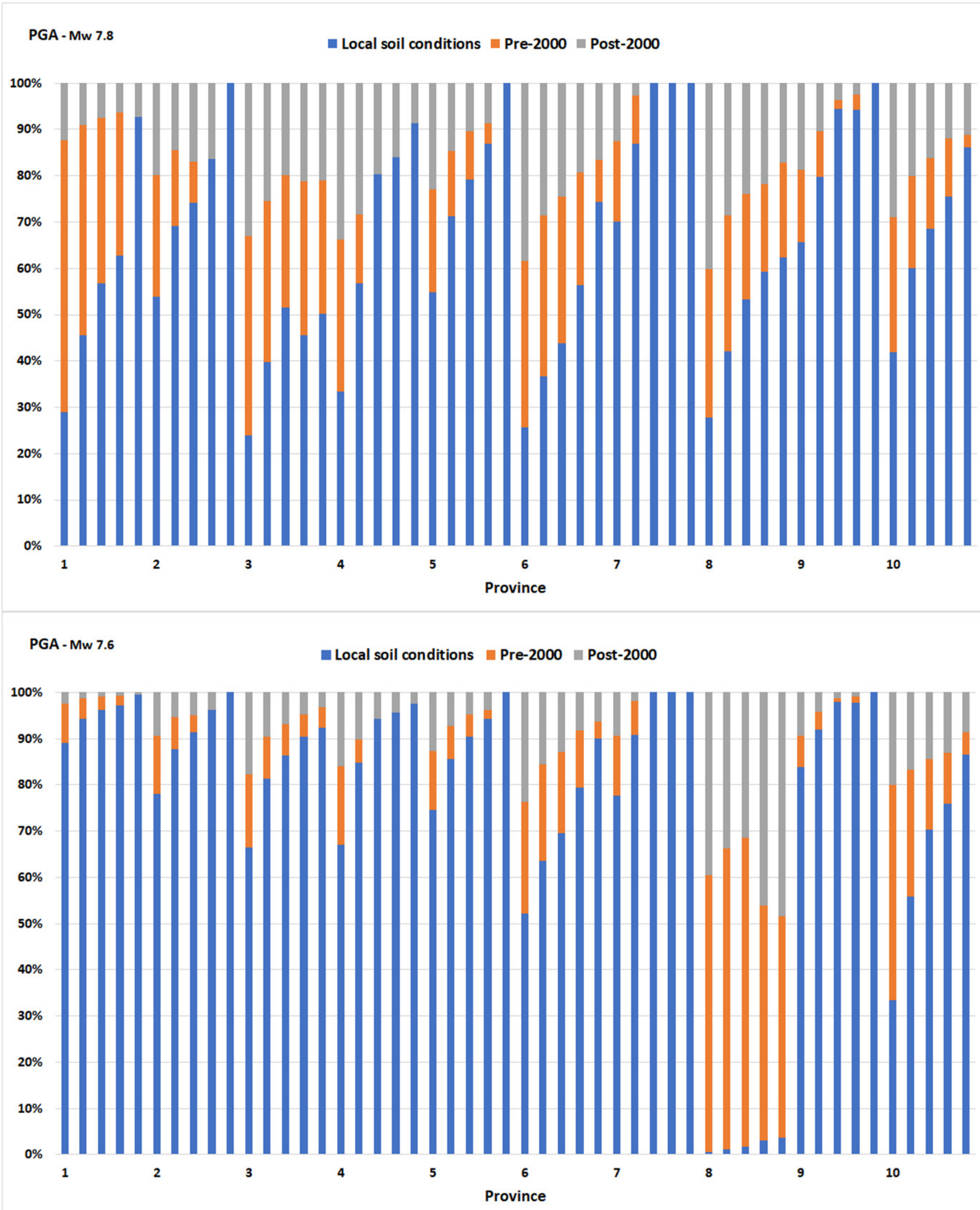

Figure 6. The effect of PGA on structural damage according to building age in the study area (numbers referring to provinces in the study area start from the first column showing local soil conditions. For earthquake doublets, the average PGA in the study area varied by province in terms of local soil conditions and building age. However, the graphic pattern of the earthquake doublet is less similar. In addition, in some provinces, there are no building records of local soil conditions, so local soil conditions fill the entire column.

