



24 January 2020 Sivrice-Elazığ, Turkey earthquake: geotechnical evaluation and performance of structures

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Received: 1 July 2020 / Accepted: 8 December 2020 / Published online: 2 January 2021
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Abstract

The January 24, 2020 Sivrice-Elazığ (Mw = 6.8) earthquake occurred on the East Anatolian Fault zone. Main shock of this earthquake was occurred 20:55 at local time. The Peak Ground Acceleration was equal to 0.3 g at the epicenter (Sivrice district) of the earthquake. Even though the main shock was moderate, its effects on the structures were rather serious. The main shock caused significant damage and resulted in 41 casualties. 1540 buildings were damaged moderately, while 8519 buildings were damaged heavily and collapsed. This main shock effected four cities surrounded the epicenter due to its shallow earthquakes. The purpose of this paper is to summarize past and present seismic characteristics of the earthquake region. In addition, the aim of this paper is to summarize the seismotectonic of the region, the general characteristics of the earthquake and more specifically to report on the structural damage, and structural damage caused by the earthquake, observed during the site investigation. The damages were classified for reinforced concrete structures, masonry dwellings and non-residential structures. All distinguished earthquake induced failures and damages were discussed. Moreover, lessons learned were presented in this study.

Keywords 2020 Sivrice-Elazığ earthquake · Seismotectonic features · Geotechnical effect · Reinforced concrete structures · Masonry dwelling · Structural failure

1 Introduction

On January 24, 2020, an earthquake occurred in Sivrice, district within the borders of Elazığ Province in the Eastern Province of the Eastern Anatolian Region of Turkey. This earthquake directly resulted in 41 death and hundreds of injured people. The main shock

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occurred on the East Anatolian Fault (EAF) and beginning of the third segment of EAF was ruptured at 20:55 local time with a Magnitude (M_w) of 6.8 according to Disaster and Emergency Management Presidency of Turkey (DEMA 2020). The Sivrice earthquake was triggered by the rupture of the EAF zone. The origin of EAF earthquakes is the northward movement of the Arabian plate and then westward movement of Anatolia. These tectonic plate movements and the connection of EAF with the North Anatolian Fault (NAF) can be seen in Fig. 1. In this figure, the white boxes represent the ENVISAT ASAR frames from tracks T264 and T400, while the shaded topography is from Shuttle Radar Topography Mission (SRTM) 90 m—posting data (Şentürk et al. 2019).

EAF is composed of seven main segments, namely Karlıova-Bingöl (#1), Palu-Hazar (#2), Hazar-Sincik (#3), Çelikhan-Erkenek (#4), Gölbaşı-Türkoğlu (#5), and Türkoğlu-Antakya (#6). The lengths of these fault lines range between 31 and 112 km (Emre et al. 2018). The Sivrice-Elazığ earthquake occurred on Hazar-Sincik fault segment. The length of this fault is around 80 km and the surface deformation has been observed along 48 km of the total length (Kürçer et al. 2020). In addition, a calculation rupture of 40 km was reported by the DEMA (2020). However, how much of this fault line was ruptured during the main shock needs further investigation. Several damaging earthquakes occurred on EAF throughout history. Ruptures associated with historical as well as recent major earthquakes are presented in Fig. 2 along with the epicentral locations of the February 9, 2007 ($M_w = 5.5$) Gözeli-Sivrice and the January 24, 2020 ($M_w = 6.8$) Sivrice-Elazığ earthquakes.

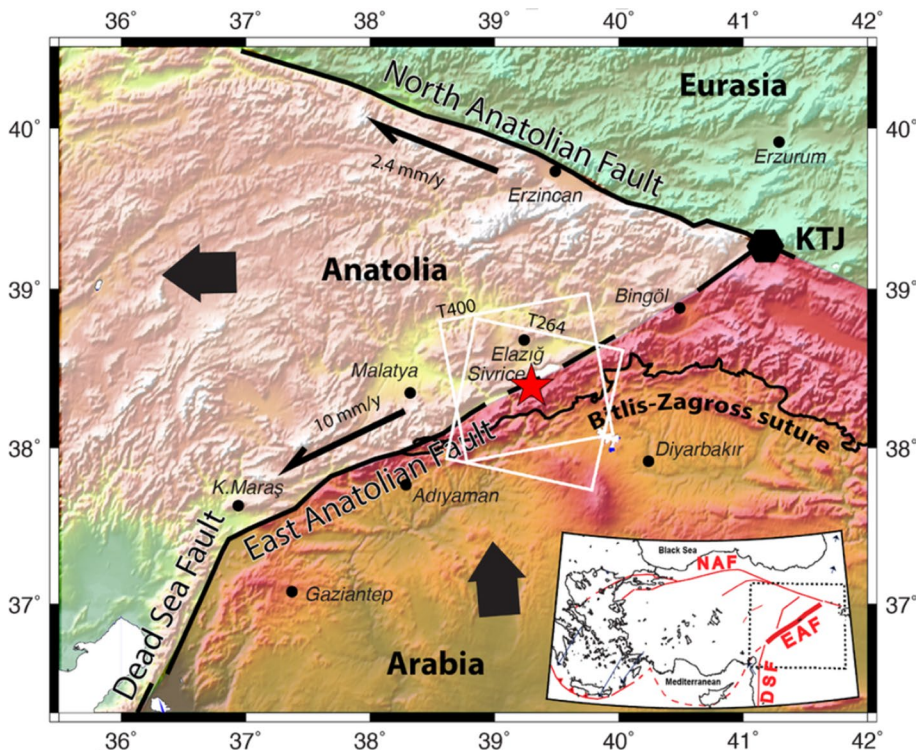


Fig. 1 Plate movement, major faults, and the epicenter of the Sivrice (Şentürk et al. 2019)

