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СТРОИТЕЛЬСТВО CONSTRUCTION

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SEISMOLOGICAL, GEOTECHNICAL ANDSTRUCTURAL ASPECTS OF THE 2023 KAHRAMANMARASH, TURKEY EARTHQUAKE SEQUENCE

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Abstract. On 6 February 2023, Turkiye was hit by a sequence of very strong and destructiveearthquakes that affected 11 populated cities close to the ruptured fault line. The damage was very extensive in the region so that it was even to understand the orderof magnitude of the huge devastation and loss caused by this earthquake sequence.Many national and international research teams have been in the affected areas fromthe first day on, trying to make field observations from all aspects and get the per- ishable field data to use for the purpose of seismic loss mitigation for future poten-tial events. The observations reveal the fact that it will take a long time for the coun-try to recover from the adverse effects of this event, but we should also start the takemeasures immediately to mitigate the potential losses from future earthquakes.
Keywords: seismic base isolation, performance-based earthquake engineering, structural dynamics, friction pendulu

Turkiye is located in a seismologically very active region that is influenced by thecomplex motions of different tectonic plates and fault mechanisms nearby. The northward motion of the Arabian and African plates causes a high rate of crustal deformation in the Anatolian plate which results in large events on the main fault zones in the country (Figure 1). On average, a destructive earthquake occurs in Turkiye every 7 years according to statistical data from past earthquakes. Among the two main fault systems in Turkiye, the North Anatolian Fault Zone (NAFZ) hasbeen very active for the last century, creating many destructive earthquakes, includ-ing the latest 1999 Kocaeli and Duzce earthquakes [1-2]. However, the East Anato-lian Fault Zone (EAFZ) had been in a quiet period with only a few moderate earth-quakes for more than a century until the year 2010. On this date, a moderate earthquake with Mw=6.0 occurred in the northeast segment of the EAFZ that caused local damage in some of the rural villages in the region [3-5]. Then, ten years later,a stronger earthquake with Mw=6.8 occurred in the adjacent segment to the south-west of the EAFZ, this time affecting both rural regions and also the city of Elazig.These earthquakes were deemed to be the signs of abnormal activity on the EAFZ,which was unfortunately verified on February 6, 2023, by a sequence of very strongand destructive earthquakes that affected 11 populated cities close to the ruptured fault line. The damage was very extensive in the region so that it was even to un- derstand the order of magnitude of the huge devastation and loss caused by this earthquake sequence. Many national and international research teams have been inthe affected areas from the first day on, trying to make field observations from all aspects and get the perishable field data to use for seismic loss mitigation for future potential events. This paper includes the field observations of a technical team fromthe Earthquake Engineering Association of Turkiye (EEAT) from seismological, geotechnical, and structural aspects.

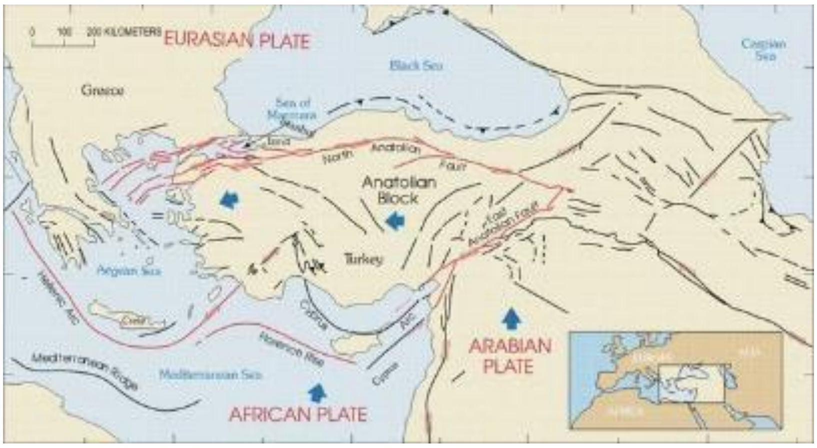

Figure 1. Tectonic map of Turkiye (modified from [6] General information about the earthquake sequence