Kilis, Adana, and Diyarbakır (METU DMAM, 2023). Indeed, it has been determined that earthquake damage in the Kahramanmaraş Province is higher in residential areas where active faults are dense and close (Bozdoğan, 2023).

The first earthquake feature that affects earthquake damage is the distance from the epicenter (Karalar and Çavuşli, 2020). Although it depends on many parameters, structural damage decreases as the epicenter distance increases under similar conditions (İnel et al., 2013). This is because the earthquake shaking intensity decreases as the earthquake moves away from the epicenter (Eyidoğan, 2022). In the study area, it was generally understood that building damage increased as epicenter distance decreased (Figure 5). The fact that two large earthquakes that occurred on the same day caused major destruction in Gaziantep, Kahramanmaras, Adıyaman, and Hatay played a critical role in the smaller epicenter distance (Şenol, 2023). Similarly, in the second earthquake, the shorter epicenter distance in Malatya caused higher levels of structural damage compared to Elazıg (METU DMAM, 2023). In addition, it is understood that there was a general increasing trend in building damage as the epicenter distance decreased in Quaternary formations and pre-2000 buildings in the study area.

PGA is the most widely accepted parameter for determining earthquake damage and reflects local soil conditions (Güllü, 2013). This factor indicates the extent to which the local soil conditions on which the foundation of a building is located affect the acceleration values of the earthquake (Selçuk and Aydın, 2012). In local soil conditions with lower PGA values, earthquake shaking increases, and structural damage increases (Uyanık, 2015). The highest acceleration in the study area was 2156,8 cm/sn² in the first earthquake and 691,1 cm/sn² in the second earthquake (AFAD, 2023c). The highest PGA was measured at Hatay in the first earthquake and at Kahramanmaras in the second earthquake (Figure 6). The highest PGA values were determined for Hatay in the first earthquake and Kahramanmaras in the second earthquake (METU DMAM, 2023). On the other hand, higher PGA values were detected in Hatay, Gaziantep, and Adıyaman in the first earthquake and in Kahramanmaras, Malatya, and Adıyaman in the second earthquake (Figure 6). It was noted that higher PGA values were generally more pronounced in Kahramanmaras, Gaziantep, Osmaniye, and Kilis in the first earthquake and Adıyaman, Malatya, and Kayseri in the second earthquake (METU DMAM, 2023). In addition, PGA values were found to be relatively higher in Quaternary formations and pre-2000 buildings in both earthquakes (Figure 6).

The ground motion parameter PGV has a very high correlation with determining the structural damage rates caused by the earthquake (Çalım et al., 2019). This parameter, which is defined as the rate of progression of earthquake shaking in the earth's crust due to local ground conditions, has a parallel relationship with structural damage. As the PGV increases, structural damage also increases (Tokgöz and Bayraktar, 2015). In the study area, the average PGV was 5134,20 cm/s in the first earthquake and 1782,25 cm/s in the second earthquake (Figure 7). In the study area, the highest PGV was recorded at Hatay (1091,87 cm/s) in the first earthquake and at Kahramanmaras (335,14 cm/s) in the second earthquake (Figure 7).

In the study area, higher PGV values were found in Gaziantep, Adıyaman, and Kahramanmaras in the first earthquake and Malatya, Adıyaman, and Osmaniye in the second earthquake (Figure 7). The PGV changed in the study area at short distances and rapidly increased the intensity of the ground shaking and the energy dissipated. Thus, it increases the magnitude of structural damage (Abdelmeguid et al., 2023). Therefore, we understood that the spatial distribution of PGV in the earthquakes in the study area was consistent with the PGA. Additionally, it was noted that the distribution of PGV values in the study area was more homogeneous than the PGA distribution (METU DMAM, 2023).

