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Geotechnical and Structural Investigations in Malatya Province after Kahramanmaraş Earthquakes on February 6, 2023

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Abstract
Two earthquakes with moment magnitudes of 7.7 and 7.6 occurred on February 6, 2023, at 04:17 a.m. (with local time, GMT+3) in Kahramanmaraş-Ekinözü Pazarcık and at 13:24 p.m. (with local time, GMT+3) in Kahramanmaraş-Elbistan, respectively, in Türkiye. The earthquake was felt in a wide area within Türkiye and caused structural destruction and heavy damage to buildings, especially in eleven cities, including Adana, Adıyaman, Diyarbakır, Gaziantep, Hatay, Kahramanmaraş, Kilis, Malatya, Osmaniye, Şanlıurfa and Elazığ. The aim of this study was to present a detailed field investigation in Malatya province, which was one of the most affected cities in the region. The strong ground motion records have been analyzed, and PGA distribution maps were presented. Structural, design, and manufacturing defects in damaged and collapsed buildings were examined. The performance of soil structures was examined, and the defects demonstrated were evaluated in the context of the geological environment. The study is essential in terms of evaluating the damage and possible causes of the building stock in Malatya city center and its districts after the earthquake. In this sense, a holistic evaluation has been carried out, which can be a useful resource for Anatolian cities with typical building characteristics.

1. Introduction

On February 6, 2023, at 04:17 local time (GMT +03:00) in Ekinözü Pazarcık Kahramanmaraş (Lat: 37.288, Longitude: 37.043) and at 13:24 (GMT +03:00) in Elbistan Kahramanmaraş (Lat: 38.089), Longitude: 37.239), two earthquakes with moment magnitudes of Mw 7.7 and Mw 7.6 occurred at a depth of 7.7 and 8.6 km, respectively. The earthquake was felt in a wide geography within the borders of Türkiye, especially in Adana, Adıyaman, Diyarbakır, Gaziantep, Hatay, Kahramanmaraş, Kilis, Malatya, Osmaniye, Şanlıurfa and Elazığ, and in Syria as well as in Türkiye, and caused significant structural destruction. Between February 6 and 9, when the earthquake took place, more than 3000 aftershocks, varying in magnitude between M 4 and M 6.6, occurred within a radius of 350 km in Pazarcık and Elbistan epicenters [1]. The settlements in the impact area of both earthquakes are located in the East Anatolian Fault Zone (EAFZ). The fault mechanism of earthquakes is left lateral strike-slip.

Various levels of destruction, loss of life and property, and injuries occurred in 11 city centers and districts within the impact area of the earthquakes. According to the Türkiye Earthquake Recovery and Reconstruction Assessment Report published by the Presidency of Strategy and Budget and the findings of the Ministry of Treasury and Finance, the total amount of material damage caused by earthquakes is 1.6 trillion ₺. It is recorded that the material and financial total cost of the earthquake was 103.6 billion dollars. Housing damages constitute the most important component of the total financial burden created by the earthquake on the Turkish economy, with 54.9 percent (i.e., 1,073.9 billion Turkish liras (₺)/56.9 billion dollars). Demolitions in public infrastructure and service buildings are considered the second-ranked damages in terms of financial burden (i.e., 242.5 billion Turkish liras (₺)/12.9 billion dollars). According to current field data, Malatya city

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center and its districts have 5,393 collapsed buildings that urgently need to be demolished.

The epicentral distances of 105 and 170 km from the epicenters of the Pazarcık (Mw 7.7) and Elbistan (Mw 7.6) earthquakes and other parameters caused significant destruction in Malatya city center and its districts (Fig. 1). When both earthquakes are evaluated from a technical point of view, he stated that the Pazarcık (Mw 7.7) earthquake undoubtedly caused demolition and structural damage, but a significant part of the destruction observed in Malatya city center occurred with the subsequent Elbistan (Mw 7.6) earthquake. Among many other parameters, epicentral distance is considered to be highly influential on the intensity of structural destruction. Official figures indicate that 8365 buildings were collapsed or heavy damaged and 9905 were moderately and slightly damaged based on the first post-earthquake damage observations carried out by the Ministry of Environment, Urbanization and Climate Change.

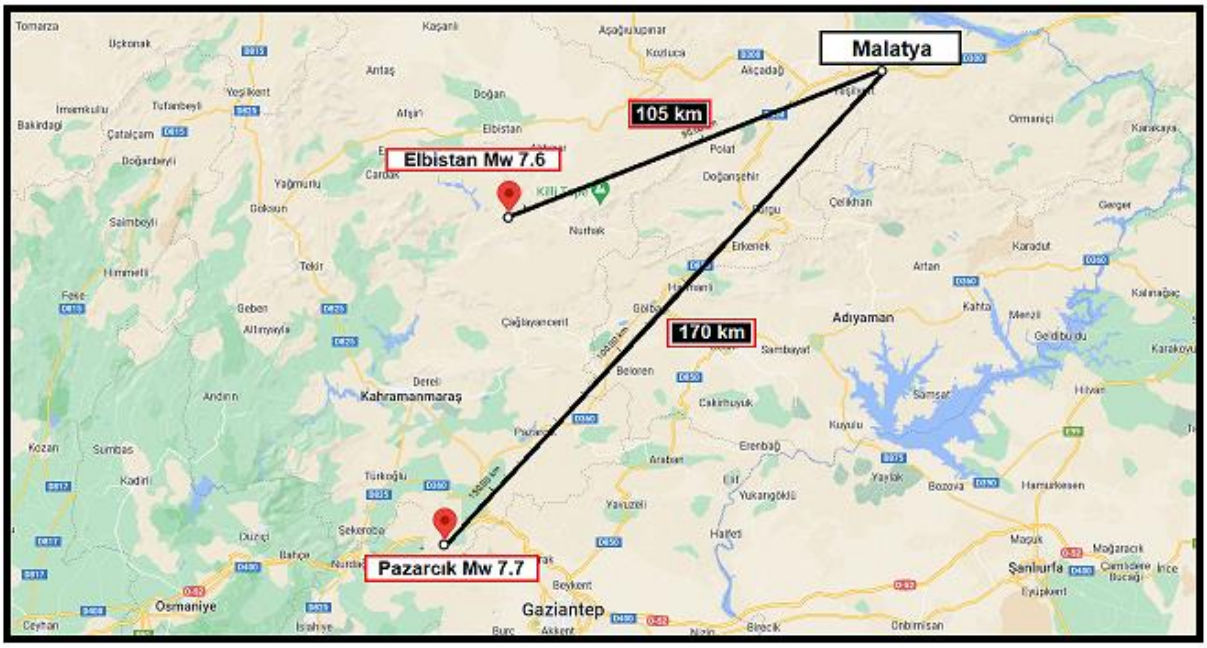

Figure 1. Distance from Malatya to the epicenter of the Pazarcık (Mw 7.7) and Elbistan (Mw 7.6) earthquakes

In general, damage is defined as a stability problem that arises during the life of a building exceeds the tolerance limits. Structural damage, on the other hand, can be defined as the complete or partial loss of the standard or defined features of a building or building element for any reason during use and the loss of its service function. Historical earthquakes show that earthquakes are the primary cause of structural damage in these buildings [2]. The probability of damage to buildings that are not taken care of during design and construction varies depending on the magnitude of the earthquake [3]. Although the destruction in residential areas is mostly in the foreground due to the loss of life it causes, the types of collapse and damage to other civil structures are also important in terms of both affecting the continuation of civil life and making engineering evaluations necessary.