On February 06, 2022, at 04:17, a major earthquake occurred in the EAFZ with the epicenter in Pazarcik, Kahramanmaras. The magnitude of the earthquake in terms of moment magnitude (Mw) was announced as 7.7 by the Disaster and Emer-gency Management Presidency (AFAD) (Latitude: 37.288 N, Longitude: 37.043 E). According to preliminary data, the depth of the earthquake was determined as ap- proximately 8.6 km. The tremors were markedly felt in the provincial capitals and districts of Kahramanmaras, Gaziantep, Adiyaman, Sanliurfa, Diyarbakir, Malatya,Osmaniye, Kilis, Adana, and Hatay. The distance of the earthquake to the nearest settlement, Akdemir village in the Pazarcik district of Kahramanmaras province, was 2.72 km [7]. Approximately six hours after the initial earthquake, another in- dependent substantial seismic event took place at 13:24 along the Eastern AnatolianFault Zone, with the epicenter in Kahramanmaras Elbistan. The earthquake's mo- ment magnitude (Mw) was declared as 7.6 by the AFAD. According to preliminaryinformation, the event's depth was ascertained to be approximately 7.6 kilometers. The seismic occurrence's proximity to the nearest settlement, Gumusdoven village within the Elbistan district of Kahramanmaras province, is 1.70 kilometers [7]. In accordance with AFAD Earthquake Deparment data, between February 6 and March 19, 2023, thousands of aftershocks were documented, 3 of which exceeded Mw 6, 44 of which exceeded Mw 5, and 510 of which exceeded Mw 4. The focal mechanism solutions published by the AFAD and the aftershocks' distribution are given in Figure 2. As of March 20, 2023, it has been confirmed by the authorities that approximately 255,000 buildings have been damaged or destroyed so far, morethan 50,000 citizens have died and more than 107,000 citizens have been injured.

The left-lateral strike-slip EAFZ, along with the NAFZ, constitutes one of Turki-ye's most active primary fault belts, extending approximately 580 km from Karliovato Antakya, and plays a crucial role in the region's geodynamic evolution and seis-micity [8-17].

The DAFZ is comprised of seven primary segments. These include Karliova, Ilica,Palu, Puturge, Erkenek, Pazarcik, and Amanos fault segments [18] extending fromthe northeast to the southwest (Fig.3). It is stated that the Mw 7.7 Pazarcik earth-quake resulted from the rupture of the Erkenek, Pazarcik, and Amanos fault seg-ments and is situated within the northeast-southwest trending DAF zone. The Mw

7.6 Kahramanmaras Elbistan earthquake occurred on the Cardak fault, which is po-sitioned in the western portion of the northeast-southwest and east-west trending Surgu fault segment. This segment is also located within the northern branch of theDAF zone.

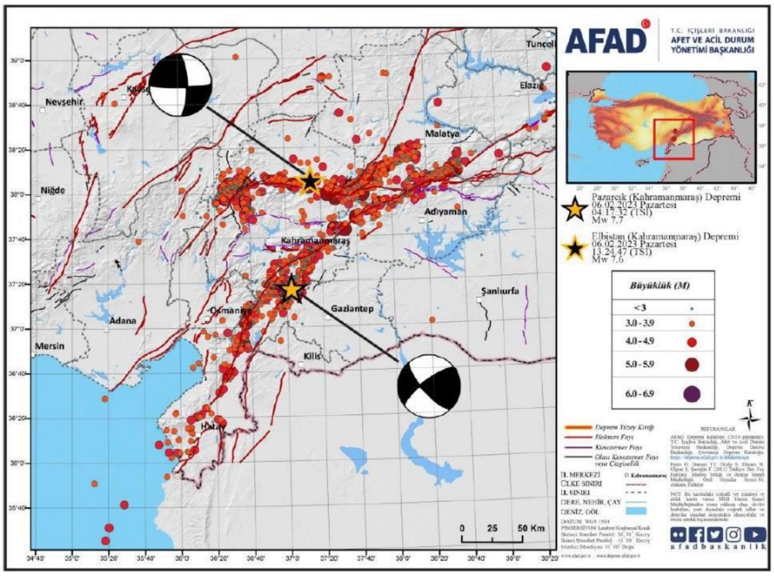

Figure 2. Mainshock activity of the Pazarcik (Kahramanmaras) Mw = 7.7 and Elbistan (Kahramanmaras) Mw = 7.6 earthquakes and their aftershocks for which focal mechanism solution was determined by AFAD [7]