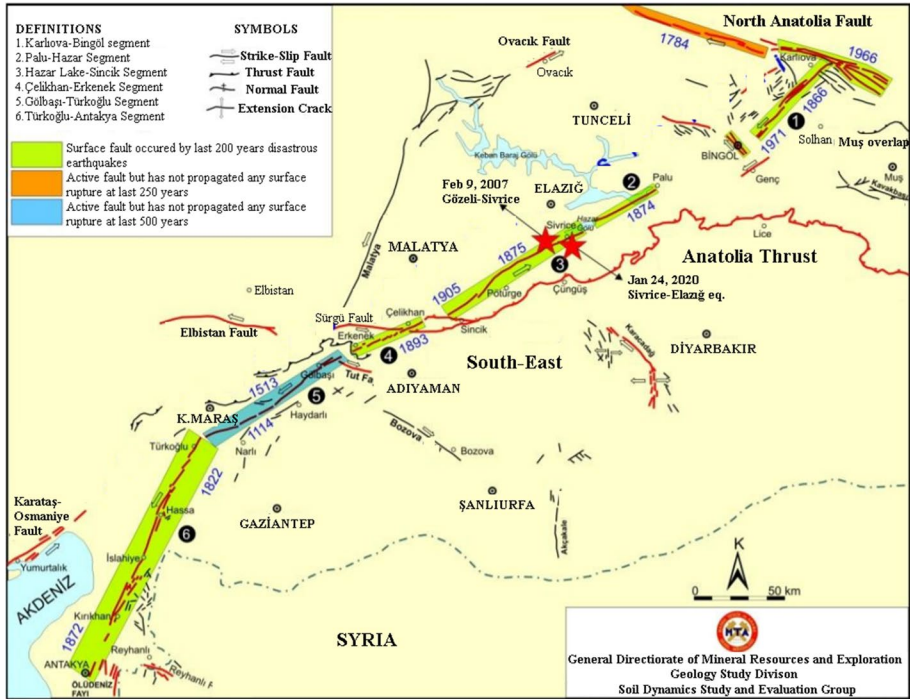


Fig. 2 Main segments of the East Anatolian Fault Zone and Historical Damaging Earthquakes (Adopted from MTA) (Kürçer et al. 2020)

The EAF zone starts from Karlıova, which is the junction of EAF and NAF, continues north of the Adiyaman, Gaziantep provinces and is linked with the Cyprean Arc, along which the Africa/Anatolia convergence is taken up by means of thrusting and strike-slip faulting as presented in Fig. 2. (Yürür and Chorowicz 1998) An annual 10–11 mm of slip rate has been measured and reported (e.g. Şentürk 2019).

The aim of this paper is to summarize the seismotectonic of the region, the general characteristics of the earthquake and more specifically to report on the structural damage. Moreover, the observation of field investigation on structural damage caused by the January 24, 2020 Sivrice (Elazığ) earthquake was carried out along the earthquake region. The observed damage was classified for reinforced concrete (RC) structures, masonry dwellings and non-residential structures. All distinguished earthquake induced failures and damages were discussed. Moreover, lessons and learned were presented in this study.

2 Historical damaging earthquakes on the EAF around Elazığ province

Elazığ is located in the Eastern part of Turkey, exactly on one of the active EAF segments. Although, the seismicity of this region is relatively high. The EAF zone, except the 1971 Bingöl earthquake, has taken yet another period namely “quiescent” in the last century, and has not experienced any earthquake of high magnitude enough to form a surface rupture. In the history, many damaging earthquakes were reported between 1700 and 1900 B.C. In the

period from 1900 to the present, the high intensity earthquakes occurred on the EAF were presented in Fig. 3 (KOERI 2020).

A catastrophic earthquake occurred between Palu and Bingöl in 1789. Approximately 51 thousand people died in a region of 75 km radius. After this earthquake, a great destruction occurred along the region from Gaziantep to Antakya even down to Aleppo, and caused surface fractures, leading to liquefaction in the Amik Plain. Approximately 20 thousand people died in the earthquake. A devastating earthquake was propagated by the Karlova-Bingöl segment in 1866 (DEMA 2020; Jackson and McKenzie 1984). Six years after this earthquake, there was another damaging earthquake produced by the Türkoğlu-Antakya segment in 1872. The earthquake destroyed most of the town within the borders of Antakya. After this earthquake, one another damaging earthquake occurred on the Palu-Hazar Lake segment in 1874 and in 1875 in the Hazar Lake-Sincik segment, respectively. Damaging earthquakes have been experienced until the end of the nineteenth century. Elazığ, Palu and Sivrice locations were experienced severe earthquakes. The last earthquake on the EAF zone occurred on Çelikhhan-Gölbaşı segment in 1893. The severe earthquakes occurred on the Hazar Lake-Sincik Segment. The 1905 earthquake caused severe damage to many villages between Pütürge and Çelikhhan towns, resulting in deaths of many people (DEMA 2020). After this last earthquake “quiescent” period has been started until the 1971 Bingöl earthquake.