Soil liquefaction is one of the most important factors in the evaluation of parameters affecting earthquake damage (Rashidian and Baise, 2020). This phenomenon, in which the ground loses its strength and behaves like a liquid, occurs as a result of the additional water pressure created by earthquake waves, especially when passing through water-saturated layers, disrupting the granular structure of the ground (Alpaslan, 2013). In the study area, soil liquefaction followed faults along meandering sections of river valleys, coastal plains, drained lakes, swamps, and lacustrine basins (Taftsoglou et al., 2023a). Therefore, it was determined that soil liquefaction in the study area was more common in Quaternary formations than in other formations (Taftsoglou et al., 2023b; Figure 8). The Quaternary formations in the study area, which are currently seismically active, have been reported to increase soil liquefaction due to high groundwater levels (Cabalar et al., 2019). In addition, it was noted that structural damage was concentrated in certain areas because Quaternary formations are not appropriate for building construction (GTU/MARTEST, 2023).

The greatest effect of soil liquefaction in the study area was found in Hatay (Figure 8). According to the soil liquefaction

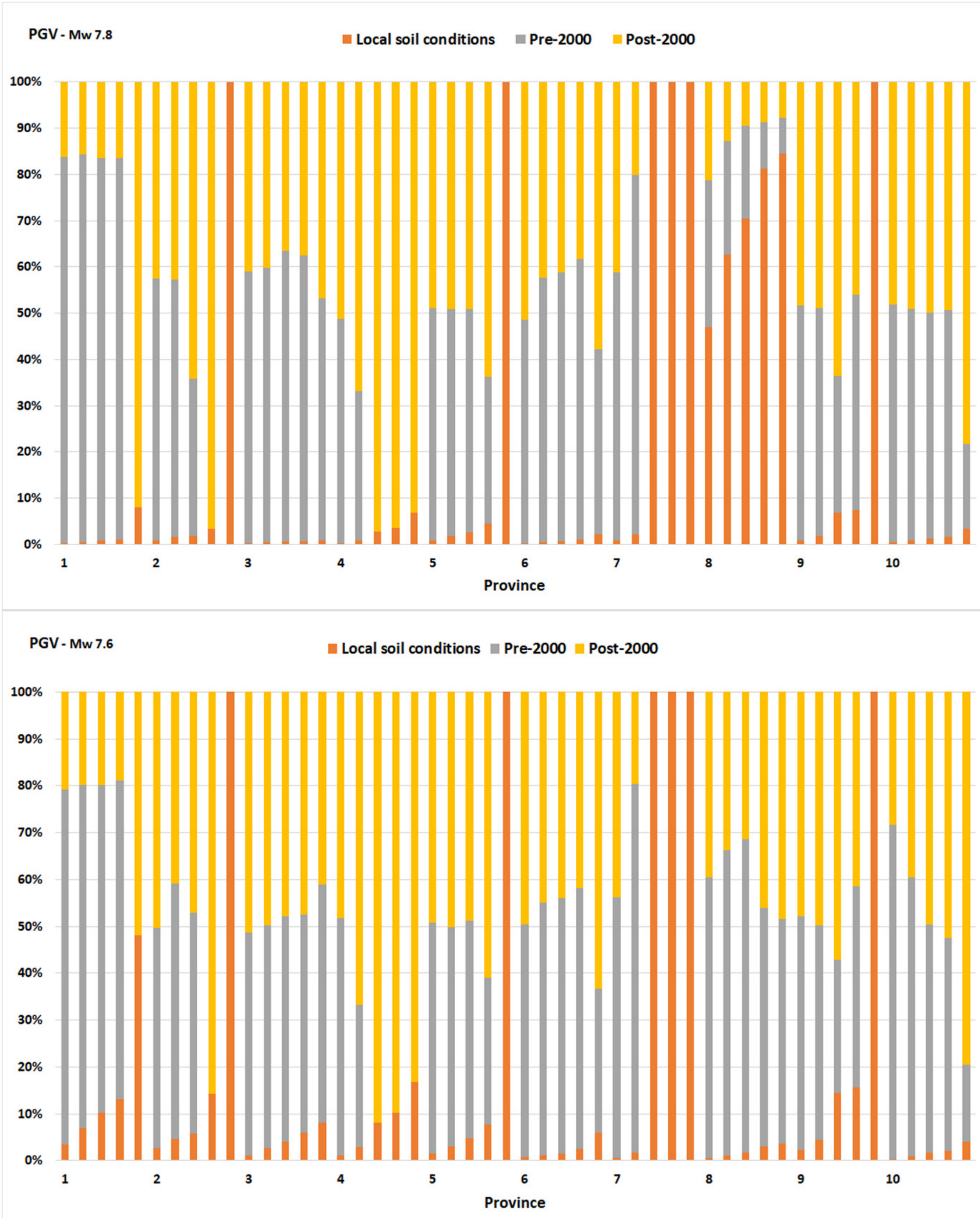

Figure 7. The effect of PGV on structural damage according to building age in the study area (numbers referring to provinces in the study area start from the first column showing local soil conditions. For earthquake doublets, the average PGV in the study area varied by province in terms of local soil conditions and building age. However, the graphic pattern of the earthquake doublet was very similar. In addition, in some provinces, there are no building records of local soil conditions, so local soil conditions fill the entire column.

locations determined from field studies and RS data, the most intense soil liquefaction was observed in Hatay, particularly in the areas around the Amik Plain (Bulut Üstün et al., 2023) and the Asi River (Yıldız, 2023). Furthermore, it was also emphasized that structural damage increased when soil liquefaction was observed in the province (ITU, 2023). In the study area,