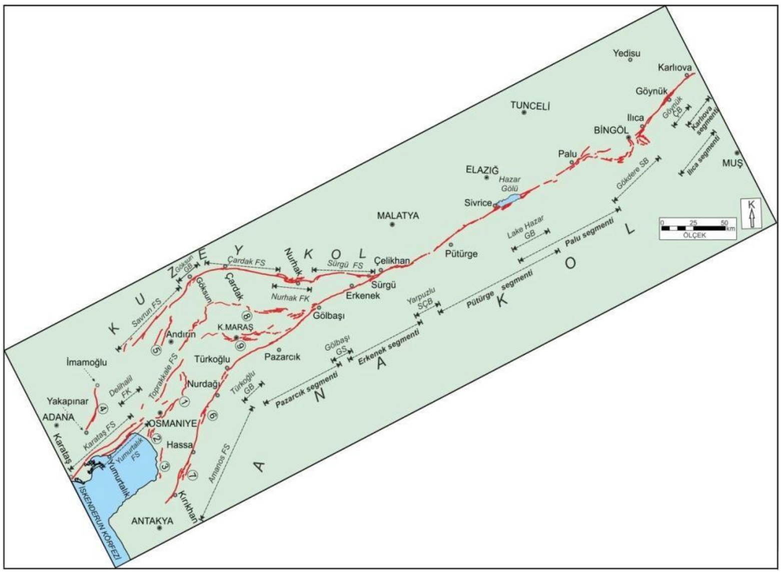

Figure 3. Map showing the segmentation of the East Anatolian Fault Zone [18]

Seismological aspects. The earthquakes occurred on the well-known seismic gap along the EAFZ including the long Pazarcik and Amanos segments. The first earthquake with Mw=7.7 (USGS) occurred on the left lateral EAFZ with an epicenter near Pazarcik, Kahramanmaras. The USGS fault planes indicate bilateral rupture on multiple seg-ments of EAFZ for a total rupture length of 400 km approximately. The second event occurred on the Northern segments of EAFZ near Ekinozu with Mw= 7.6 (USGS). Both events resulted in a large set of strong motions recorded by the net- work in the region, however, the first event has more near-field records than the second one. The shaking intensities in the region indicate an extreme event, partic-ularly for the first earthquake.

Figure 4 displays two selected records from the first earthquake. The rupture dis-tances and site conditions are also provided. The station with code 3138 is located on relatively stiff soils in Hassa, Hatay. The response spectra of the horizontal com-ponents are very broadband in nature and they exceed the maximum design earth-quake at almost all periods while they exceed also the maximum credible earth- quake level at longer periods. Station 4615 is located in relatively softer soil conditions in Pazarcik, Kahramanmarash.

Next, a comparison of the recorded strong motions against two existing ground motion models is made. Figure 5 demonstrates the recorded PGA and PGV levels against models by [20] and [21], respectively. The comparisons show that PGA val-ues overall confirm the median estimates of GMMs with a few exceptions. How- ever, PGV values overestimate the median levels of the GMMs. This could be at- tributed to long-period enhancements from basin effects, forward directivity pulses,or local soil behavior. Further conclusions can be obtained by performing detailed residual analyses for PGA, PGV as well as spectral accelerations.

Further details on the recorded peak motion parameters, several intensity measures, and felt intensity values of the Kahramanmaras sequences can be found in the reference [19].

Ground damages and geotechnical findings. Adiyaman City0 in the Golbasi district of Adiyaman province, the presence of groundwater levelsnear the surface and alluvial soils has led to remarkably high damage, particularly due to liquefaction-induced phenomena. In the flat areas of the city center, nearly all structures, although not exhibiting structural damage, have experienced substan-tial settlements. Structures built under similar conditions but extending towards thehighland topography, however, have not encountered settlement or other types of damage.