There are some studies in the literature related to the damage to buildings caused by the earthquakes in the different seismic regions. Nemutlu et al. [4], Sayın et al. [5], and Işik et al. [6] investigated the structural damages of masonry and reinforced concrete buildings after 2020 Elazığ-Sivrice earthquake. Bilgin et al. [7] carried out a detailed field survey after the 2019 Albania earthquake and evaluated the performance and damages of masonry buildings. Işık et al. [8] studied the time-dependent seismicity model of the North Anatolian Fault Zone earthquakes. Nemutlu et al. [9] investigated the assessment of earthquake preparedness of existing buildings in Bingöl province, and in another work [10], they estimated the probabilistic hazard for Bingöl province. In the study of Işık [11], the seismic parameters were obtained for M $\geq$6 earthquakes in Türkiye after 1900, and the measured and current peak ground acceleration values were compared. The structural damages to masonry buildings, mosques, and minarets in Adıyaman after the Kahramanmaraş earthquakes were also investigated by the studies of Işık et al. [12], [13]. Besides, Kocaman [14] investigated the influence of Kahramanmaraş earthquakes on historical masonry minarets and mosques.

In this study, the damage and collapse of the structures in Malatya center and its districts caused by the earthquakes on February 6 are evaluated. Inferences are presented as a result of field observations and examinations carried out in 8 districts, two of which are central districts. Earthquake damages are examined in relation to local soil properties and other earthquake parameters. The structural damage caused by these two major earthquakes in the historical period is revealed, and the local construction practices are criticized.

2. Seismicity and Site Description

The EAFZ, which lies between Bingöl Karlıova and Antakya, consists of six segments from northeast to southwest between Karlıova-Bingöl, Palu-Hazar Lake, Hazar-Sincik, Çelikhan-Gölbaşı, and Gölbaşı-Türkoğlu. In the historical period, the Eastern Anatolian Fault System formed an earthquake series that started with the 1822 Antakya earthquake. Erdik [15] reports two devastating earthquakes in CE115 and 526 that claimed more than 500.000 lives. A devastating earthquake was produced by Karlıova-Bingöl segment in 1866, and in 1872, another damaging earthquake was propagated by the Türkoğlu-Antakya segment. The other destroyed earthquakes occurred on the Palu-Hazar Lake and Hazar Lake-Sincik segments in 1874 and 1875, respectively. The last earthquake on the EAFZ occurred in 1893 on Çelikhan-Gölbaşı segment. The 1905 earthquake destroyed many villages between Çelikhan and Pütürge towns. In the last century, except for the 1971 Bingöl and 2020 Sivrice earthquakes, the Eastern Anatolian Fault System entered a quieter period and did not produce an earthquake large enough to cause a surface rupture. The EAFZ System, with a total length of 600 km and consisting of 6 different segments with lengths ranging from 50 to 145 km, dates back to BC 17-1900 in the historical period (Fig. 2). 30-AD 100; M.S. 700's; M.S. 1100's, M.S. It produced five main series of earthquakes in the 1500s and 1800s. Since EAFS has a very low shear rate of 5-8 mm/year, earthquakes with a magnitude of 7.0-7.5 are repeated at very long intervals [16]. The province of Malatya is located in the east of Türkiye, with an area of 12,313 km^2 and a population of approximately 800,000, in a geography surrounded by this intense tectonic activity. As can be seen in the active fault map of Türkiye, Doğanşehir-Surgu Faults are located in the south, and the part of the EAFZ passing through Pürge-Doğanyol and the Malatya Fault are tectonic structures that affect the city significantly. Coulomb stress transfer studies carried out after the Sivrice (Mw 6.8) earthquake indicated that the seismic potential of the Palu-Hazar and Çelikhan-Gölbaşı segments increased [17]. According to the 1996 Earthquake Zones Map published by the Türkiye Ministry of Public Works and Settlement General Directorate of Disaster Affairs, Malatya and its districts are located in the I to III degree earthquake zones. Malatya PGA is defined as 475 (years) in the earthquake hazard map of Türkiye, and the maximum acceleration value varies between 0.2g and 0.7g [18]. Considering the geology of the Malatya, detailed simulations were performed to assess the seismic response of the local soils under recent earthquakes [19], [20].

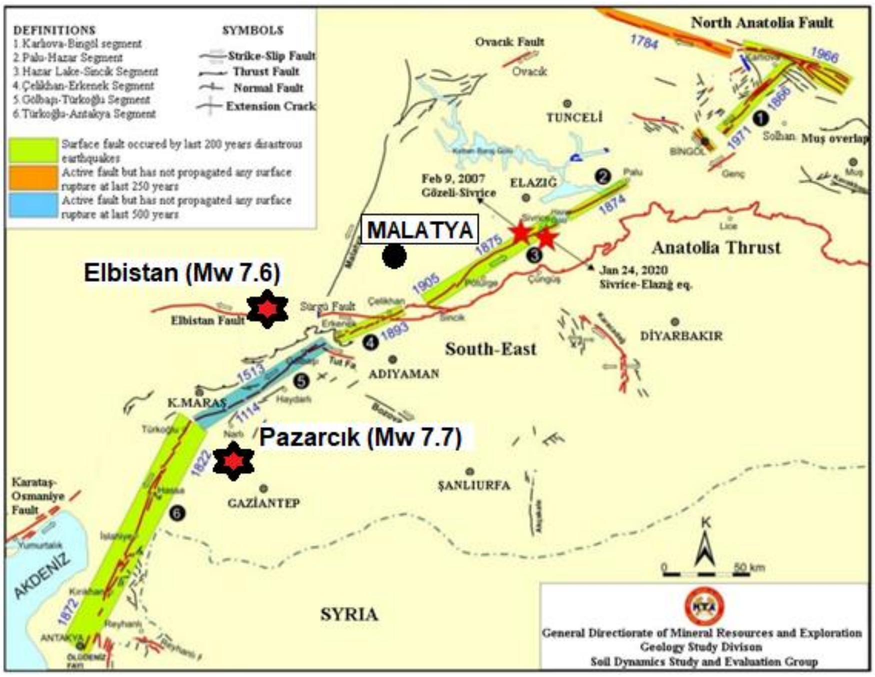

Figure 2. Main segments of the East Anatolian Fault Zone and damaging earthquakes [18]

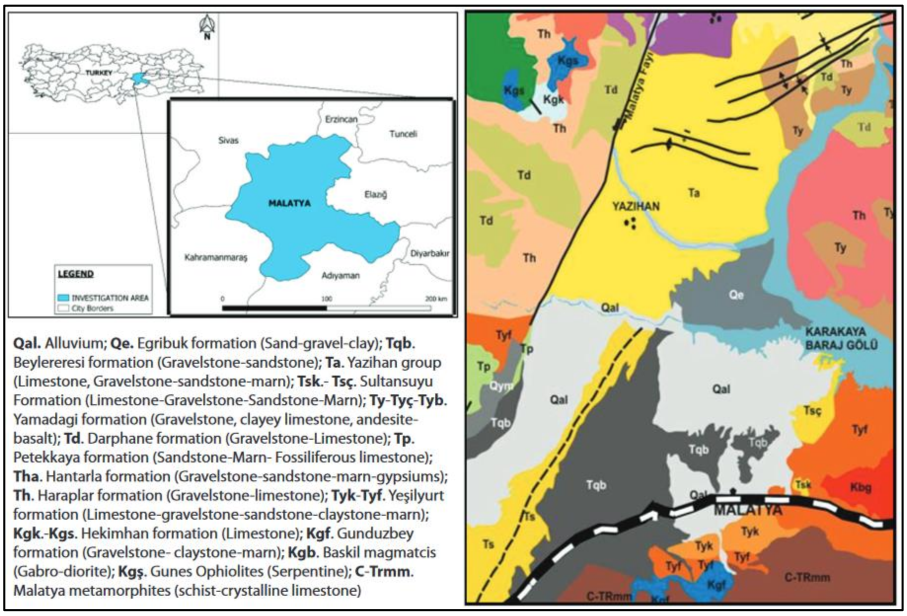

Figure 3. Site location and general geological map of the region [21]

The general geological map of Malatya is presented in Fig. 3. The geological units on which the city center is built can be evaluated in two categories: the south and north of the highway extending on the east-west axis. The northern part of the city consists mostly of the Beylerderesi formation, where alluvial units and conglomerate-sandstone units are stacked. In the south, the lithology is represented by limestone-conglomerate-marl units known as Yeşilyurt formation. The eastern side of the city was built on units where magmatic rocks were stacked.