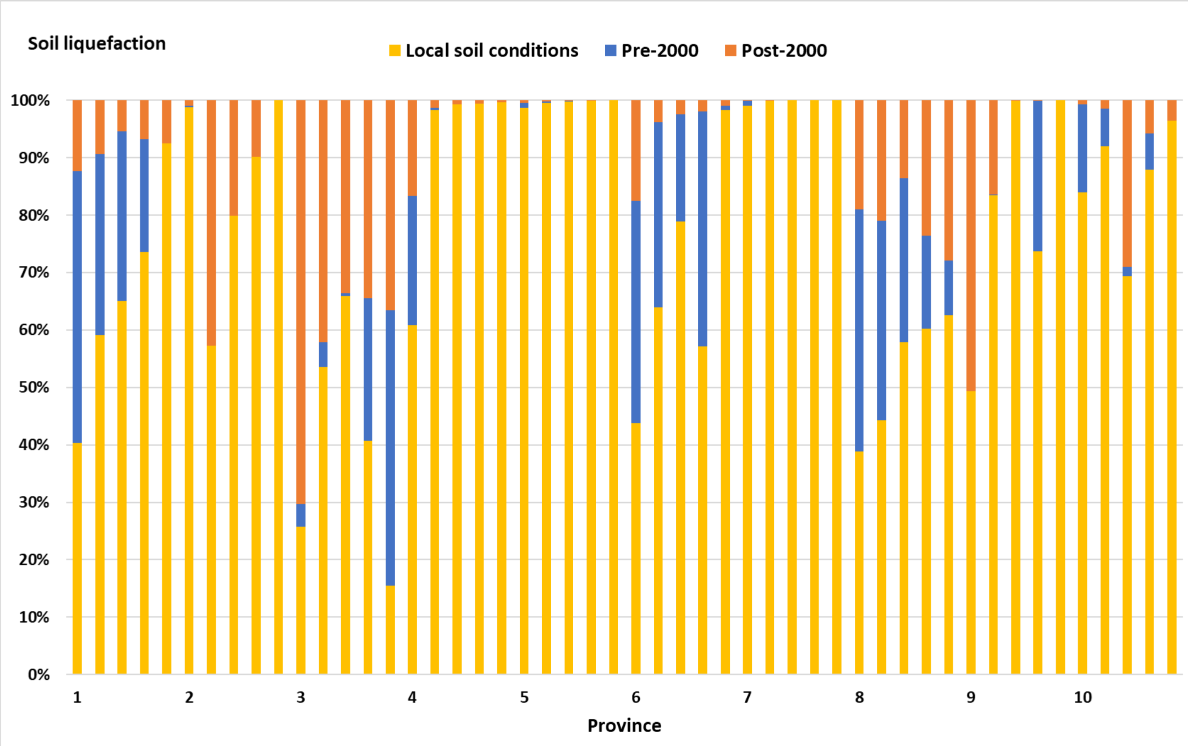

Figure 8. The effect of soil liquefaction on structural damage according to building age in the study area (numbers referring to provinces in the study area start from the first column showing local soil conditions. Accordingly, although average soil liquefaction in the study area varied by province, local soil conditions were more dominant than building age. In addition, in some provinces, there are no building records of local soil conditions, so local soil conditions fill the entire column.

Gaziantep, Kahramanmaras, Malatya, Adıyaman, and Osmaniye correspond to areas where soil liquefaction is intensively observed (Figure 8). In these provinces, structural damage, such as lateral spreading and collapse, has occurred due to soil liquefaction (METU DMAM, 2023).

As the result of the evaluation of the relationship between the structural damage in the study area and the factors causing this damage with RF, it was determined that the main causative factors of structural damage were PGA, PGV, epicenter distance, and soil liquefaction (Table 4; Figure 9). In this context, PGV and PGA for the second earthquake, PGA and PGV for the second earthquake, epicenter distance, and soil liquefaction were found to have significance levels above 10% (Table 4).

Table 4. Importance of factors affecting structural damage in the study area (%)

No	Factor (Variable)	Importance (%)
1	PGV (Mw 7.6)	17,186
2	PGA (Mw 7.6)	16,737
3	PGA (Mw 7.8)	14,405
4	PGV (Mw 7.8)	13,517
5	Epicenter distance (Mw 7.8)	11,395
6	Epicenter distance (Mw 7.6)	10,273
7	Soil liquefaction	10,196
8	Fault distance	6,137
9	Building age	0,082
10	Local soil conditions	0,071

Correlations between structural damage and the factors causing this damage in the study area were analyzed, and a correlation heat map was created (Figure 10). Correlations clearly show the relationships between structural damage and the factors leading to it. According to the correlations, there was a strong positive correlation between PGA and PGV for the earthquake pairs and a strong negative correlation between the epicenter distance and PGA and PGV (Figure 10). There is a moderate correlation between Province and PGA (Elbistan) and PGV (Elbistan) and between Fault distance and PGA (Pazarcık) and PGV (Pazarcık). Building age was weakly correlated with most variables, whereas structural damage, soil liquefaction, and local soil conditions were generally weakly correlated with other variables (Figure 10).

4. DISCUSSION

In the study area, the spectral acceleration values of the earthquakes were found to be greater than the building design values specified by the Turkish Earthquake Code (GTU/

