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RESEARCH ARTICLE

Seismic damage assessment based on site observation following the Düzce (Gölyaka) earthquake (M_w = 5.9, November 23, 2022)

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Abstract

On November 23, 2022, at 04:08 local time, the Gölyaka district of Düzce, which is located in the west of the Black Sea Region of Turkey, struck an earthquake with a magnitude of M_w = 5.9. A total of 181 reinforced and masonry buildings were severely damaged due to the earthquake and it is reported that need to be demolished urgently throughout the province of Düzce. In this study, the seismological characteristics and recorded ground motion accelerograms of the earthquake are evaluated. The case studies of damaged reinforced concrete and masonry buildings because of the earthquake are also investigated. The factors that cause the buildings to be damaged during the earthquake are evaluated based on site observations.

1. Introduction

Turkey is a country located in the seismically active zone known as the Alpine-Himalayan belt, which extends from the Mediterranean to the Himalayas. The convergence of the African and Arabian tectonic plates with the Eurasian plate causes high levels of seismic activity in this region (Fig. 1) [1]. Turkey is particularly vulnerable to earthquakes due to its geology, which is characterized by the presence of major fault lines, such as the North Anatolian Fault (NAF), the East Anatolian Fault (EAF), and the West Anatolian Fault (WAF). These fault lines are responsible for a number of significant earthquakes that have occurred in the country in the past which caused loss of life and property. According to the General Directorate of Mineral Research and Exploration, the number of active faults or fault segments capable of producing earthquakes of magnitude 5.5 and higher on Turkey's mainland is 485. The active fault map of Turkey is given in Fig. 2 [2].

The risk of earthquakes in Turkey is further compounded by the country's high population density and the presence of many major cities, which are located in seismically active areas. The Turkey Earthquake Hazard Map (2019) clearly shows that a significant part of the country's population and building stock is at risk of earthquakes and that measures should be taken against earthquakes (Fig. 3) [3].

Over the last 100 years, a series of destructive earthquakes such as the 1939 Erzincan (M_s = 7.9), 1975 Diyarbakır (M_w = 6.6), 1999 İzmit (M_w = 7.4), 1999 Düzce (M_w = 7.4), 2003 Bingöl (M_w = 6.4), 2011 Elazığ

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earthquake ($M_L = 5.3$), 2011 Van ($M_w = 7.1$), 2019 İstanbul ($M_w = 5.7$), 2020 Elazığ ($M_w = 6.8$), 2020 Aegean Sea ($M_w = 6.9$) earthquakes, etc. have occurred on the NAF, EAF and WAF [1]. In addition to the loss of life, heavy structural damages and collapse occurred in a significant part of the building stock in earthquakes with such devastating effects that occurred in Turkey (Fig. 4).

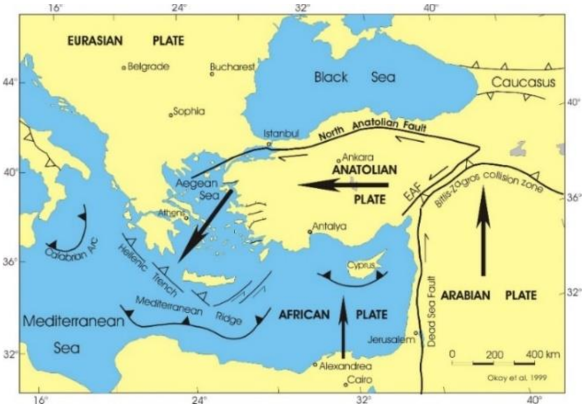

Fig. 1. Tectonic map of Turkey [1]

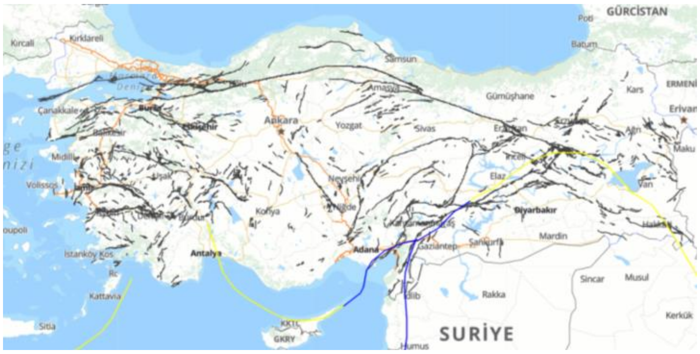

Fig. 2. Active fault map of Turkey [2]

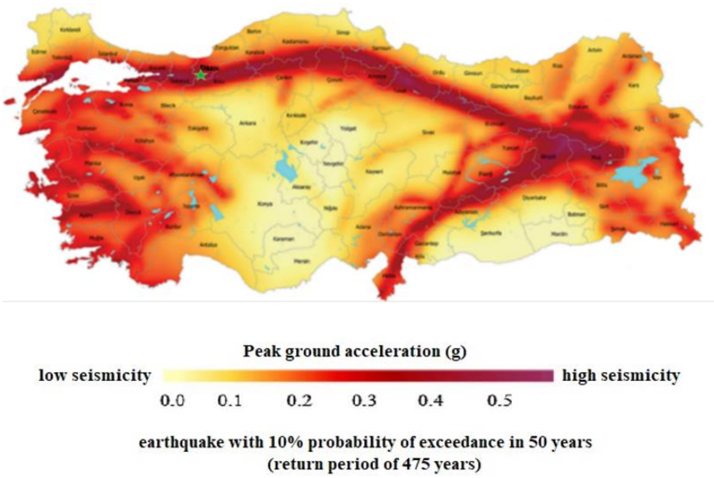

Fig. 3. Turkey Earthquake Hazard Map [3]

(a) 1999 Kocaeli (İzmit) Earthquake [2, 4-6]