3. Ground Motions

The acceleration records of the February 6 earthquakes were downloaded from the 'General Directorate of Disaster Affairs' (i.e., AFAD) official site on February 11. The measured instrumental peak ground acceleration of the Pazarcık (Mw 7.7) earthquake was recorded at TK4614 Kahramanmaraş station, with 1966.74 cm/s^2 (2.00 g) belonging to the EW component (Fig. 4a, b). The activity depth was 8.6 km, and the Vs_{30} shear wave velocity of the station location was reported as 671 m/s. The epicentral distance to the focal point of the earthquake was recorded at 31.42 km. According to the 5% damping ratio, the dominant period of the spectral acceleration was found to be in the range of 0.1-0.2 s. The peak velocity value was calculated as 0.552 m/s and the maximum displacement as 0.186 m. The significant duration of the earthquake was calculated as 24.06 s between 39.71 and 63.77 s. The acceleration time history and response spectra of the NS component of the motion are presented in Figs.4c, d. The highest measured instrumental peak ground acceleration of the north-south (NS) component was recorded as 1948,767 cm/s^2 (1.99 g). It was observed that the dominant period of the spectral acceleration occurs in the range of 0.1-0.2 s, according to the 5% damping ratio. The peak velocity value was calculated as 0.818 m/s and the maximum displacement was calculated as 0.232 m, respectively. The significant duration of the earthquake was calculated as 23.15 s between 39.81 and 62.96 s. The peak acceleration of the vertical component of the earthquake (UD) was recorded as 1352.510 cm/s^2.

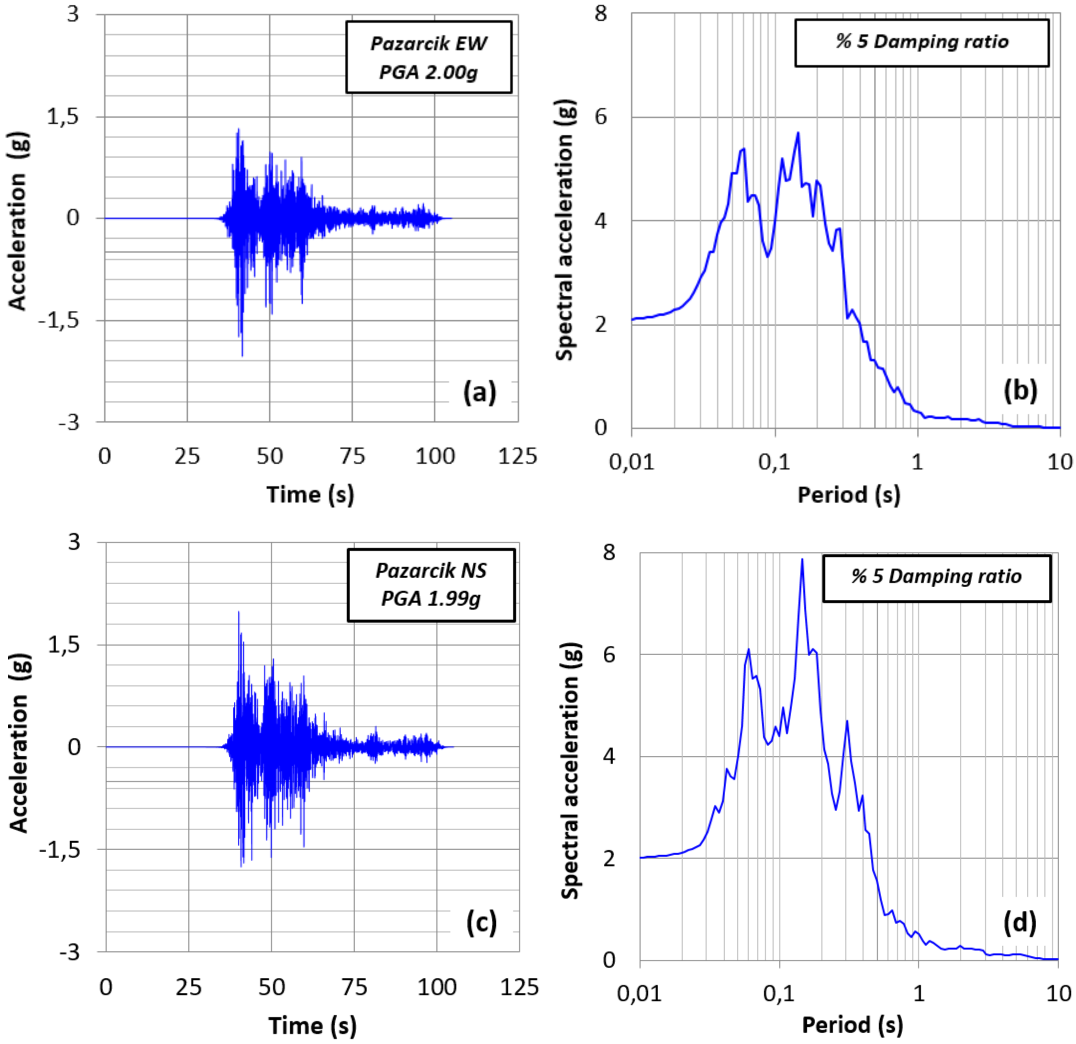

Figure 4. Acceleration-time history and response spectra of Pazarcık earthquake (Mw 7.7); (a, b) EW and (c, d) NS components

The highest acceleration record of the east-west (EW) component of the Elbistan (Mw 7.6) earthquake that occurred during the period following the Pazarcık (Mw 7.7) earthquake was at TK4612 Göksun station at 520.662 cm/s^2 (0.531 g), (Fig. 5a). The dominant period of the spectral acceleration was recorded as 0.4 s according to the 5% damping ratio (Fig. 5b). The activity depth is 7 km, and the V_{s30} shear wave at the station location is reported as 246 m/s. The epicentral distance to the focal point of the earthquake was calculated at 66.68 km. The peak velocity value was calculated as 0.725 m/s, and the maximum displacement was calculated as 0.574 m. The significant duration of the earthquake was calculated as 25.9 s between 30.60 and 56.50 s. The peak acceleration value of the vertical component of the earthquake was recorded as 430.195 cm/s^2. The highest acceleration record of the north-south (NS) component was measured at 627.184 cm/s^2 (0.64g) (Fig. 5c). The dominant period was recorded as 0.5 s according to the 5% damping ratio (Fig.5d). The peak velocity value was calculated as 1.707 m/s, and the maximum displacement was calculated as 0.679 m. The significant duration of the earthquake was calculated as 20.14 s between 30.99 and 51.13 s. The spectra obtained from the EW and NS components of Elbistan earthquake (#4406 Akçadağ station) are quite above the elastic design spectra defined by Turkish Building Earthquake Code [22], which corresponds to the DD-2 earthquake level with a 10% probability of exceedance in 50 years (Fig. 6)