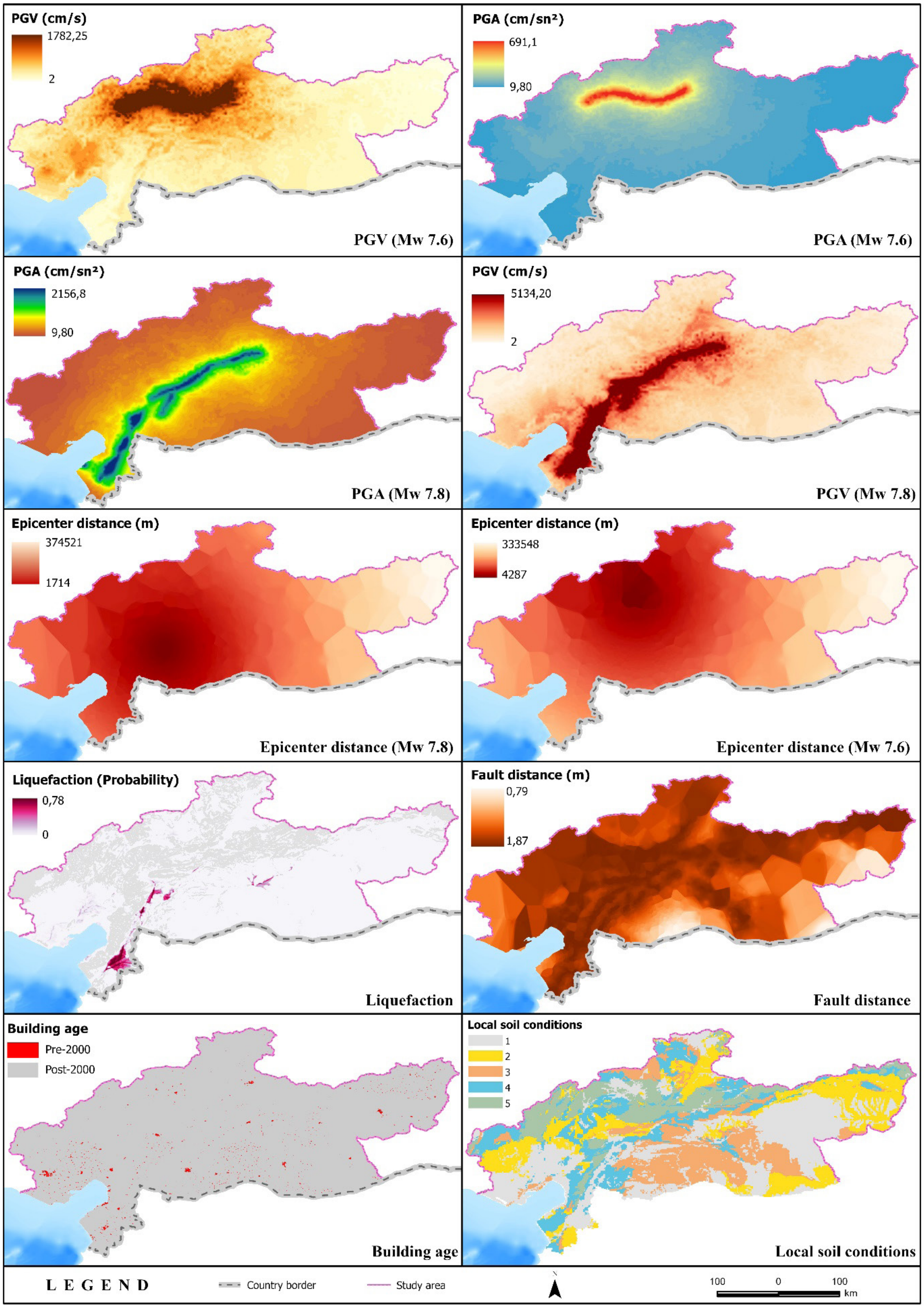

Figure 9. Map of factors affecting structural damage in the study area. The maps were categorized according to the importance of the factors that caused structural damage in the study area. Epicenter distance, PGA (AFAD, 2023c), PGV, and soil liquefaction (U.S. Geological Survey, 2023a; 2023b), Fault distance (Emre et al., 2013), burial age (European Environment Agency Corine Land Cover, 2000), and local soil conditions (MTA, 2002) were obtained from relevant sources. All the data were processed using GIS techniques and mapped for the study.