(b) 1999 Düzce Earthquake [2]

Fig. 4. Examples of damaged and collapsed reinforced concrete and masonry structures during recent earthquakes in Turkey

(c) 2003 Bingöl Earthquake [1, 7-9]

(d) 2011 Van Earthquake [10-13]

Fig. 4. Continued

(e) 2020 Elazıg Earthquake [14-16]

(f) 2020 Aegean Sea Earthquake [17-21]

Fig. 4. Continued

Overall, past earthquakes and their consequences indicate that the earthquake hazard in Turkey is a significant concern, requiring continued attention and effort to mitigate the risk of damage and loss of life. Therefore, to mitigate the risk of earthquakes, several measures should be taken, including ensuring that new construction is more resistant to earthquakes, and the existing buildings to make them more resistant to seismic activity. Several guidelines have been released by the Disaster and Emergency Management Authority (DEMA) since the founding of the Republic of Turkey in 1923 to prevent loss of life and damages caused by natural disasters. These guidelines were released in the following years: 1940 (TEC 1940), 1944 (TEC 1944), 1949 (TEC 1949), 1953 (TEC 1953), 1962 (TEC 1962), 1968 (TEC 1968), 1975 (TEC1975), 1998 (TEC 1998), 2007 (TEC 2007), and 2018 (TBEC 2018) [22-31]. Over time, design sections in the guidelines for reinforced, adobe, and masonry structures have become more detailed and developed.

The Düzce (Gölyaka) Earthquake, which struck on November 23, 2022, with a magnitude of 5.9, occurred in a seismic zone that had previously seen in both historical (before 1900) and instrumental (after 1900) periods of significant earthquake activity. In the regions, there are active Karadere Segment, Düzce Segment, Hendek, Çilimli, and Yığılca faults located within the North Anatolian Fault Zone (Fig. 5) [32]. The closest major earthquakes to the location where the Düzce (Gölyaka) Earthquake (November 23, 2022) occurred in the instrumental period are İzmit Earthquake (August 17, 1999, $M_w = 7.4$), in which the Karadere Segment was also broken, and Düzce Earthquake (November 12, 1999, $M_w = 7.2$), in which the surface rupture developed on the Düzce Segment [33,34]. Düzce earthquake (November 12, 1999) resulted in 710 deaths and 2678 injured. Thousands of people were left homeless. Due to the earthquake, almost 70% of the building stock was damaged in the city. In the earthquakes that occurred in 1999, 16666 residential buildings and 3837 workplaces were severely damaged throughout the province of Düzce. Moderate damage was detected at 10968 residential buildings and 2573 workplaces, while minor damage was detected at 13070 residential buildings and 1606 workplaces [2]. After the 1999 earthquakes, Düzce became a province in the same year and its population increased over the years. In the years following these earthquakes, quick structuring took place throughout the region.

This study aims to investigate the damaged structures after the Düzce (Gölyaka) Earthquake (November 23, 2022, $M_w = 5.9$). Performance evaluation of engineering structures shortly after earthquakes is very important in terms of making the experience permanent and usable in the future and taking necessary precautions against earthquakes. Especially considering the population growth and current building stock of Düzce province and region over the years, any earthquake that may occur in the region may have a devastating effect in terms of damage and loss of life for two types of building groups:

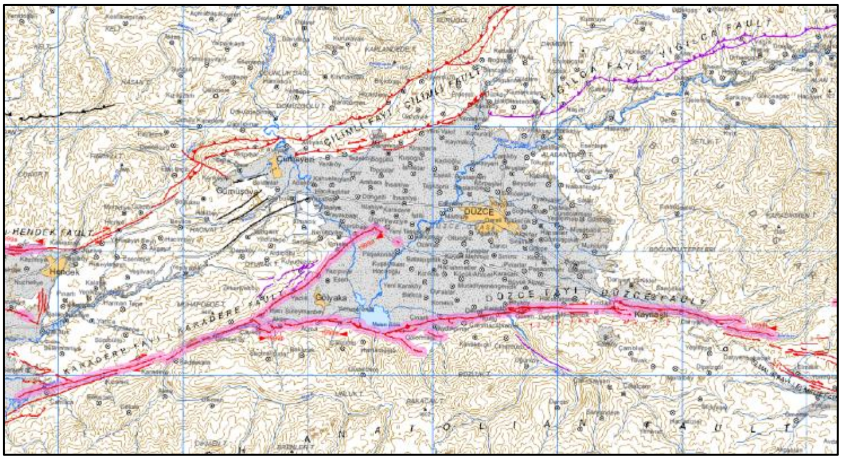

Fig. 5. Active fault map of the region and its surroundings where the Düzce (Gölyaka) Earthquake occurred on November 23, 2022 [32]

(i) the structures built before 1999, which did not receive good engineering service; (ii) the structures built after 1999, where sufficient care was not taken in site selection, load-bearing system selection, and application. For these reasons, the authors visited the city center, districts, and villages of Düzce province to examine the damages that occurred to the structures. Some evaluations of damaged structures are presented based on the site observations. Also, the seismological characteristics and recorded accelerograms of the earthquake are given in the study.

2. Seismological aspects

On November 23, 2022, at 04:08 local time, the Gölyaka district of Düzce, which is located in the west of the Black Sea Region of Turkey, had an earthquake with a magnitude of Mw = 5.9 (Fig. 6). The Earthquake Department of the Disaster and Emergency Management Presidency (AFAD) reported that the epicenter of the earthquake was located 40.8230N-31.0250E an earthquake's depth was 6.81km. The earthquake with a shallow depth of focus was 0.82 km away from Kemeryani village of Gölyaka district of Düzce province, which is the nearest settlement [35].