3 Seismic characteristics of the earthquake and damage distribution

The January 24, 2020 Sivrice earthquake is the most recent earthquake that occurred on the EAF. This ground motion has been recorded by six seismological station as declared by the DEMA. Depth, magnitude and location of the stations were tabulated in Table 1.

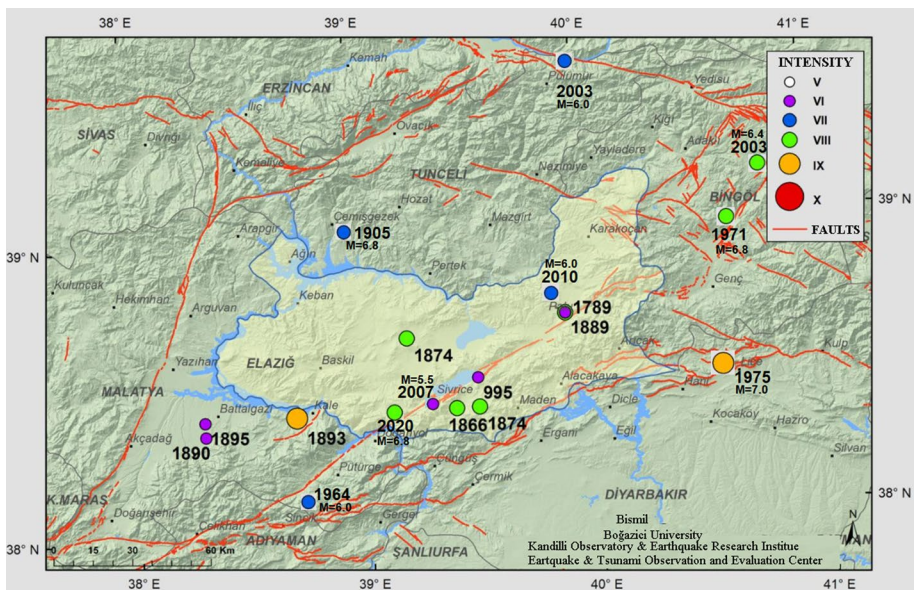


Fig. 3 The epicentral intensities assigned to historical earthquakes (Adopted from KOERI 2020)

Table 1 Earthquake characteristics and location of earthquake

Parameter	DEMA ^a	KOERI ^b	INGV ^c	GFZ ^d (Geofon)	USGS ^e	CSEM ^f
Magnitude (M_w)	6.8	6.5	6.8	6.8	6.7	6.8
Depth (km)	8.06	5.0	11.0	10.0	11.9	15.0
Location						
Longitude	39.06	39.24	39.12	39.20	39.08	39.22
Latitude	38.36	38.37	38.39	38.36	38.39	38.37

^aTurkish Ministry of Interior Disaster and Emergency Management Presidency

^bKandilli Observatory and Earthquake Research Institute

^cInstituto Nazionale di Geofisica e Vulcanologia

^dGerman Research Center for Geosciences

^eUnited States Geological Survey

^fEuropean-Mediterranean Seismological Centre

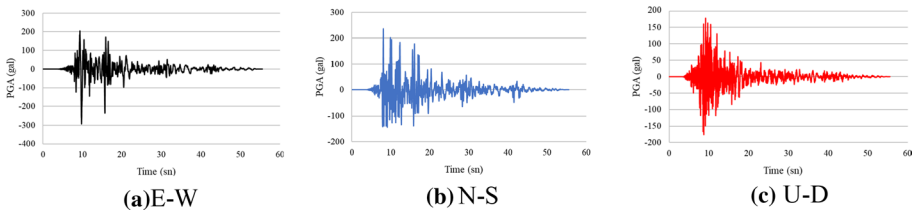


Fig. 4 Acceleration time history

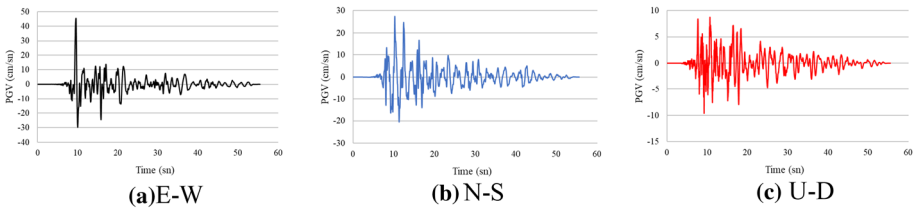


Fig. 5 Velocity time history

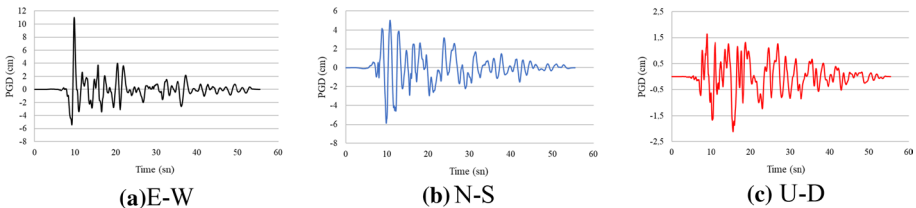


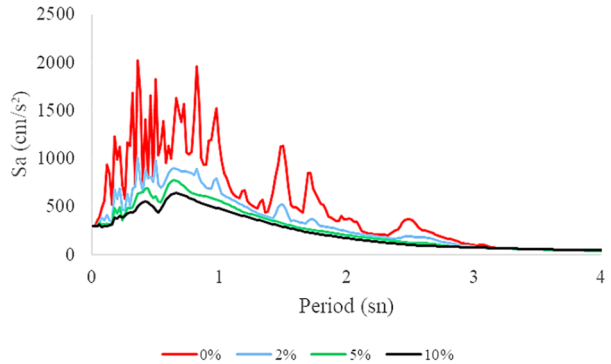
Fig. 6 Displacements time history

All components of the time histories of acceleration, velocity and displacements of earthquake record were plotted and presented in Figs. 4, 5 and 6 respectively. Three components of one record were obtained from addressed site (URL1). The highest