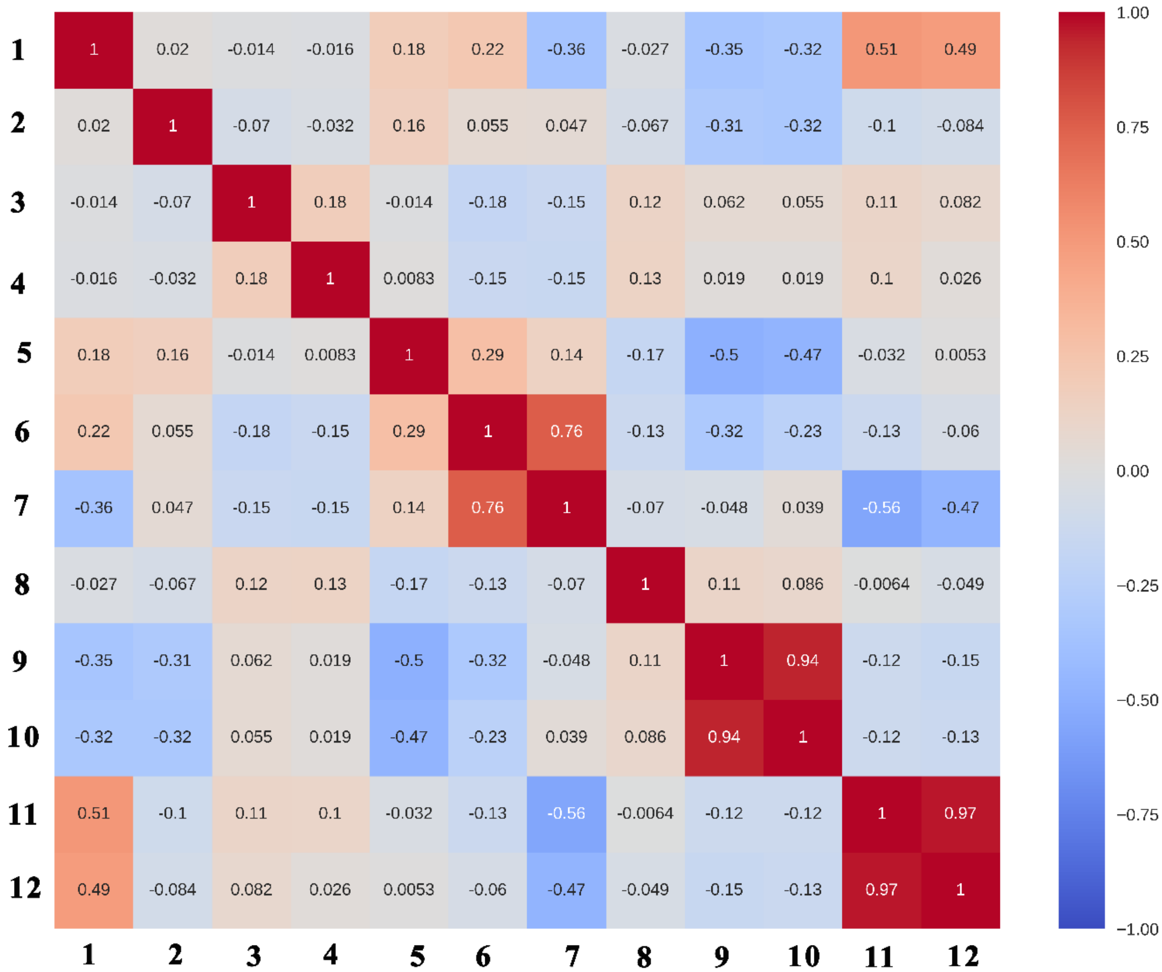

Figure 10. Correlation matrix for factors triggering the occurrence of structural damage (1: Province, 2: Structural damage, 3: Building age, 4: Local soil conditions, 5: Fault distance, 6: Epicenter distance (Mw 7.8), 7: Epicenter distance (Mw 7.6), 8: Soil liquefaction, 9: PGA (Mw 7.8), 10: PGV (Mw 7.8), 11: PGA (Mw 7.6), and 12: PGV (Mw 7.6))

MARTEST, 2023). For this reason, when combined with other seismic components, PGV and PGA were found to be the primary factors contributing to the occurrence of structural damage in the study area (Papazafeiropoulos and Plevris, 2023). Indeed, structural damage was noted to increase significantly as the buildings in the study area experienced earthquakes stronger than the design level (Qu et al., 2023).