The earthquake was also effective in the surrounding provinces, especially in Düzce province and its districts. The earthquake, the epicenter of which was Gölyaka district, caused 93 injuries [36]. 128 tents were set up in 10 different points of the city for citizens whose houses were damaged and who were afraid of earthquakes, and 627 people spent the night in tents. It has been reported that 181 heavily damaged buildings need to be demolished urgently throughout the province of Düzce [37].

After the earthquake, the automatically generated predicted intensity map depicts the center of the earthquake to have an intensity value of Io = VII (the felt concussion is strong and the potential damage is slight) (Fig. 7) [38].

It is evaluated that the earthquake that occurred originated from the section at the approximately 10 km long northeast end of the Karadere Segment with a total length of approximately 35 km, which did not fully rupture in the 1999 Izmit and Düzce earthquakes [35]. According to the primary moment tensor solutions taken from different national and international earthquake monitoring centers, the magnitude of the earthquake, which occurred as a result of the rupture of a NE-SW trending right-slip fault, varies between Mw 6.0-6.1 and its depth varies between 10-19 km [39]. Fig. 8 shows the proposed epicenter, depth of focus, and moment tensor solutions for the earthquake from different earthquake monitoring stations.

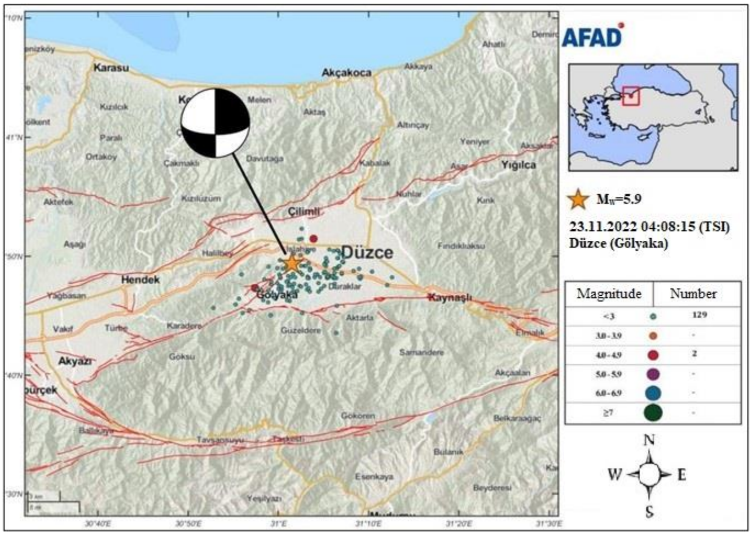

Fig. 6. November 23, 2022, Düzce (Gölyaka) Earthquake [35]

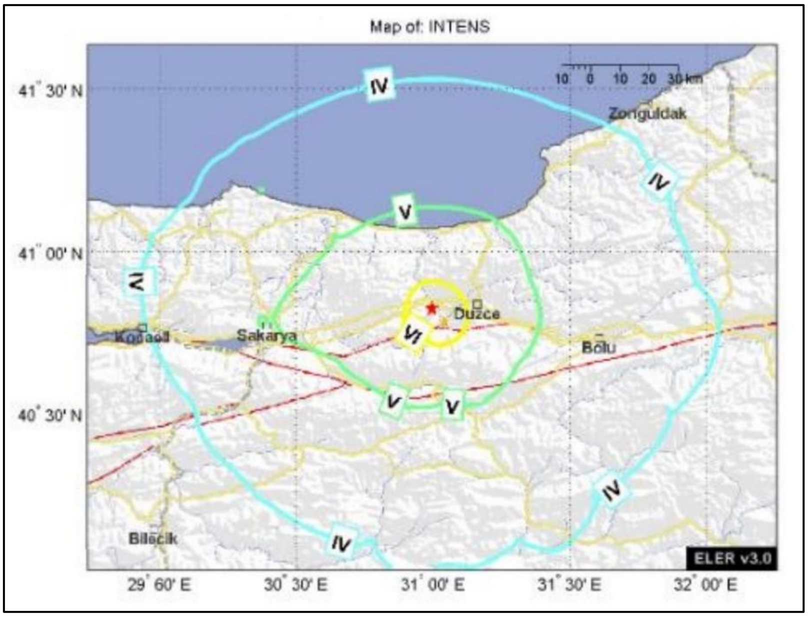

Fig. 7. The predicted intensity map [38]

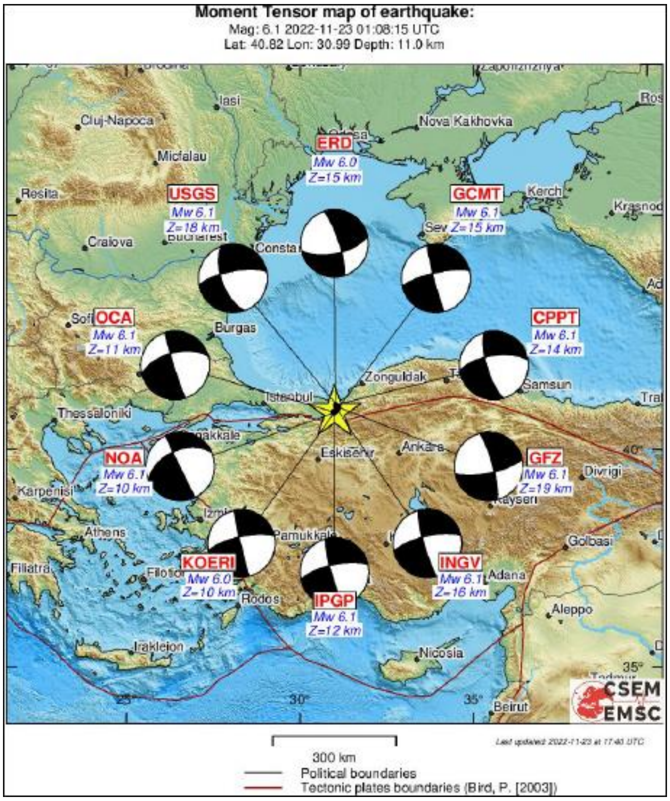

Fig. 8. Proposed epicenter, depth of focus, and moment tensor solutions for the earthquake obtained from different earthquake monitoring stations [39]

According to the report (November 30, 2022, at 09:00 local time) of the Kandilli Observatory and Earthquake Research Institute (KOERI), 481 aftershocks occurred in the first 7 days, three of which were greater than $M_w = 4.0$ (Fig. 9). The magnitude distribution of aftershocks and the number of occurrences per day are given in Fig. 10.