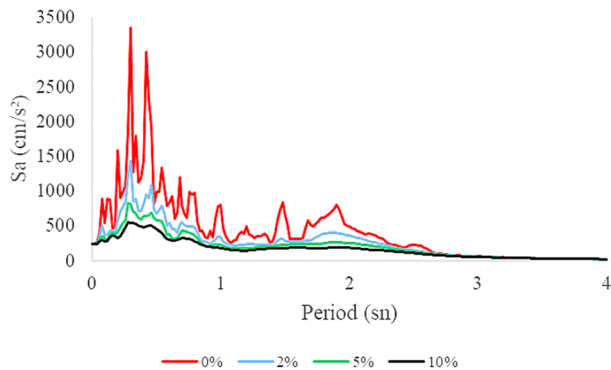
station record belongs to Sivrice station and the values are 0.292 g in the East–West (E–W) direction and 0.238 g in the North–South (N–S) direction. The Peak Ground Acceleration (PGA) value decreases to 0.141 g in the E–W direction and 0.119 g in the N–S direction in Elazığ city center.

The acceleration response spectra of each component of Sivrice Station acceleration records are plotted in Fig. 7 for damping ratios of $\zeta = 0, 2, 5,$ and 10%

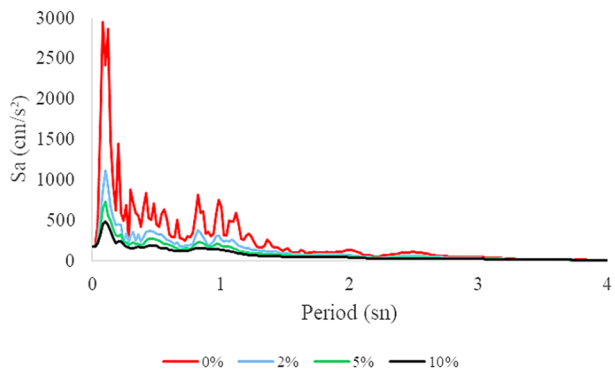
Fig. 7 Acceleration response spectra for North–South, East–West and vertical components of Sivrice station acceleration records



(a) E-W component



(b) N-S component



(c) U-D component

Figure 8 represents the comparison of acceleration response spectra of the PGA in both E–W and N–S directions. The comparison is performed by considering the former Turkish Earthquake Code 2007 (TEC-2007) and the current Turkish Building Earthquake Code 2018 (TBEC-2018). As seen from the Fig. 8, TBEC-2018 provides safer spectra. The soil type of the earthquake induced territory was assumed as soft soil (ZC) according to TBEC-2018 and Z3 for TEC-2007. Soil profile of the centre of Elazığ province is composed of the quarters, old alluvium, and accumulation of the stream debris flowed from steep slopes. Moreover, consists of a mixture of gravel, sand, mud and slope debris. In the alluvial area of the city, the groundwater level generally varies between 10 and 20 m (Tabban 2000).

The EAF was rather quiescent until the beginning of the millennium as reported compared to NAF (Demirtaş and Erkmén 2008; Yön et al. 2020). This quiescence was intervened by 2003 Bingöl earthquake, then 2010 Kovancılar earthquake as presented in Fig. 3. Finally, after 145 years later from the last damaging earthquake in Elazığ, the January 24, 2020 Sivrice—Elazığ earthquake occurred on the same fault segment. After the main shock, many aftershocks were recorded and plotted in Fig. 9 for 32 days after the main shock.

After the main shock, 488 earthquakes (maximum number in a day) occurred the region on January 25, 2020 with a maximum 5.1 magnitude and then 20 earthquakes (minimum number in a day) were measured on February 24, 2020 with a maximum 2.1 magnitude.

Half of the magnitudes were classified between 3.1 and 4.0. 28% of aftershocks were between 2.1 and 3.0. The magnitudes of 16% of aftershocks were between 4.1 and 5.0. Finally, 3% of the magnitude ranges of 5.1–6.0 and 3% is between 6.1–7.0, respectively.

Ground motion relationships of PGA values of Sivrice Earthquake were also employed in this study for a further and detailed investigation. Two latest ground motion models, i.e. Akkar et al. (2014) and Erken et al. (2018) were considered and plotted in Fig. 10 for E–W and N–S directions. The maximum PGA of the earthquake was measured through the E–W direction. The ground motion models were evaluated for both E–W and N–S components of the earthquake and plotted in the same figure. As