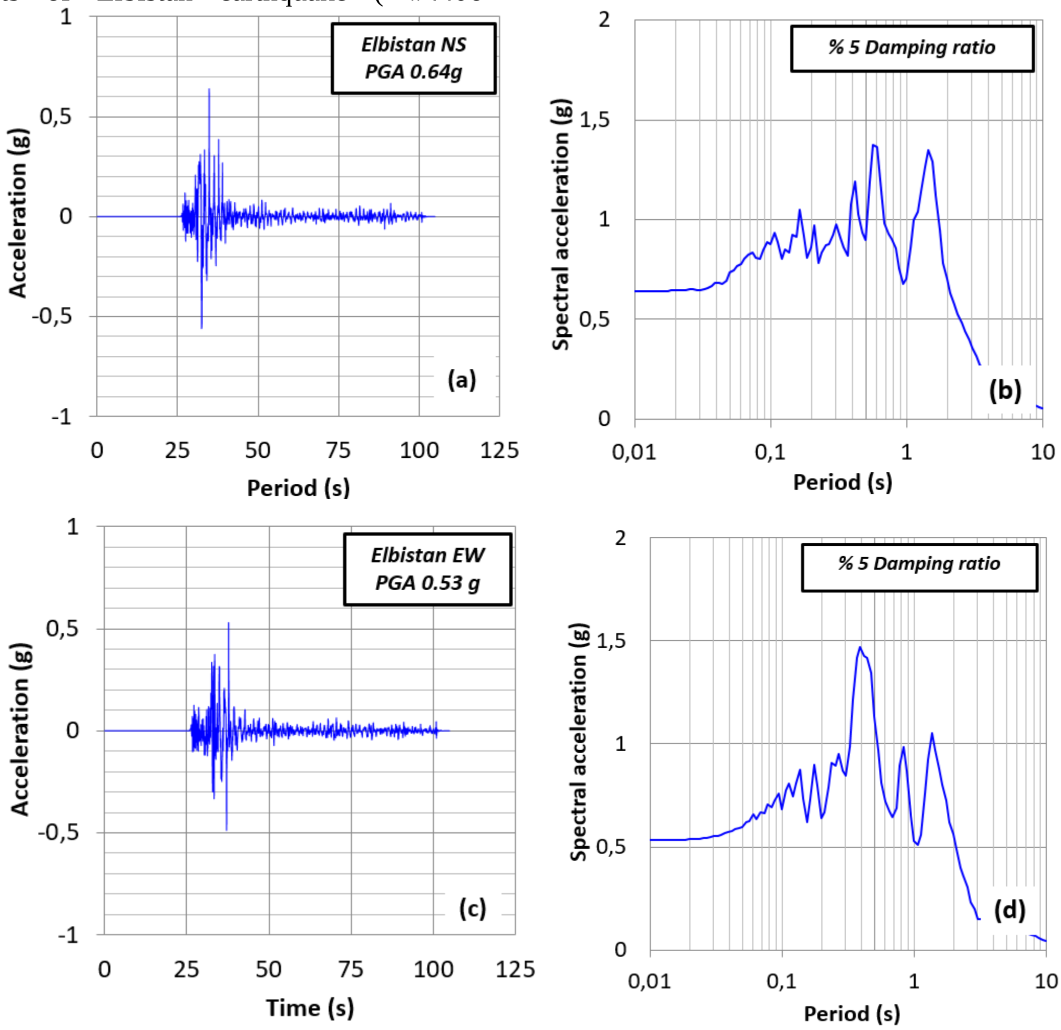

Figure. 5 Acceleration-time history and response spectra of Elbistan earthquake (Mw 7.7); (a, b) NS and (c, d) EW components

The damages and destruction caused by the Pazarcık and Elbistan earthquakes occurred as a result of many parameters. The intensity distribution of the earthquake in Malatya city center and its districts, with distances of 105 and 170 km, respectively, is shown on maps. It is observed that the intensity of the Pazarcık (M_W 7.7) earthquake increases from the city center to the southwest as expected (Fig. 7). While the earthquake was felt in the city center with a magnitude of MMI 7-8, it caused damage and destruction in buildings with low construction quality. It is seen that MMI 6 is felt as one moves north from the city center (i.e., in the direction of Darende and Akçadağ in the north and in the direction of Kale in the east). Instant investigations on the effects of the Elbistan earthquake (Mw 7.6), which took place within the hours following the Pazarcık (Mw 7.7) earthquake (i.e., approximately nine hours later), showed that a significant part of the destruction occurred as a result of the Elbistan earthquake. This situation also coincides with the Elbistan earthquake intensity distribution map. In fact, the effects of the earthquake in the city center correspond to much greater intensities (Fig. 8). In general, intensity distribution maps largely reflect post-earthquake observations in the area.