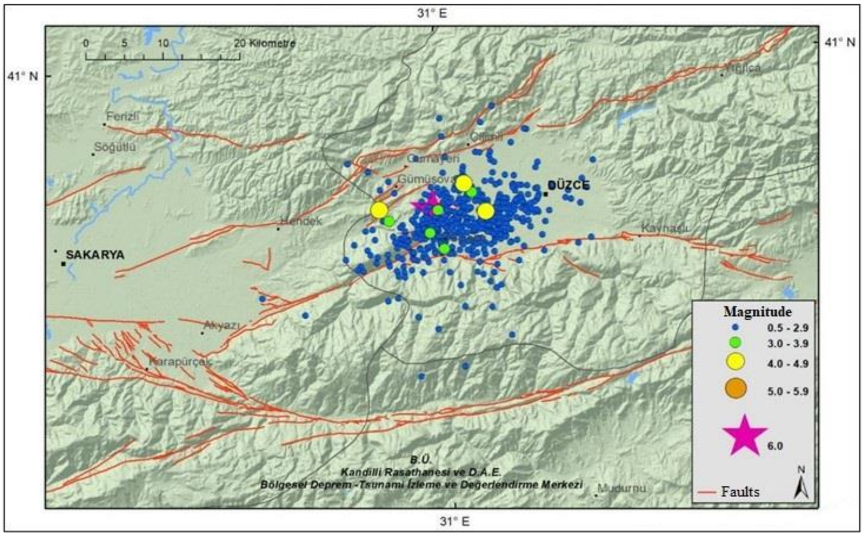

Fig. 9. Aftershocks occurred in the first 7 days after November 23, 2022, Düzce (Gölyaka) Earthquake [38]

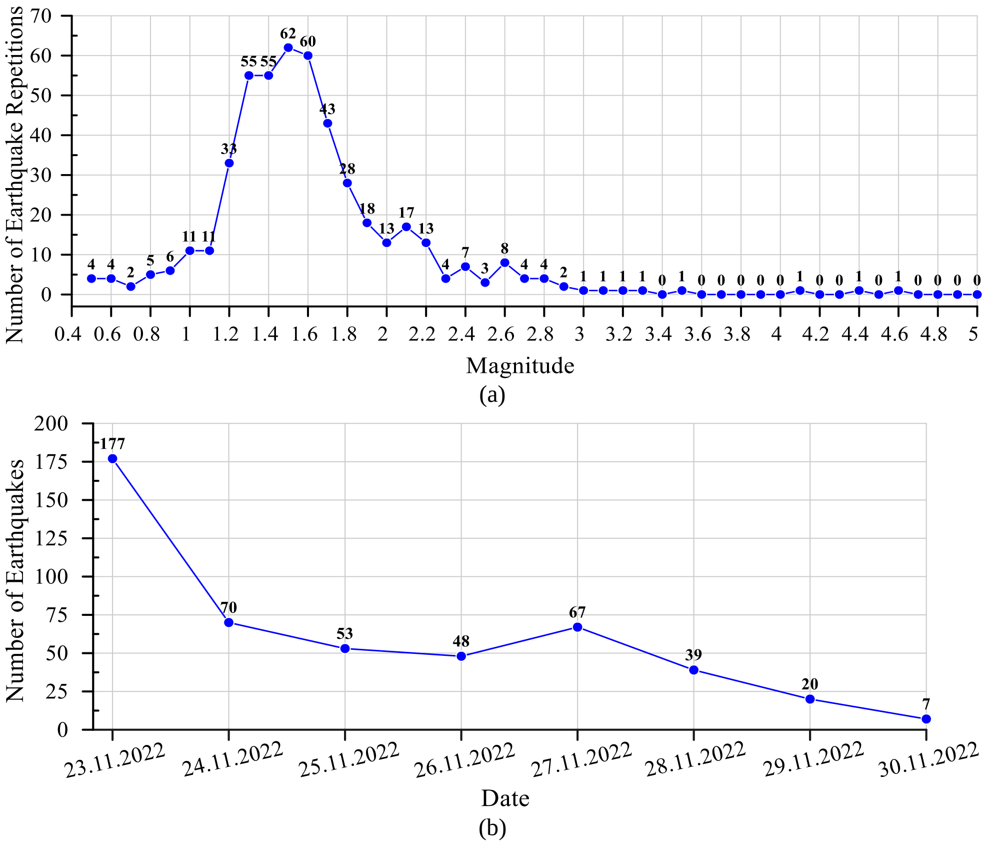

Fig. 10. (a) Magnitude distribution and (b) number of occurrences per day of aftershocks [38]

In the Turkey Earthquake Hazard Map, the maximum ground acceleration (PGA) value of Düzce province for 475 years varies between 0.3-0.7g (Fig. 3). The PGA value of the coordinates where Düzce (Gölyaka) earthquake (November 23, 2022) occurred is 0.593g (are marked with a green star in Fig. 3). This value shows that the earthquake risk at the location where the earthquake occurred is quite high [35,38].