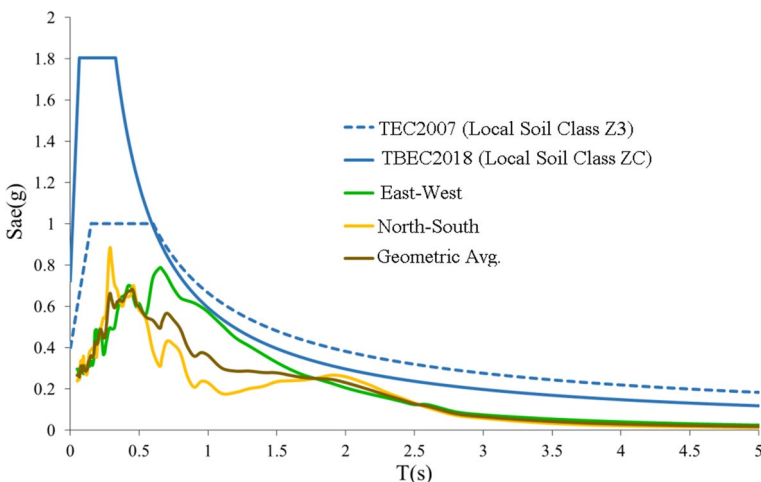


Fig. 8 Comparison of response spectra with former and current design spectra (DEMA 2020)

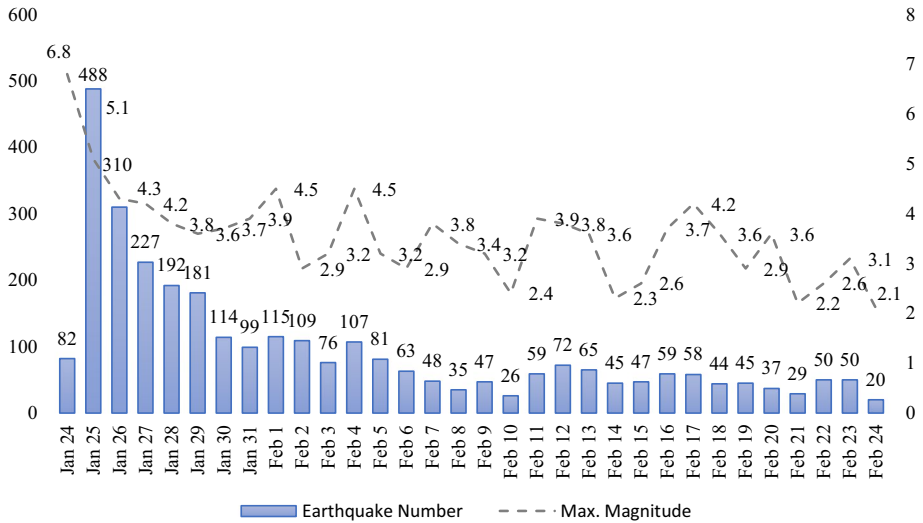


Fig. 9 After-shock number and magnitudes during the 32-day period (Adopted from DEMA 2020)

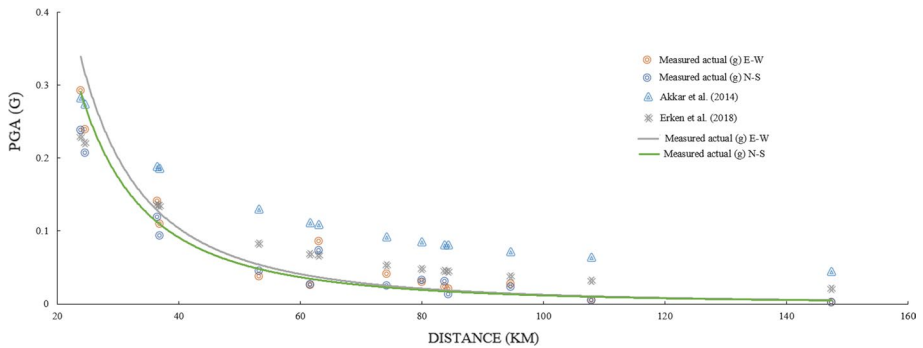


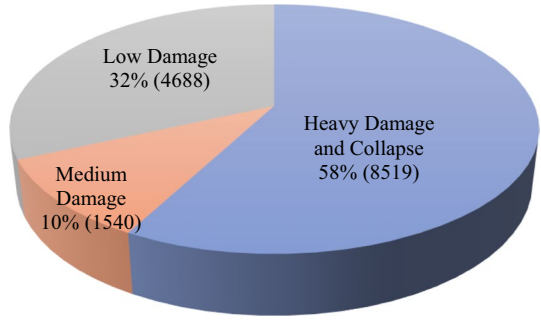
Fig. 10 The PGA and distance relationship for the E–W and N–S direction along 150 km

presented in the figure, the commonly used latest ground motion models were used for European and Middle East.

Field reconnaissance was carried out between 15 and 40 km distance from the epicenter. Between this distance, structural systems were exposed to PGA from 0.3 to 0.15 g. In addition to this, geotechnical observations were performed around the Hazar lake. Investigated area is between the 23 and 41 km from the epicenter.

Even if the 2020 Sivrice-Elazığ earthquake was a moderate earthquake, 41 people died, and 1607 people were injured. This earthquake caused collapses and failures of dwellings. Immediately after the seismic shock, a field observation and damage classification process were started by expert teams. Figure 11 shows statistical data based on damage and collapse.

Fig. 11 Damage and collapse percent (URL2)



4 Geotechnical findings

Geotechnical observations were conducted in Sivrice district, the epicenter of the earthquake, and in the villages connected to it as well as on the shores of the Hazar Lake in the region. As a result of the observations at seven investigation areas shown in Fig. 12, four geotechnical findings (lateral spreading, soil liquefaction and sandy soil, rockfalls, and soil deformations) were obtained in general (Fig. 13).