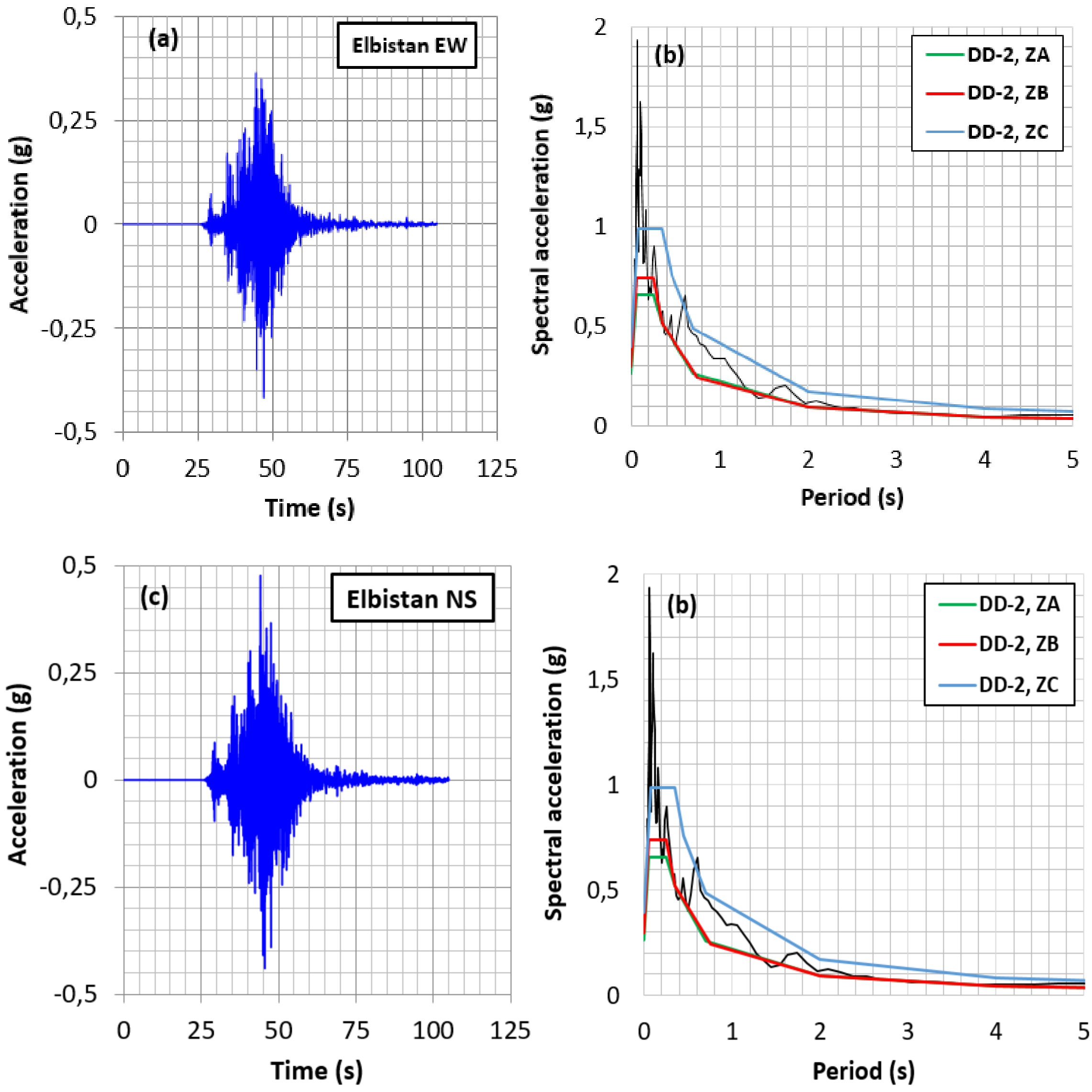

Figure. 6 Acceleration-time history and response spectra of Elbistan earthquake (Mw 7.6); (a, b) EW and (c, d) NS components (#4406 station)

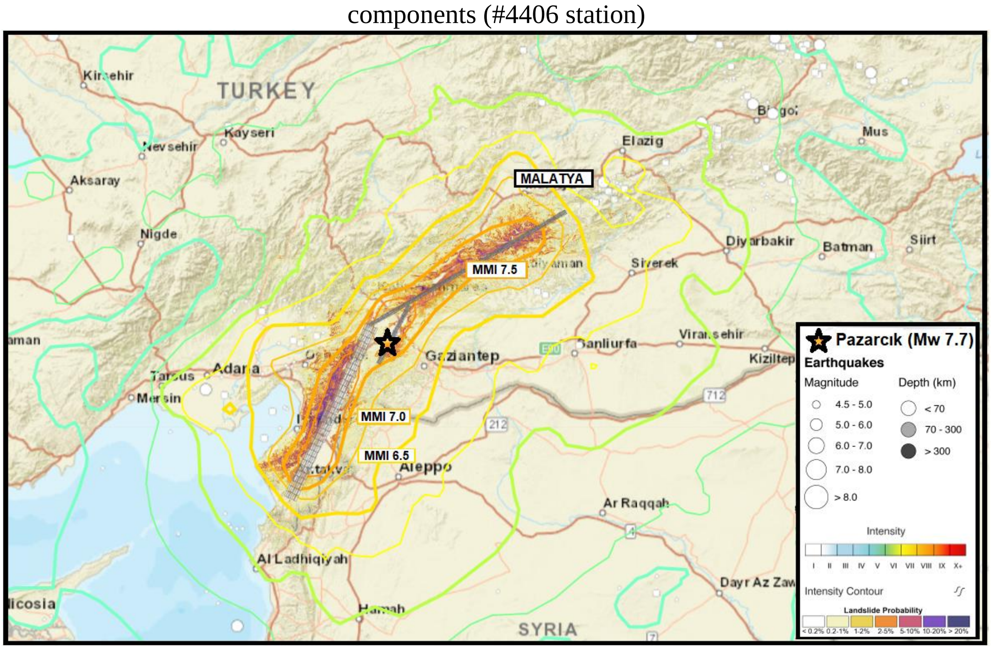

Figure 7. The intensity distribution map of Pazarcık (Mw 7.7) earthquake

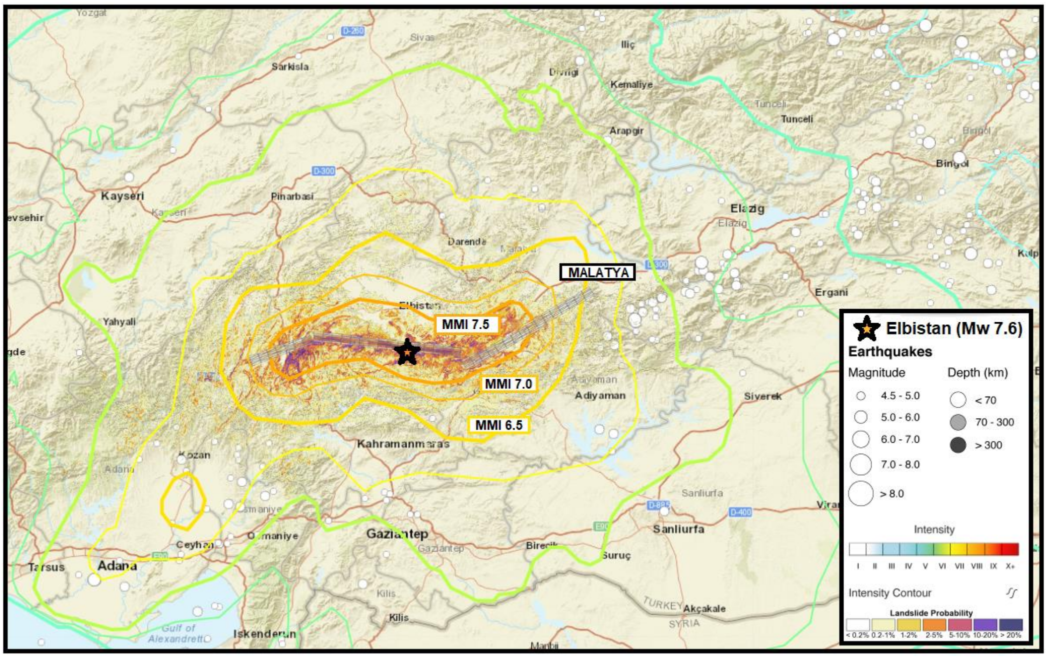

Figure 8. The intensity distribution map of Elbistan (Mw 7.6) earthquake

4. Distribution of Structural Damages

The building stock of the city center of Malatya involves generally reinforced concrete buildings and masonry buildings in rural areas. In the city center and in the countryside of Doğanşehir, Akçadağ, and Darende villages of Malatya, structural and non-structural damage as well as collapses were observed in most of the buildings, resulting in more than 1000 deaths.

The population of Malatya is nearly 815.000, and there are 32.344 buildings in the city center. According to the first post-earthquake damage observations carried out by the Ministry of Environment, Urbanization, and Climate Change, the damage distribution in Malatya province was shown in Fig 9.

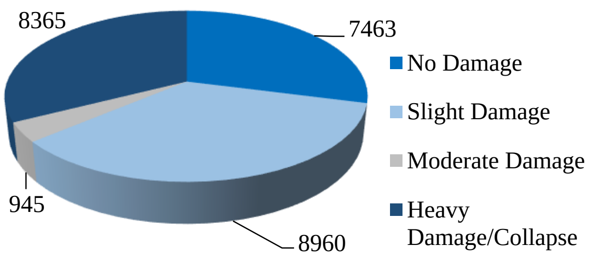

Figure 9. Ministry of Environment, Urbanization and Climate Change damage detection findings on February 16, 2023

4.1. Structural Properties of the Building Stock

The quality of the buildings in the city center of Malatya shows variations. In the building stock, there are old and newly built reinforced concrete buildings with up to 15 stories and also lots of masonry buildings in the rural areas. It is seen that the buildings in the very center of the city, especially in the region where commercial enterprises are concentrated, were generally built before the year 2000. The building inspection was arranged and legally regulated after the earthquakes on August 17 and November 12, 1999, in Kocaeli and Düzce. As a result of these earthquakes, awareness of seismic resistance increased, and a new reinforced concrete design requirement (TS500) [23] was started to be used, so buildings built prior to the year 2000 can be defined as uncontrolled buildings. According to the observations, these old adjacent reinforced concrete structures with no separation distance exhibited heavy damage and many of them even collapsed.