3. Ground motion records

The Düzce-Gölyaka (M_w = 5.9) earthquake was recorded by different accelerometer stations at different distances from the epicenter. The locations of the 5 accelerometer stations closest to the epicenter of the earthquake are given in Fig. 11. Also, Table 1 presents geographical details of these accelerometer stations, peak ground acceleration values, and distances to the epicenter in R_{epi} unit. As can be seen, the highest peak ground acceleration (PGA) value of the earthquake was measured as 407.76gal (0.410g) in the E-W component at the 8102 coded Düzce Merkez accelerometer station [35]. It is worth noting that the PGA value recorded at the 8102 coded Düzce Merkez station does not exceed the PGA set (0. 593 g) for the coordinates where the earthquake occurred on the Turkey Earthquake Hazard Map. The ground motion acceleration records of three components of the earthquake recorded by stations are given in Fig. 12.

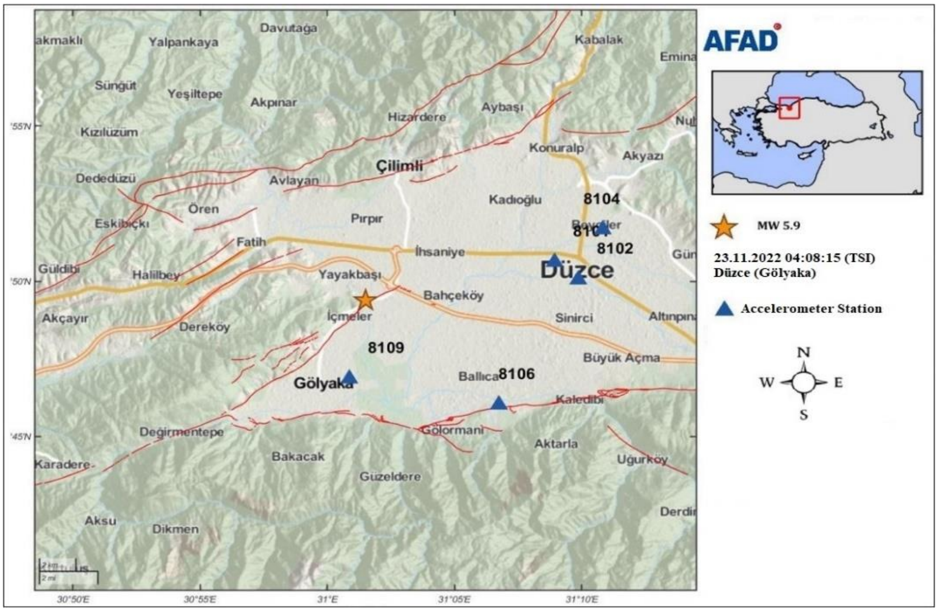

Fig. 11. The locations of the 5 accelerometer stations closest to the epicenter of the earthquake [35]

Table 1. Some ground motion characteristics were recorded by 5 acceleration stations closest to the epicenter of the earthquake [35]

Station					Measured acceleration (g)			Distance (km)
Code	Province	District	N	E	N-S	E-W	Vertical	R_{epi}
8101	Düzce	Merkez	40.844	31.149	0.270	0.310	0.232	10.62
8102	Düzce	Merkez	40.834	31.164	0.219	0.410	0.229	11.79
8104	Düzce	Merkez	40.861	31.180	0.360	0.374	0.231	13.74
8106	Düzce	Merkez	40.767	31.112	0.344	0.378	0.203	9.63
8109	Düzce	Gölyaka	40.781	31.014	0.271	0.364	0.242	4.75