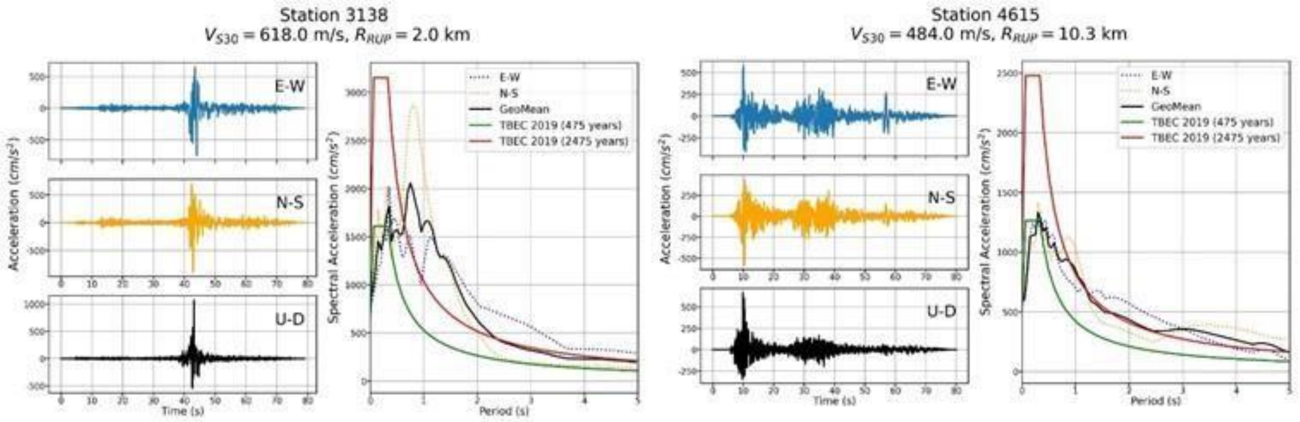

Figure 4. Acceleration time histories and response spectra at selected stations thatrecorded the Mw=7.7 Kahramanmaras earthquake
(figures are modified from the originally published versions in [19])

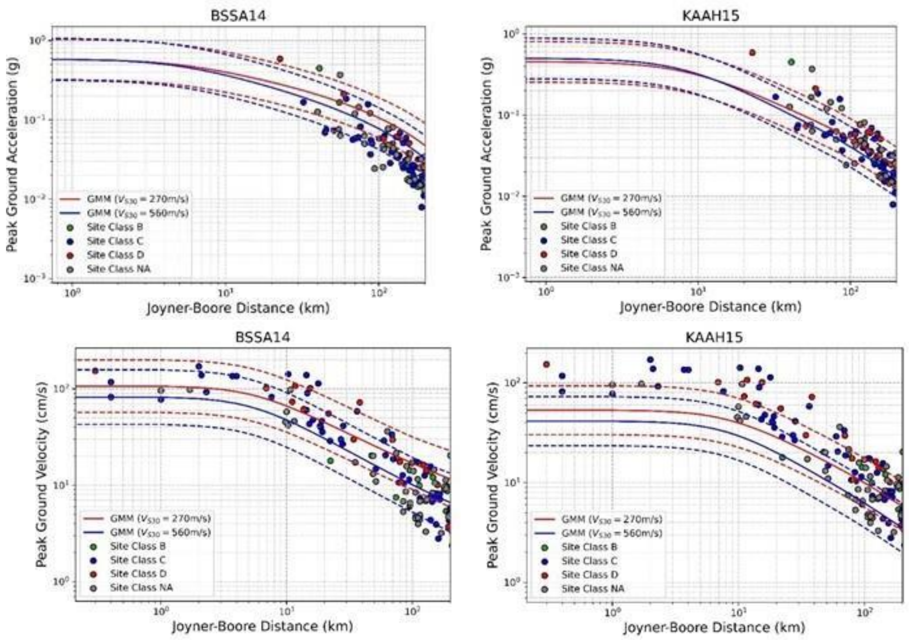

Figure 5. Comparison of recorded peak ground motions against selected empirical models [19]

Figure 6 displays a building that has entirely tilted backward on its foundation without any deformation in its structural elements. The other photographs illustratethe soils have liquefied, leading to the settlement of the building foundations and bulging of the soils surrounding the foundations.

Figure 6. Tilting of buildings and heaving of soils around foundations due to liq-uefaction (Adiyaman- Golbasi) [19]

Gaziantep City. There are few damages in the Gaziantep city center. In the villages close to the city center, a few collapsed single-story buildings were observed. Cave collapses, slope failures and rock falls caused by earthquakes are existing both in the city cen-ter and its immediate vicinity.

Nurdagi is one of the districts in Gaziantep that was directly affected by surface fault rupture. Due to surface faulting, large damages occurred in houses (Fig.7.a)and large deformations and settlements occurred on road routes (Fig.7.b).

Figure 7. a) Major damage to houses due to surface faulting (left), b) defor-mations and settlements due to surface faulting on the road in Nurdagi (right) [19]

Large mass failures due to rockfalls were encountered on the slopes along the Gaziantep Osmaniye road east of Nurdagi (Fig.8.a). The retaining structure alongthe water canal on the railway route in the Fevzipasa neighborhood of Islahiye (Gaziantep province) collapsed towards the canal due to lateral spreading (Fig.8.b).