Fig. 12 Region and observation points where geotechnical investigations were performed (adopted from Google Earth)

Fig. 13 Some geotechnical incidents that may occur after an earthquake (Adopted from Mollamahmutoğlu and Babuçcu 2006)

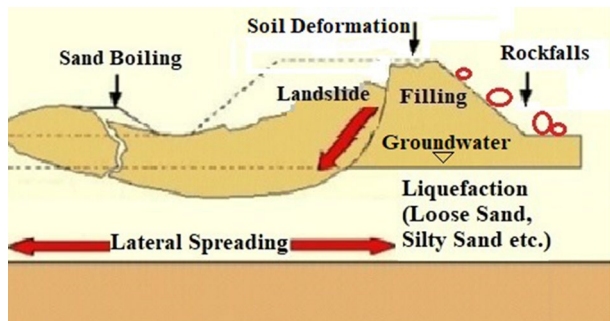




Fig. 14 Active fault (yellow line), dock, lateral spreading area (investigation area 1) (modified Google Earth)

Fig. 15 Lateral spreading (investigation area 1)



4.1 Lateral spreading

During the observations in this region, it was seen that the slope was low and there were lateral spreading incidents in the fields close to the water body (Fig. 14). The inclination of the area with lateral spreading was between 2° – 3° , and 2–6 cm displacements occurred on the soil because of lateral spreading (Fig. 15). The failed dock caused by the liquefaction

and lateral spreading incidents in the investigation area and the fractures occurring in the concrete blocks of the dock were shown in Fig. 16.

4.2 Soil liquefaction and sand boil

Liquefaction is that the layers below the groundwater level temporarily lose their strength due to the dynamic loads that occur during an earthquake and act like a viscous liquid rather than like a solid. Figure 17 shows sand boils caused by soil liquefaction in the investigation areas 2, 3, and 5 after the earthquake. The soils are seen to consist of non-plastic silty fine sand.

4.3 Rockfalls

Mass movements triggered by the earthquake are one of the important natural disasters. Especially, massive earthquakes trigger mass movements such as landslides, rockfalls, and debris flows. Earthquakes are one of the most important factors affecting the stability of rocks. Fractures and falls can be seen in rocks because of earthquakes. In the field investigations carried out in the region, it was seen that the rocks with sizes ranging from 20 to 110 cm fell in investigation areas 4 and 7. Because of the incline of the slope, these rocks rolled up to the existing vehicle road and the Hazar Lake (Fig. 18).

4.4 Soil deformations

Deformations occur on the soils because of seismic effects like earthquakes. These deformations can occur in different ways depending on the magnitude of the earthquake, the soil class, and the inclination of the soil where the deformations occur. In the field investigations carried out at investigation areas 6 and 7, soil deformations were seen, which not caused stability failures and landslides. These soil deformations that occurred after the earthquake caused cracks in the asphalt pavements of existing roads in the sizes of 0.5 to 2.0 cm. Soil deformations occurring after the earthquake can be seen in Fig. 19.

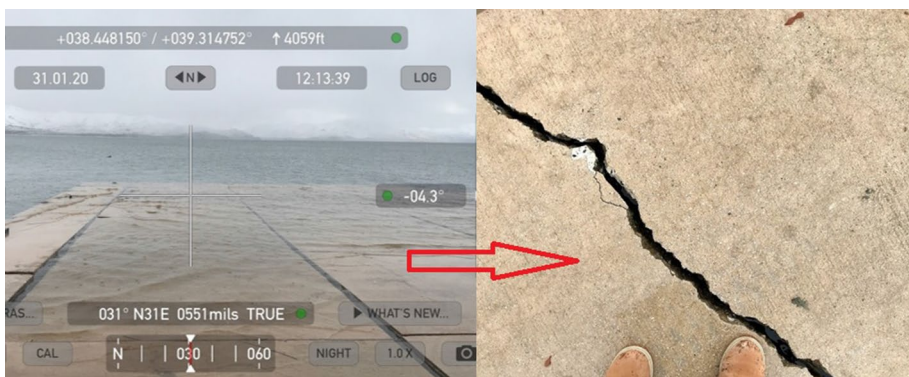


Fig. 16 Failed dock because of lateral spreading and liquefaction, and concrete block crack (investigation area 1)

Fig. 17 Sand boils caused by soil liquefaction



(a) Investigation area 2



(b) Investigation area 3



(c) Investigation area 5

Fig. 18 Rockfalls**(a)** Vehicle road (Investigation area 4)**(b)** Hazar Lake (Investigation area 4)**(c)** Vehicle road (Investigation area 7)

5 Seismic performance of reinforced concrete (RC) buildings

Earthquake originated RC structure damages draws attention of researchers after the earthquakes. This damage and failure reason of the RC structures were investigated, and possible solution procedures were proposed for 1999 Kocaeli earthquake (Sezen et al. 2003), for 2011 Van earthquake sequences (Ateş et al. 2013), for 2011 Simav earthquake (Yön et al. 2013), for 2011 Van earthquakes (Bayraktar et al. 2015; Yön et al. 2015) and finally 2020 Sivrice earthquake (Atmaca et al. 2020a, b). Effect of design and construction practices on the response of RC buildings was discussed in this section. Failure reasons listed below was reported and discussed in detail. For a better comparison, some code requirements