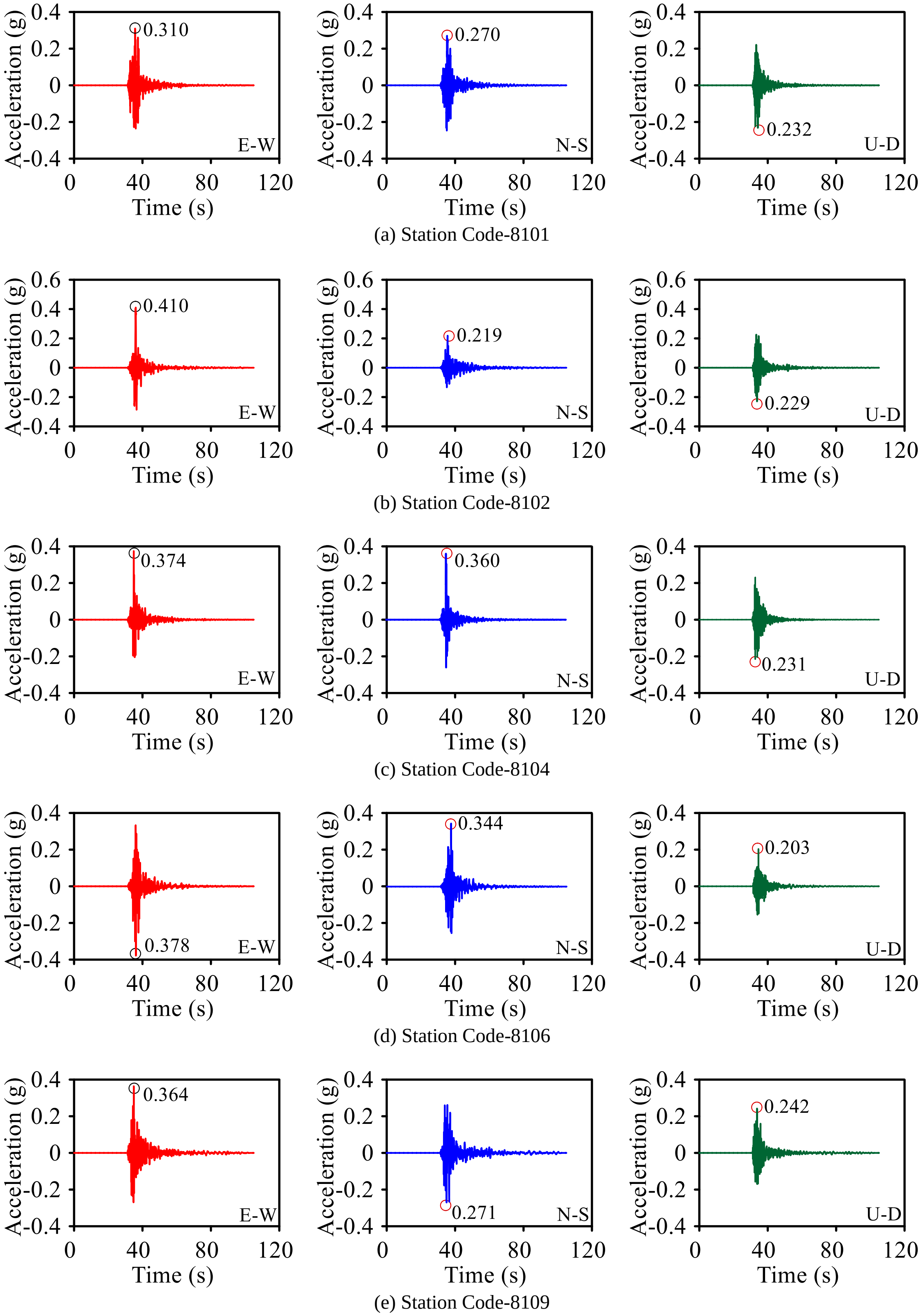

Fig. 12. The ground acceleration records of three components of the earthquake

4. Structural damages observed

This section aims to give the findings of the site observation for the buildings in the most-affected regions following the November 23, 2022, Düzce (Gölyaka) earthquake. Several damaged buildings in the city center, districts, and villages were visited for this site observation. It has been observed that most of the housing stock in the province of Düzce and its districts is made up of reinforced concrete (RC) and masonry buildings. The effects of the earthquake on these types of buildings have been severe. The sections that follow include information on the observed damages to RC and masonry buildings and mosques.

4.1. Damage assessment of reinforced concrete buildings

Particularly in the urban areas of Turkey, a significant part of the structures, including residential, medical, educational, etc. were built using RC construction techniques. These structures contain weaknesses that resulted from mistakes made during the design or construction phases, which have led to damage or collapses during the earthquake. Based on the site observation done after the November 23, 2022, Düzce (Gölyaka) earthquake, the main errors made during the design and construction phases that caused damage to RC buildings are given in this section.

In a significant part of the existing buildings, the gaps left between the infill walls, the windows left on the ground level of the buildings for lighting and ventilation, half-walls in the basement and ground floors, etc. conditions cause the formation of short colons (Fig. 13). Short columns have high stiffness and low ductility. Therefore, this situation causes the short columns to be damaged by shear failure by losing strength.

In the event of an earthquake, it is necessary to eliminate the effects of the horizontal movements of the adjacent buildings on each other and to apply a gap distance that allows the buildings to work independently from each other in all directions during the earthquake. In cases where the gap distance is not sufficient and the floor levels of the buildings are different, pounding damages can occur during the earthquake (Fig. 14). To prevent the formation of such damages, gap distances should be left between adjacent buildings in accordance with the regulations.

Column-beam connection areas are exposed to great stresses under the effect of earthquakes. Shear forces and principal tensile stresses occurring in the connection areas cause cracks and dispersion of the concrete. Structural damage in the RC buildings because of column-beam connection failures was detected in the site observations. Inadequate use of transverse ties was confirmed in the beam-column connection areas (Fig. 15). Also, the existence of insufficient lap splice, which is the length of the two reinforcements in the common area, affects the seismic performance of RC structures negatively (Fig. 16).

Because of the limited construction areas in city centers, cantilevers above the ground level are usually often preferred. But, in the building floor plans, heavy cantilevers are formed when the dimensions of the cantilever parts in two perpendicular directions are each greater than 20% of the total plan dimensions of that floor in the same directions [31]. Heavy cantilever formation causes the vertical center of mass of the building to shift and increases the earthquake effect on the building (Fig. 17).

Fig. 13. Damages caused by short column

Fig. 14. Damages caused by the inadequate safe distance between adjacent buildings

Fig. 15. Damages caused by column-beam connection failures

Fig. 16. Observed damages due to insufficient lap splice

Fig. 17. Damages caused by the long and heavy cantilevers

On the other hand, soft story formation is a common occurrence on ground floors in residential buildings. The soft floor, which is formed as a result of the high entrance floors of the building and the lack of infill walls, causes more horizontal displacement of the lower floors during the earthquake and severe damage to the load-bearing system (Fig 18).

Weak infill wall damages occur more quickly in walls built with low-strength materials. X-shaped cracks appear on the infill walls and spills are observed on the plaster (Fig. 19).

The main functions of the transverse reinforcement used in reinforced concrete structural elements, which create a wrapping effect, are to prevent buckling of the longitudinal reinforcements, to increase the ductility of the core concrete, and to meet the shear force. However, observations made after Düzce (Gölyaka) earthquake (November 23, 2022) showed that these requirements were not considered in some damaged reinforced concrete buildings (Fig. 20).