In the study area, the earthquakes were shallow in depth and of large magnitude, resulting in strong tremors that caused structural damage (Chadha, 2023). In this respect, the epicenter distance had a great impact on structural damage, although its importance varied according to the earthquake. However, the epicenter distance was more distinct in the first earthquake than in the second. In addition, in buildings that suffered structural damage at the level of heavily damaged buildings or that needed to be demolished due to the first earthquake, the damage and demolition increased even more with the effect of the second earthquake (Mai et al., 2023).

Soil liquefaction caused by earthquakes in the study area caused significant structural damage. Because of earthquakes in the study area, it has been stated that structural damage occurring many kilometers away from the epicenter of the earthquake was mainly caused by soil liquefaction (Chadha, 2023). Furthermore, the Quaternary formations and buildings constructed pre-2000 in the study area were noted to be vulnerable to the effects of soil liquefaction because they were exposed to excessive ground motion (Carrera-Cevallos and Carrera-Cevallos, 2023).

In the study area, fault distance, building age, and local soil conditions were factors affecting structural damage, with a significance level below 10% (Table 4). In the study area, the combination of the first earthquake and second earthquake events resulting from the stress change caused by its main shock led to an increase in stress in many fault zones (Karabulut et al., 2023). Consequently, this situation triggered an increase in structural damage in the study area due to the decrease in fault distance (GTU/MARTEST, 2023). On the other hand, building age and local soil conditions in the study area also played decisive roles in structural behavior and damage (METU DMAM, 2023). Mertol et al. (2023) Since the 6 February 2023 Kahramanmaras earthquakes caused more damage to buildings built pre-2000 and with less fault distance, it is strongly recommended that the structural performance inspection of all buildings of this type in the earthquake zone be completed. Further, these are important factors that affect the amplitude parameters and response spectra of earthquakes (GTU/MARTEST, 2023).

Correlations between structural damage in the study area and factors causing this damage reflect the complex nature of earthquake effects and structural damage. This result also shows that structural damage is not caused by a single factor but is the result of the interaction of many factors. Therefore, the results of this analysis can be used in earthquake risk assessment and structural design.

5. CONCLUSION

This study, which evaluated the parameters affecting structural damage of the 6 February 2023 Kahramanmaras earthquakes, showed that the structural damage in the study area was the result of the combined effects of building age, local soil conditions, fault distance, epicenter distance, PGA, PGV, and soil liquefaction factors at different rates. However, the results of this study show that the most important factor affecting the occurrence of structural damage in the study area was the PGV of the first earthquake, and the least important factor was local soil conditions. In addition, although this study showed that not enough lessons had been learned from previous earthquakes, it indicated that we should be more prepared for future earthquakes. Therefore, this study has produced results that can be used effectively to understand the effects of the 6 February 2023 Kahramanmaras earthquakes more accurately and reduce damage caused by future earthquakes. The main measures that can be taken in this regard are summarized as follows:

1. After damage assessment studies in the study area are completed, studies for the evaluation of the parameters affecting earthquake damage characterizing the whole region affected by the 6 February 2023 Kahramanmaras earthquakes should be repeated.

2. The spectral acceleration values for building design under the Turkish Earthquake Directive should be updated.

3. According to the evaluation of the parameters affecting earthquake damage, large-scale earthquake susceptibility maps should be prepared for Türkiye using GIS-based techniques. These maps should be prepared at the province and district levels to facilitate the planning phase.

Consequently, even if we do not know where and when earthquakes will occur or even if we cannot prevent them, we can be protected from their effects by taking the necessary precautions and making accurate predictions in light of scientific data.

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