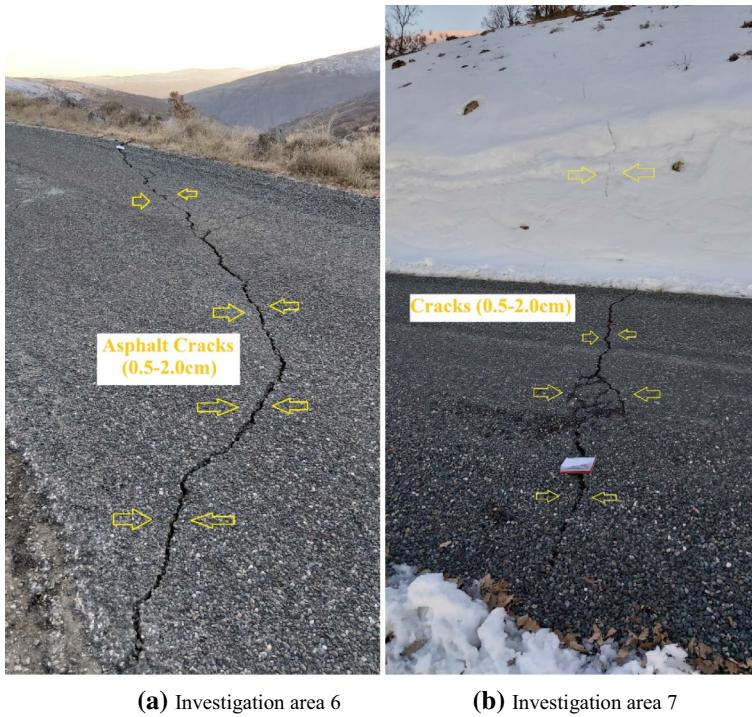


Fig. 19 Cracks from soil deformation

and field observations are discussed and presented in the related sub-title. Moreover, well-performed RC buildings were also discussed under this title. Damages of the structural elements observed by the technical team can be listed as follows:

- Insufficient transverse reinforcement in structural members
- Short column
- Inadequate gaps between adjacent buildings
- Strong beam–weak column
- Poor concrete quality and corrosion
- Failures of gable walls
- Damages to infill walls

5.1 Insufficient transverse reinforcement in structural members

Transverse reinforcement is of prime importance to provide adequate ductility of buildings and to meet increasing shear forces during an earthquake. Especially, occurring shear forces affect the end of columns and beams, and beam–column joints. Majority of heavily damaged buildings have 25–30 cm spacing of transverse reinforcement. Therefore, the details of the transverse reinforcement should be designed in the project and built specifically for the building during the field observations, it was seen that many buildings had inadequate transverse reinforcement, especially in plastic hinge regions

of structural members. Also, longitudinal reinforcement bars were buckled owing to this wrong implementation. This situation caused the columns to display low performance against the shear forces of earthquake and lose the axial load carrying capacity. During bending the seismic ties and hooks, the achieved bending degree should be 135° and reinforcement bar should not deformed. But the transverse reinforcement of structural elements in damaged buildings were smooth and hooks of the ties had been bended 90° . Figure 20 demonstrates this type of failure.

During an earthquake, the structural performances of buildings substantially reduces due to improper design of beam-column joints. The joints must be remained in the elastic region to prevent serious failures after an earthquake. These joints are particularly important for the distribution of force and moment. The shear and bond mechanisms are the common failures of these joints. In Elazığ earthquake, many RC buildings heavily damaged because of the failures of these joints. It was seen that poor detailing at joints of beam-column and poor quality of materials with low workmanship were the main reasons of these failures. Also, the lack of transverse and seismic cross ties, and inadequate anchorage bars of beam and column in reinforced concrete elements lead to joint failure. In this region, the maximum tie spacing should not be exceed 10 cm. In only RC frame systems, sum of ultimate moment resistances of columns framing into a beam-column joint should be at least 20% more than the sum of ultimate moment resistances of beams framing into the same joint. Figure 21 shows beam-column joints failures.

Fig. 20 Damaged structures (a Rüstempaşa district; b Abdullağaşa district; c, d Mustafapaşa district) due to inadequate spacing between shear reinforcements during the Elazığ-Sivrice earthquake

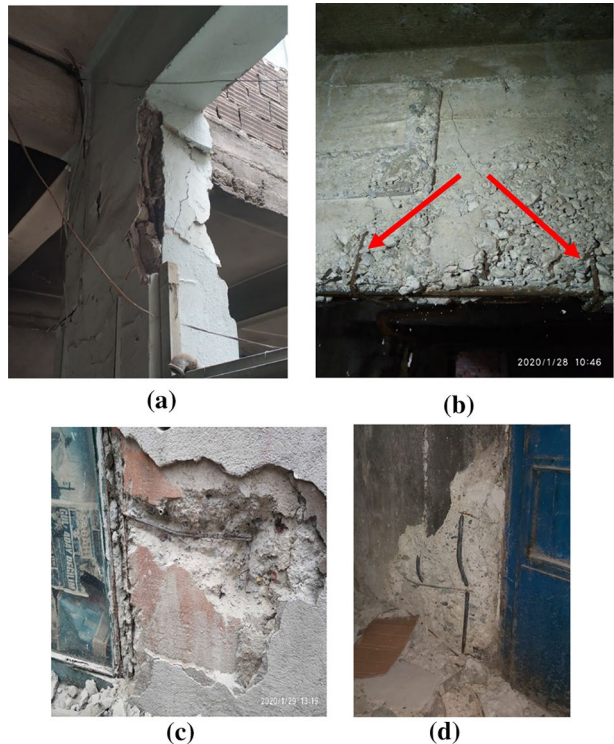


Fig. 21 Beam-column joint damage



(a) Rüstempaşa district



(b) Abdullahpaşa district



(c) Mustafapaşa district



(d) Kırklar district

5.2 Short column

Short column application is created by opening a band window on the exterior wall to provide lightening for basements of buildings. This implementation diminishes the effective length of a column and shortened column becomes more rigid and brittle than other columns. Hence, a short column is exposed to more shear forces arising from dynamic loads. The occurring shear effect lead to serious damages in this structural element. Figure 22 illustrates this kind of critical failure. According to TEC-2007 and current code shear force for transverse reinforcement should be calculated. Then, the moments at bottom and top