Figure 8. a) Rockfall on the road route around Nurdagi, b) damages due to lateralspreading along the stream channel in the Fevzipasa neighborhood of Islahiye [19]

Hatay City. Hatay has been subjected to major and destructive earthquakes in the historical process. The city has developed on an alluvial valley basin, plains, and terrace sed-iments of different levels created by the

Asi River. Especially in the center and dis-tricts of Antakya along the Asi River, settlements and lateral spreading due to allu-vial soils increased the structural damage (Fig.9).

Figure 9. Settlements in alluvial soils along the Asi River in Hatay and damageto retaining walls due to lateral spreading [19]

In the Cay neighborhood located within the borders of the Iskenderun district of Hatay province, sand boils due to seismic liquefaction was observed intensively. The seaside fishing harbor in Iskenderun was heavily damaged in the earthquake, and differential settlements were observed in the region (Fig.10).

Figure 10. Surface manifestations of the sand boil as seismic liquefaction in Is- kenderun Hatay (left), lateral spread due to liquefaction in the fishing harbor area in Iskenderun, Hatay (right) [19]

Kahramanmaras City. No significant geotechnical damage was reported in Kahramanmaras city center. There had been completely collapsed buildings concentrated in the southern parts of the city. Although geotechnical damage has not been reported observationally, detailed site investigations should be carried out on the quaternary alluvial sedi- ments in this region to determine whether the damage is soil related.

Traces of surface faulting along the EAFZ in the Turkoglu district are observed atthe east of the district. Since a significant part of the district is located on alluvial deposits, these soils were especially effective in increasing the damage in the area.Lateral spreading and sand boil due to soil liquefaction were observed in the region(Fig.11.a and 11.b).

Figure 11. a) Lateral spreading (left), b) sand boiling due to soil liquefaction(right) [19]

Structural aspects. It can be observed that structural damage is severe and widely spread in the af- fected areas due to the high demands imposed by the seismic action of the earth- quake sequence and also the high seismic vulnerability of the building stock. The most affected cities are Antakya, Kahramanmaras, Adiyaman, and Malatya with tens of thousands of buildings either collapsed or severely damaged beyond repair.The number of collapsed (or to be immediately demolished), severely damaged andmoderately damaged buildings declared by the Ministry of Environment, Urbaniza-tion and Climate Change by 19 March 2023 are provided in Table 1 for the affectedcities, which add up to more than 300,000 buildings in total. In addition, provincesclose to the ruptured fault line like Elbistan (Kahramanmaras), Pazarcik (Kahramanmaras), Nurdagi (Gaziantep), Islahiye (Gaziantep) and Golbasi (Adi- yaman) lost most of their building stock so that the authorities are even planning tocarry some of these provinces to new and seismically safe settlement areas. Some major site observations related to this inconceivable structural damage are given inthe rest of this section.

Table 1. The statistics related to structural damage in the affected cities [19]

City	Collapsed/To Be Demolished	SeverelyDamaged	Moderatelydamaged
Adana	176	929	2112
Adiyaman	8202	21909	6876
Diyarbakir	87	4592	3363
Elazig	101	7442	506
Gaziantep	5679	13833	7426
Hatay	21003	64895	13102
Kahramanmaras	11815	37549	6696
Kilis	609	1803	642
Malatya	5482	33603	2305
Osmaniye	1187	8863	1397
Sanliurfa	1543	5468	3020

Antakya, Hatay is the most adversely affected city from this earthquake sequence.This is due to the fact that the ground motion intensities had been drastically ampli-fied due to soft site conditions and the directivity effect of the ruptured fault in the first earthquake. In addition, a large aftershock with Mw=6.4 took place in the vi- cinity of the affected region and caused further destruction among the damaged structures. At the center of the city near the Asi River, there is total destruction as seen in Fig.12.

Figure 12. The photos of total destruction in Antakya, Hatay (courtesy of the EEAT) Antakya city was recognized for its cultural diversity and richness and it resided many historical structures, including invaluable heritage belonging to different re- ligions. Unfortunately, most of these structures were either severely damaged or collapsed during the sequential earthquakes of February 2023 in Turkiye (Fig.13) [19]

Figure 13. Damaged historical structures in Antakya after earthquake sequence;
a) Habib-i Neccar Mosque (courtesy of the EEAT), b) Rum Orthodox Church [19]

Another highly affected city center, which is close to the epicenters of both Mw7+ earthquakes is Kahramanmaras. Especially the mid-rise reinforced concrete (RC) buildings in the old city center that resides on soft soil deposits were razed down under strong shaking (Fig.14).