There have been many major earthquakes in the history of Türkiye, resulting in a great deal of destruction and death. After these tragic events, the earthquake regulations of Türkiye have been revised many times, and some vital practical and conceptual changes have occurred. One of the most striking improvements from the Turkish Building Earthquake Code-1975 [24] to Turkish Building Earthquake Code-2018 [22] was the change in column and column-beam connection sections. In

Malatya region, there are many buildings built before the Turkish Building Earthquake Code-2007 [25]. However, the collapsed and heavily damaged buildings were generally built before 2000. The most important drawbacks of these buildings were the use of non-deformed bars, the insufficiency of stirrups, and not using ready-mixed concrete.

4.2. Damages in Reinforced Concrete Buildings

- *The damage in old buildings (prior to 2000)*

The building stock in the very center of the city, especially in the region where commercial enterprises are concentrated, is commonly old and adjacent structures with no or not enough dilatation. These buildings, which were generally built prior to 2000, are mid-rise with infill walls. A modern reinforced concrete design guide (TS 500) [22] was issued on October 12, 2000, and it mandated the use of ready-mixed concrete and ductile low-carbon steel. Besides, this guide improved the detailing of the steel bars and banned the use of non-deformed bars. It was observed that most of the buildings built prior to 2000 were collapsed, immediately demolished, or heavily damaged (Fig. 10). The main defects in these buildings were the use of non-deformed bars, the inadequacy of stirrups, and the low strength properties of concrete due to the use of hand-mixed concrete.

Figure 10. Totally collapsed buildings in Malatya

Figure 11. The observed damages in the old buildings in the city center, caused by the insufficiency in stirrups and the use of non-deformed steel bars

Observing Fig. 11, the longitudinal bars buckled due to the wide stirrup spacing, so the bond strength of the concrete-steel bar could not be achieved and the concrete was crushed. Besides, it is also striking that the bond strength of concrete-steel bars was not provided due to the use of non-deformed steel bars.

- *Pounding effect*

As mentioned above, the old building stock in the city center was commonly built as adjacent structures with no or not enough seismic gaps. For these kinds of structures, in order to exhibit the least damage caused by the earthquake motion, a sufficient seismic gap element should be placed or a seismic gap should be left between the buildings. Based on the code, the minimum seismic gap should be 30 mm up to 6 m in height. Moreover, a minimum of 10 mm should be added for every 3 m of height increase. In the opposite case, a pounding effect can cause harm to the structural elements of buildings. Another defect observed in the collapsed or damaged reinforced concrete buildings can be explained by the fact that they were built at different times as adjacent buildings, and they damaged each other’s load-bearing elements due to the lack of or insufficient seismic gap. Considering Fig. 12, the pounding of the adjacent structural elements of two buildings induced damages due to an insufficient seismic gap or element.

Figure 12. Pounding effect in adjacent reinforced concrete buildings caused by the lack of seismic gap

- *Inadequate reinforcement detailing*

The load-bearing capacity of the elements and their connection zones in the structures must have the required ductility and strength to provide the structural safety of the buildings built in the earthquake zones. Within this scope, in the structural system, the most vital and critical areas are the column-beam connections during an earthquake. Turkish Building Earthquake Code-2018 [22] includes some rules and restrictions on structural element design. For example, the spacing of stirrups must be reduced in the confinement area, and at their ends, the ties must have hooks with a bent of 135 degrees. It can minimize the damage in the connection areas during the earthquake caused by the use of insufficient stirrups. According to the present code [22], for columns, the minimum transverse reinforcement spacing is 5 cm and the maximum spacing is 1/3 of the smaller cross-section dimensions. Besides, it shall not be higher than ¼ of the beam depth and eight times of the minimum diameter of longitudinal reinforcement for beams. In Fig. 13, the defects in the structural elements caused by the lack of stirrups in the columns and column-beam connections were depicted. As shown, sufficient stirrup spacing was not applied in the columns, and the distance between the stirrups was also widened due to insufficient anchoring. Therefore, the longitudinal bars were buckled by the effect of both vertical load and moment, and thus, severe damage occurred in the core of the concrete.

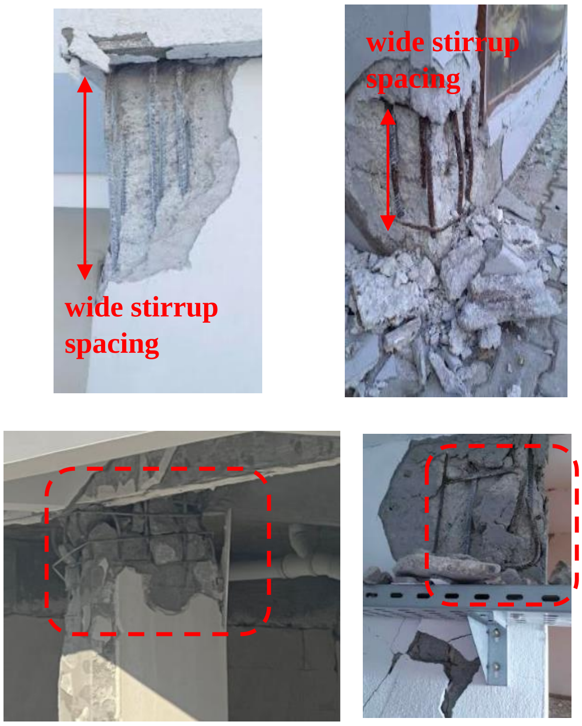

Figure 13. Improper stirrup spacing and 90-degree hook bends

During observations, some mistakes were also detected due to straight hooks bent 90 degrees at their ends. Considering Fig. 13, the improper 90-degree hook bends could not provide a sufficient confinement effect. In some cases, ruptures in the stirrups were also observed due to the insufficient detailing of the transverse reinforcements, as shown in Fig. 14. It was seen that in some buildings, especially in the lower parts of the columns, the stirrup spacing was so high that there was no stirrup in those parts. Besides, when the columns were subjected to a high axial load, the longitudinal reinforcements buckled, resulting in the spalling of the cover concrete (Fig. 14). This fact can also be attributed to the use of wide stirrup spacing, insufficient concrete strength, and column-cross section dimensions.

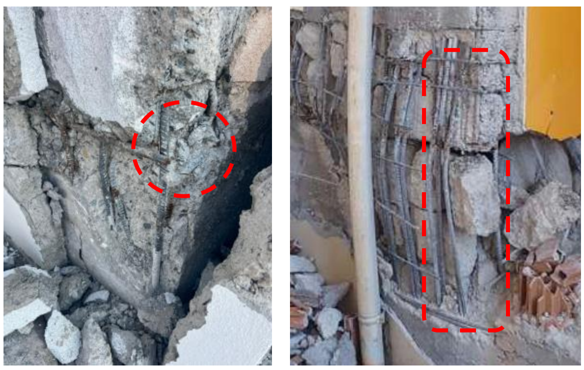

Figure 14. Rupture in stirrup and buckling of longitudinal reinforcement

- *Workmanship defects*

The workmanship defects can also cause tragic damage to the buildings during an earthquake. One of the main defects is the poor placement of concrete in the buildings. In some columns, coarse aggregates were observed and a homogeneous distribution was not achieved, so segregation took place. In these load-bearing structural elements, the reinforcement bars were also seen on the surface of the members, which can be due to the use of insufficient concrete cover around the longitudinal reinforcement (Fig. 15). Therefore, the bond strength between the reinforcement and concrete could not be achieved. Besides, it was seen that, in one of the beam elements, wood and large stone pieces mixed with the concrete during concrete pouring prevented the concrete from entering the mold, resulting in gaps between the reinforcements (Fig 16). The voids in the column and beam elements where concrete was not well placed showed faults in workmanship.