The adherence between concrete and construction steel enables reinforced concrete to be used as a composite building material. To increase the adherence between concrete and reinforcement, recesses are formed on the reinforcement at certain angles and ribbed reinforcements are produced. In Turkey, the use of unribbed reinforcement was allowed in TEC-1975, but the use of ribbed reinforcement was made mandatory in TEC-1998 [28,29]. Another factor that weakens the adherence between concrete and reinforcement is the corrosion of the reinforcement. Corrosion reduces both the cross-sectional area and bearing capacity of the reinforcement. Poor concrete quality, insufficient concrete cover, and lack of waterproofing in basements increase permeability, causing corrosion of the reinforcement and cracks or mass segregation in the concrete cover layer to parallel the reinforcements. In the site observations made after Düzce (Gölyaka) earthquake (November 23, 2022), it was observed that many reinforced concrete structures were damaged due to the use of unribbed reinforcement and corrosion (Fig. 21).

Fig. 18. Damages caused by the soft story

Fig. 19. Weak infill wall damages

Fig. 20. Damages caused by insufficient transverse reinforcement

Fig. 20. Continued

Fig. 21. Damages caused by corroded and unribbed reinforcement steels

Even though RC buildings comply with guidelines and standards in terms of design, the workmanship in the construction phase is also very important. Poor workmanship and errors in the construction phase cause the buildings not to meet the expected performance (Fig. 22). To prevent damage caused by such mistakes, the construction phase of the buildings should be carried out carefully by qualified workers in accordance with the project.

There are limitations in old and current guidelines for concrete quality, which is one of the effective parameters in the structural performance of RC buildings. While the minimum characteristic compressive strength of concrete was 20 MPa according to TEC-1998 and TEC-2007, this value was increased to 25 MPa with TBEC-2018 [29-31]. Although there are limits in the guidelines related to concrete quality, it is seen that the concrete quality is below these limits when the buildings damaged or destroyed in past earthquakes are examined. The main causes of these damages are not combining the materials that make up the concrete in appropriate proportions, sloppy aggregate distribution, not pouring the concrete from the appropriate height, not applying sufficient vibration, not casting at the appropriate temperature, etc.

Fig. 22. Damages caused by workmanship defects

These factors lead to a significant decrease in concrete quality and the loss of homogeneous structure by separating the materials that make up the concrete. In the site observations made after Düzce (Gölyaka) earthquake (November 23, 2022), it was determined that the size distribution of the aggregates in the concrete used in the buildings was carelessly prepared and segregation occurred. Therefore, damages due to low concrete quality were observed (Fig. 23).

Another factor causing damage in RC buildings is weak gable walls. The garret attics of some RC buildings are covered with gable walls, usually with brick or briquette-like materials. In cases where these gable walls are not adequately enclosed, they can collapse under the effect of earthquakes and cause loss of life and damage (Fig. 24).

4.2. Damage assessment of masonry buildings

Although masonry buildings consist of only a few materials, it is very difficult to determine the seismic response of masonry buildings due to the inhomogeneity of the material properties and their anisotropic forms. The damages detected in the masonry buildings after Düzce (Gölyaka) earthquake (November 23, 2022) are evaluated in this section considering the site observations. Most of the damaged masonry buildings identified are located in the village centers in the rural areas of Düzce.

Fig. 23. Damages caused by poor concrete quality

Fig. 24. Damages caused by the weak gable wall

In masonry buildings, unsuitable connection details of the vertical walls may cause vertical or oblique cracks to occur and the wall units to separate from each other. In the site observations made after the earthquake, damages were detected in the connection sections of the vertical walls of the masonry buildings (Fig. 25). Other factors causing damage in masonry buildings are the unsuitable length of load-bearing walls (with and without reinforced concrete vertical beams) and any openings to be provided in load bearing walls (Fig. 26).

It is widely acknowledged that the degree of adhesion between the mortar and the masonry units affects the shear strength of masonry walls. Low-strength adobe and masonry units reduce the strength of such masonry walls and make them vulnerable to earthquake effects (Fig. 27 and Fig. 28). Also, shear cracks in load-bearing masonry walls typically form as a straight crack and diagonal tension cracks along the bearing joint. These cracks can occur due to various reasons such as unqualified workmanship, poor material properties, a large window or door openings, insufficient locking between wall units, etc. (Fig. 29).

The lintel is formed by lining up the materials such as solid wood, stone, etc. by the gap edges. In case of missing or insufficient length of the lintel, serious damage may occur in the corners of windows and doors in masonry buildings. It was observed that damages were caused by the insufficient length of the lintel in the site observations (Fig. 30).

One of the causes of damage in masonry buildings can be considered as errors in foundation design and different foundation settlements. Masonry buildings can easily be damaged or even collapse due to the slightest foundation problem. In the site observations made after the November 23, 2022, Düzce (Gölyaka) earthquake, heavily damaged masonry buildings due to foundation damage were detected (Fig. 31). In these buildings, the bottom of horizontal supports, which serve as the foundation, was emptied and damaged by the earthquake. Therefore, the buildings were damaged due to settlement.

Fig. 25. Damages caused by unsuitable connection details of the vertical walls

Fig. 26. Damages caused by unsuitable door and window openings

Fig. 27. Vertical crack damage in low-strength adobe units

Fig. 28. Vertical crack damage in low-strength masonry units

Fig. 29. Wall damages

Fig. 30. Damage occurred due to insufficient lintel length

Fig. 31. Damages caused by foundation movement

4.3. Damage assessment of reinforced concrete and masonry mosques

Structural damages were detected in many RC and masonry mosques in the site observations made after Düzce (Gölyaka) earthquake (November 23, 2022) (Fig. 32). These observed damages can be classified as follows: (i) columns, beams, shears, etc. Structural cracks and articulation in the carrier system elements, (ii) column-beam junction damage, (iii) openings in the dome drum, (iv) damage to the side vaults on which the domes sit, (v) minaret damage, (vi) inadequate material quality, (vii) cracks around the cavity on the walls, (viii) floor deflections, (ix) lack of reinforcement detailing, (x) damages due to previous earthquake history.