Figure 14. Complete destruction in Kahramanmaras city center (courtesy of the EEAT) [19]

Similar views of damaged buildings exist in the city centers of Adiyaman and Malatya. This high percentage of building damage seems to depend on many factorsfrom the design stage to the construction stage of these buildings. The adversely affected buildings with ordinary beam-column framing systems have been observedto be very flexible. This dynamic nature seems to have caused extensive drifts dur-ing strong shaking beyond the deformation capacity of columns. In addition, the ground story with commercial use worked as a soft-story mechanism in most of these buildings leaving no chance of survival for the occupants. Poor concrete strength, insufficient detailing, and improper supervision during the construction stages of these buildings are among the major issues that caused the high seismic vulnerability of these buildings (Fig.15).

Figure 15. Structural deficiencies observed in damaged buildings (courtesy of theEEAT) [19]

It was also observed that the buildings on the hillsides of the aforementioned citycenters with relatively stiff soil conditions performed better during the earthquake with light damage on the non-structural infill walls only (Fig. 16.a). Even old low-rise buildings with poor construction stood still without serious damage (Fig.16.b). This shows the significant variations in seismic demand with changing topo-graphical and soil conditions.

Figure 16. Buildings on the hillside of Kahramanmaras city center; a) (left) new high-rise RC frame buildings with no/slight damage, b) (right) old and low-rise RCand masonry buildings that performed relatively well during the earthquakes (cour-tesy of the EEAT) [19]

Critical structures like hospitals and school buildings behaved relatively well dur-ing the earthquakes. Some hospitals with old and deficient construction collapsed during the earthquake, killing the patients and the medical people inside the build- ings. Some others were damaged, especially with extensive non-structural damage, causing the interruption of the medical services during the post-earthquake emer- gency period (Fig.17.a). Base isolation systems had been used in some newly constructed hospitals and they all showed satisfactory behavior during the strong shaking (Fig.17.b).

The school buildings also experienced varying levels of structural damage from none to severe damage (Fig.18). It was fortunate that no students were injured during the earthquake sequence since the first main shock happened at 4 a.m. beforedawn and none of the schools were open during the second main shock.

Figure 17. a) Existing city hospital in Kahramanmaras with extensive non-struc- tural damage, b) a new hospital construction in Kahramanmaras with base isolationsystem (the isolators worked and performed well during the earthquake although most of them were not installed yet) (courtesy of the EEAT) [19]

Figure 18. a) A school building with no damage in Golbasi (Adiyaman), (top) b) a severely damaged school building in Kahramanmaras city center (bottom) (cour-tesy of the EEAT) [19]

Summary and conclusions. On 6 February 2023, Turkiye was hit by a sequence of very strong and destructiveearthquakes that affected 11 populated cities close to the ruptured fault line. The damage was very extensive in the region so that it was even to understand the orderof magnitude of the huge devastation and loss caused by this earthquake sequence.Many national and international research teams have been in the affected areas fromthe first day on, trying to make field observations from all aspects and get the per- ishable field data to use for seismic loss mitigation for future potential events. In this study, the seismic performance of the base-isolated hospital buildings at the Kahramanmaras earthquakes was evaluated. Several base-isolated hospitals locatedin the cities affected by the earthquakes were inspected in a field study. Isolator displacements as well as structural damage if present were documented. The fol- lowing conclusions were reached:

This paper summarizes the field investigations of a technical team from the Earth- quake Engineering Association of Turkiye (EEAT) from seismological, geotech- nical, and structural aspects. The observations reveal the fact that the seismic de- mand imposed by the earthquake was very high. On the other hand, the majority ofthe building stock in the region is highly vulnerable to earthquakes since the area did not experience a large earthquake for a long time. The RC frame structures arevery flexible and brittle, so they could not resist the earthquake forces imposed by these earthquakes. There are also damages caused by the rupture and the ground failures. Overall, it seems that it will take a long time for the country to recover from the adverse effects of this event, but we should also start the take measures immediately to mitigate the potential losses from future earthquakes.

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