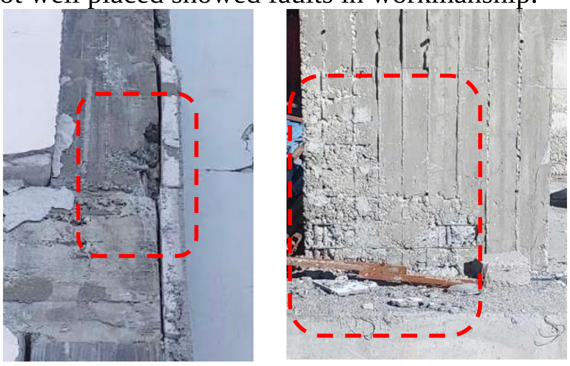

Figure 15. Insufficient concrete cover, concrete settlement problems and segregation

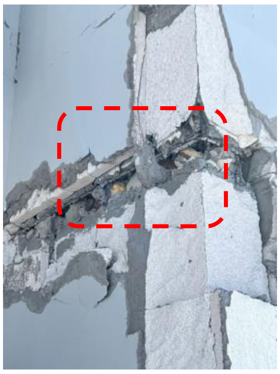

Figure 16. Foreign materials in concrete

- *Damaged staircase*

Staircases are one of the most important load-bearing structural elements and should not be damaged during an earthquake in order to ensure the safe evacuation of people from the buildings. The seismic damages in the joints of the staircase and landing were observed, as shown in Fig. 17. The spalling of the concrete cover occurred both on the landing and staircase-landing joint parts. Besides, on some staircases of buildings, splitting cracks were also observed on the concrete elements.

Figure 17. Damages in staircase

- *Defects in beam-column joint*

According to the earthquake regulations, it is aimed at absorbing the energy caused by the earthquake in the buildings by the beam elements and keeping the columns undamaged. Therefore, columns must be designed to be stronger than beams. A design implemented in this way will allow plastic hinges to form on the beam elements so that most of the energy will be absorbed in the damaged areas that will occur on the beams. The fact that the columns remain undamaged under the effects of an earthquake also prevents the structure from experiencing stability problems. However, from the observations, it was seen that there were structures that did not comply with this design principle. Observing Fig. 18, in some structures, the beams remained undamaged, and plastic hinges were formed at the lower and upper ends of the column elements. This situation led to the deterioration of the building's stability.

Figure 18. Stability problem due to weak column-strong beam situation

- *Shear damages in shearwalls and columns*

Shear damages caused by insufficient shear strength were observed in columns and shearwalls. Observing Fig. 19, cracks with a slope of 45 degrees were formed. This brittle type of damage can be considered heavy damage. The shearwalls were damaged due to the inability of the lateral reinforcement in the web of the element to meet the shear force caused by the earthquake. It caused the spalling of the concrete cover and crushed the concrete.

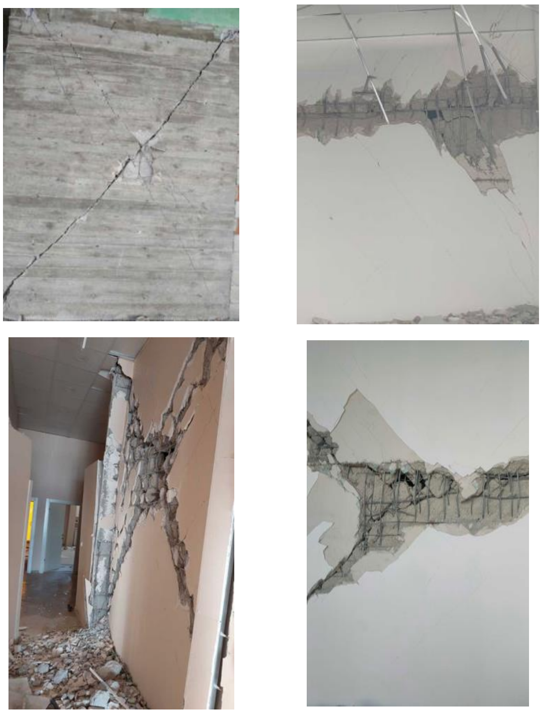

Figure 19. Shear damages in the shearwalls and columns

- *Shear cracks at the beams*

In the Turkish Building Earthquake Code, there are some restrictions that must be obeyed in the design of the end sections of the structural elements. According to this code, the reduction in the spacing of stirrups in the confinement area causes an increase in the energy consumption of this region. The shear cracks in the beam elements shown in Fig. 20 formed due to the increase in shear stress near the beam-column joint section. This type of damage can be due to the use of wide spacing between the stirrups in the beam-column joint section and inadequate transverse reinforcement. It was seen that the lack of reinforcement in the beam and beam-column joint sections caused critical damage.

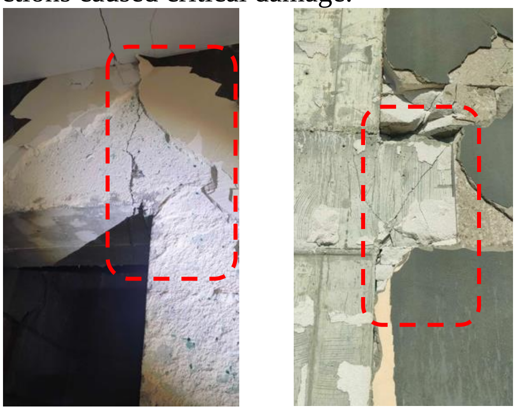

Figure 20. Shear cracks at the beams

- *Nonstructural damages*

The non-structural elements are the components such as curtain walls, chimneys, walls, cladding, etc. that are not in the load-bearing system of the building. Such damages can cause interruptions in the use of buildings after the earthquake. As seen in Fig. 21, cracks have formed on the outer surface of almost all buildings, and plaster and paint spills have been observed.

Figure 21. Cracks and plaster spills observed on the exterior of the buildings

Although the load-bearing capacities of the infill walls are ignored, they contribute to the lateral strength of the structure. The damages in the brick wall show the insufficiency of the lateral stiffness of the structure. The shear cracks were observed because of the inadequate rigidity of the structural system and as a result of the reversed cyclic lateral loading during an earthquake. Lots of shear cracks in the form of X were observed on both the interior and exterior walls of the buildings, as seen in Fig. 22.

In some buildings, the damages caused by the deflection of the walls in an out-of-plane direction due to the strong ground motion were observed. This type of damage can be due to inadequate adhesion between the walls and structural elements. Besides, it was observed that during lateral motion, the frame with no adequate lateral stiffness caused shear damage in the infill walls (Fig 23). In order to reduce this type of damage, in Turkish Building Earthquake Code-2018 [22], the use of elastic materials between the infill walls and structural system has been advised.