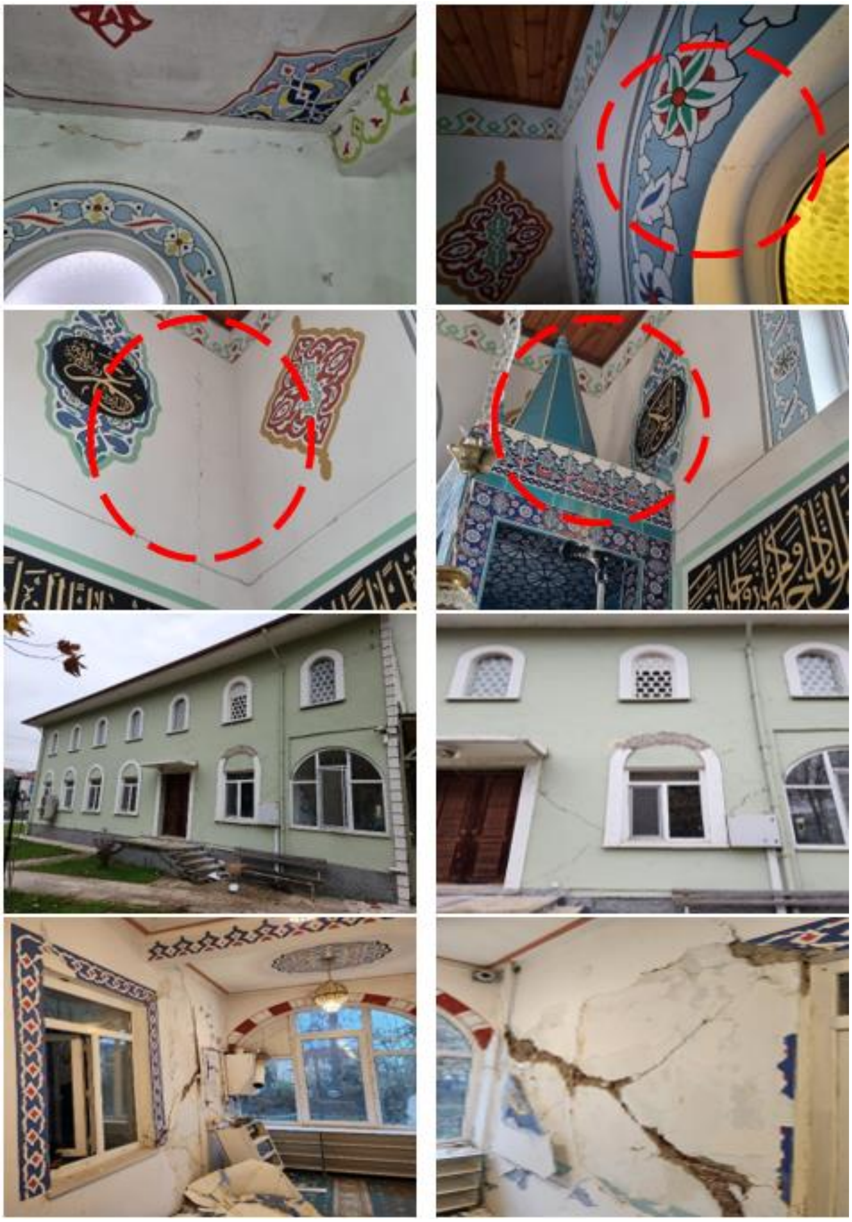

Fig. 32. Damages observed in (a) reinforced concrete and (b) masonry mosques

5. Conclusion

In this study, after the Düzce (Gölyaka) Earthquake (November 23, 2022) with a magnitude of Mw = 5.9, the relationship between the tectonic structure of Düzce province and the earthquake occurred, earthquake ground motion records and the causes of structural damage to the structures determined by site observations were evaluated. The following conclusions can be drawn from the study:

- The maximum ground acceleration (PGA) value of Düzce province for 475 years varies between 0.3-0.7g in the Turkey Earthquake Hazard Map. The PGA value of the coordinates where the Düzce (Gölyaka) Earthquake (November 23, 2022) occurred is 0.593g. This value shows that the earthquake risk at the location where the earthquake occurred is quite high.
- The highest peak ground acceleration (PGA) value of the earthquake was measured as 407.76gal (0.410g) in the E-W component at the 8102 coded Düzce Merkez accelerometer station.
- The PGA value recorded at the 8102 coded Düzce Merkez station does not exceed the PGA set (0. 593 g) for the coordinates where the earthquake occurred according to the Turkey Earthquake Hazard Map.
- After the earthquake, it was observed that various levels of earthquake damage occurred in many RC and masonry buildings in the center, districts, and villages of Düzce province.
- The main causes of damage in RC buildings were detected as the short column, inadequate safe distance between adjacent buildings, column-beam connection failures, insufficient lap splice, weak infill walls, heavy cantilevers, soft story, insufficient transverse reinforcement, unribbed reinforcement steel and corrosion, workmanship defects, poor concrete quality, weak gable walls.
- The main causes of damage in masonry buildings were detected as unsuitable connection details of the vertical walls, unsuitable door, and window openings, low-strength adobe and masonry units, insufficient lintel length, wall damage, and foundation movement.

It is seen that the damage to the reinforced concrete and masonry structures given in the study also occurred in past earthquakes when the earthquake history of our country is examined. Therefore, the earthquake hazard in Turkey is significant and required attention and effort to mitigate the risk of damage and loss of life. Especially, in regions that have significant earthquake activity such as the province of Düzce, to mitigate the risk of earthquakes, several measures should be taken, including ensuring that new construction is more resistant to earthquakes, and the existing buildings make them more resistant to seismic activity. Furthermore, evaluations following devastating earthquakes are critical in terms of making the experience permanent and applicable in the future, as well as establishing required measures.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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