Figure 22. Shear cracks in walls

Figure 23. Out-of-plane toppling of walls and frame-wall separations

- *Soft storey irregularity*

As the brick infill walls used on the upper floors of the buildings are not continued on the ground floors due to the presence of shops or stores, a sudden decrease in rigidity occurs on these floors. This causes the formation of 'soft storey' irregularities. The presence of mezzanines on the ground floors of the buildings, which makes the floor height higher than the other floors, also causes a sudden decrease in rigidity. In this case, the lateral displacements between the ground and first floors of the buildings reach relatively high levels, and the stability of the building deteriorates. Especially in the district of Doğanşehir, many buildings were heavily damaged due to the formation of soft storey irregularities, and the ground floors were completely demolished (Fig. 24).

Figure 24. Collapsed structures due to sudden stiffness changes on the ground floor.

4.3. Damages in Masonry Buildings

The rural buildings in the countryside of Doğanşehir, Akçadağ, and Darende villages of Malatya have been heavily damaged, and it was observed that many masonry buildings constructed by their users without any engineering services collapsed (Fig. 25). These rural buildings in the villages were built with local materials found in the close vicinity, such as stone and adobe. In general, they are in the form of a one or two storey masonry structure.

In the villages of Doğanşehir, Akçadağ, and Darende, it was observed that the bearing walls were built using mud mortar as a binder. However, according to Turkish Building Earthquake Code-2007 [25], the use of lime mortar supported with cement or cement mortar was suggested as a binder in load-bearing walls. The minimum compressive strength of mortar for masonry buildings should be higher than 5 MPa, so the use of mud mortar as a binder could cause deficiencies. Besides, their flooring includes beams made of wood and plank decking. The wooden logs were placed in one direction, parallel to the walls. No mechanical connection between the wall sections was observed, so during the earthquake motion, the walls separated. The out-of-plane failures were observed in some buildings, as shown in Fig. 26. The quality of the workmanship of these buildings was so poor such that there were no horizontal bonding timber beams inside the bearing walls.

Figure 25. Collapsed structures in the rural areas

Figure 26. Wall damages in Gündüzbey and Akçadağ

It was observed that the loads formed during the earthquake caused the formation of shear cracks on the walls of the masonry structure (Fig. 27). In order to prevent this type of damage, during the construction of the building, continuous beams should be placed at certain heights that surround the structure.

Vertical cracks have occurred in the corners of the masonry buildings due to the effect of ground movement. With the growth of these cracks, the walls separated from the building were partially demolished, as seen in Fig. 28. This damage can be avoided by installing corner joints during the construction of the masonry structure.

Figure 27. Shear cracks in masonry buildings

Figure 28. Corner collapses due to vertical cracks in Akçadağ

5. Performance of Earth Structures and Geotechnical Evaluations

The dense construction in Malatya's city center makes it difficult to observe the surface traces created by the earthquake. However, in rural areas, data that allow observational evaluation, such as surface fractures, ground traces, and slope movements, can be encountered. Surface ruptures (i.e., ground rupture or ground displacement) occur as the apparent slip of the ground surface when an earthquake rupture affects the ground surface along a fault. Those ruptures, which pose a great risk for structures built along a fault belt that may be active, were observed in Akçadağ, the district of Malatya on the western border. The slit width reaches 1.5 m, and the height reaches 80 cm. The observed surface crevices were formed in a rural area with no settlement. Therefore, no structural effects were noticed (Fig. 29).

Figure 29 View of surface ruptures in Akçadağ district

Significant asphalt pavement damages were observed on the roads between Yeşilyurt and Gündüzbey districts, on the border of the city of Adıyaman in the south. It was observed that the deformation and cracks on the surface are deduced by the movement in the earth retaining structures supporting the road, which have an approximate height of 4 m. The lateral movement of the retaining structure supporting the road and the ground structure has also caused the movement of the abutment structure on the upper side. Rock masses broken off from the backfill caused significant deformations on the asphalt pavement (Fig, 30). Again, in this region, where the superstructure damage density is quite high, displacements and settlements have occurred on the highways supported by the retaining walls. Due to the lateral movement of the bearing structure, fractures and displacements of up to 40 cm occurred at the asphalt pavement level (Fig. 31).

Figure 30. The asphalt pavement cracks due to the lateral movement of retaining wall in Yeşilyurt district

Figure 31. The slided pavement due to lateral movement of retaining wall

Figure 32. Retaining wall failures and flow of backfill material

Even in small magnitude earthquakes, lateral displacement of retaining walls can be expected within certain limits. The movements of massive, weighted walls built on rock are more limited. The performance of the reinforced earth structures against these earthquakes has been observed to be quite successful. It has been concluded that this is largely due to the flexibility provided by the strip reinforcements used. Local and global failures were observed in the load-bearing structures built, especially in regions where soil amplification effects are observed. It is also considered that wall height is an important parameter of structural performance. Vegetation and afforestation, which correspond to significant surcharge loads in the abutment structures at the border of the public parcels, especially in the backfills, triggered the effects on wholesale collapses (Fig. 32).

6. Conclusion and Discussion

The aim of this study was to reveal the detailed field investigation in Malatya province after Kahramanmaraş Earthquakes on February 6, 2023. The field investigations showed that alluvial units in Malatya city center consist of unconsolidated gravel, sand, schist, and clays. This situation indicates that soil augmentation is effective in the damages that occur, especially in the city centre of Malatya (Bostanbaşı, Fahri Kayhan, Yüzakı, Battalgazi, Eski Malatya, Orduzu, and Fuzuli locations) where these units are stacked. In the region where commercial enterprises are concentrated, the building stock consists of relatively older buildings (built prior to 2000). It has been determined that significant destruction occurred in these structures, especially after the Elbistan (M_w 7.6) earthquake. While significant structural damages and destruction are observed in Doğanşehir, Akçadağ, and Yeşilyurt districts, the density of structural damage is lower in the districts of Kale, Hekimhan, and Yazıhan.

There are major problems with the way buildings were made, such as soft storey formations at the ground and normal storey levels, not enough dilatation joints between buildings, problems with concrete settling at column-beam junctions, not connecting transverse reinforcements as required, and damage caused by not having enough anchorage lengths. According to the local soil conditions, soil amplification affects a sizable portion of the buildings. However, no liquefaction or ground settlements due to liquefaction were observed in the building stock. The absence of soil liquefaction despite high acceleration earthquake loads and groundwater levels is attributed to the high content of fine materials in the soil layers. Cracks, swellings, and collapses on asphalt pavements have been observed at different widths and levels in the city and on the ring road.

Turkish Building Earthquake Code-2018 [22], which determines the necessary design and construction rules for buildings to be earthquake resistant and to minimize the damage caused by earthquakes, imposes building height restrictions depending on the building usage class and earthquake design classes, taking into account the standard. It was determined in the field investigations that the relevant criteria of the regulation were not complied with, especially in multi-storey and newly constructed buildings with high damage levels. In the field investigations, it was observed that the buildings were heavily damaged and collapsed due to design and construction errors. The buildings designed according to Turkish Building Earthquake Code-2007 [25] and Turkish Building Earthquake Code-2018 [22] survived the Pazarcık and Elbistan earthquakes with less damage. In general, the main construction defects are the low quality of concrete in the structural elements constituting the load-bearing systems of the structures built before the implementation of Turkish Building Earthquake Code-2007 [25], the arrangement of the reinforcements without considering the ductile design principles, and the failure to use suitable stirrups. In addition, it was determined that the structural irregularities that should have been taken into account in the design were not complied with. In masonry buildings, the use of low-strength wall materials, incorrect wall connections, and a lack of maintenance were determined to be the main construction defects. The settlements were selected and the structures were built without considering the amplification effects of the local soil characteristics during the earthquake.

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Contributions of the authors

All authors contributed equally to the study.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics

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