Fig. 22 Shear failure of a column (Mustafapaşa district)



(a)



(b)

ends of the short column should be calculated as $M_{bottom} = 1.4M_{r_{bottom}}$ and $M_{top} = 1.4M_{r_{top}}$ with l_n represents the length of the short column.

5.3 Inadequate gaps between adjacent buildings

Inadequacy of building land in the city center forces people to build adjacent buildings. Therefore, one or two façades of buildings contacts to one another or there is little gap between buildings. Therefore, these structures collide each other during an earthquake. A more dangerous situation may occur when the floor levels of adjacent structures are not aligned. The base of a building can hit the columns of another building, causing damage. To prevent such damages, there must be adequate gaps between the adjacent buildings. According to the code, minimum size of gaps should be 30 mm up to 6 m height and from there on a minimum 10 mm should be added for each 3 m height increment. Unless a more unfavorable value is obtained in accordance with requirement defined in previous statement, sizes of gaps should not be less than the sum of the absolute values of average storey displacements multiplied by the coefficient α . If adjacent floor levels of buildings at all stories are the same, then the amount of gap is $\alpha = 0.25\left(\frac{R}{I}\right)$, and $\alpha = 0.50\left(\frac{R}{I}\right)$, if not. In these equations, the structural behavior factor and building importance factor are shown as R and I , respectively. Damaged buildings due to inadequate gap are given in Fig. 23.

5.4 Strong beam–weak column

In Turkey, especially available old RC building stock was constructed with strong beam and weak column design before the improvement of current earthquake codes. The beams of these buildings are deep and rigid while the columns weak and flexible. Therefore, flexible columns failure before beams. In this type of design, deep and rigid beams exhibit elastic behavior, while shear failure or compression crushing cause brittle failures at these weak columns during an earthquake. The design of strong beam–weak column was the main reason of the partial and total collapse of buildings during the Sivrice-Elazığ earthquake. Figure 24 shows columns of different buildings which failed severely. To prevent this kind of damages or collapses arising from the strong beam–weak column design, current and former seismic codes require that sum of ultimate moment of columns framing into a beam–column joint should be at least 20% more than the sum of ultimate moment of beams framing into the same joint. Thus,

Fig. 23 Damages to adjacent buildings during the Elazığ earthquake (a Rüstempaşa district; b Abdullapaşa district)

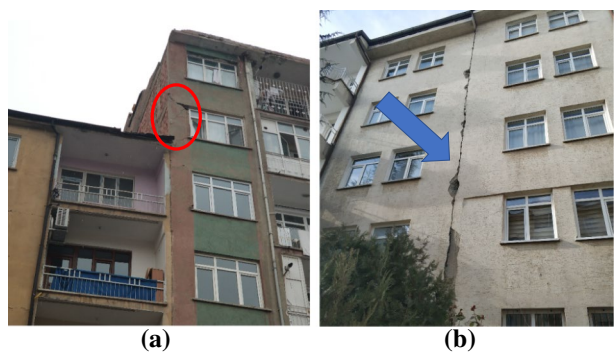
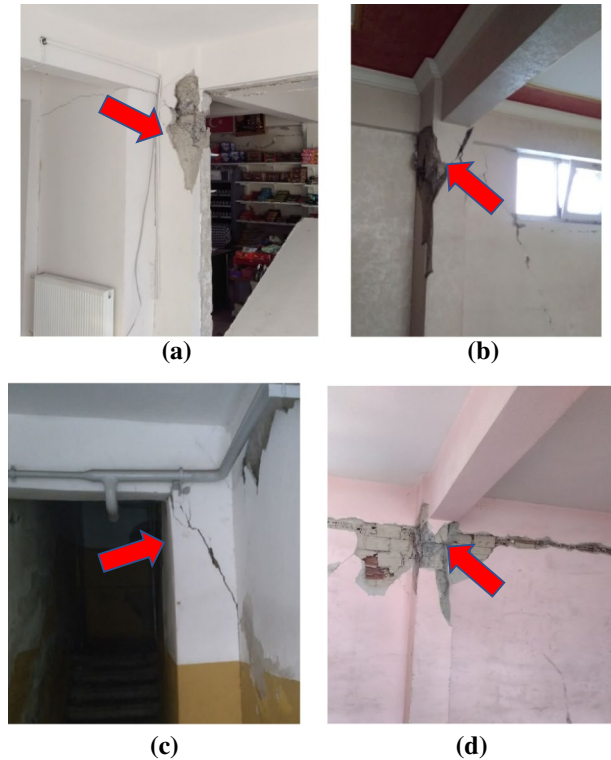


Fig. 24 Failure of a due to strong beam–weak column effect during the Sivrice-Elazığ earthquake (a, b Rüstempaşa district; c, d Mustafapaşa district)

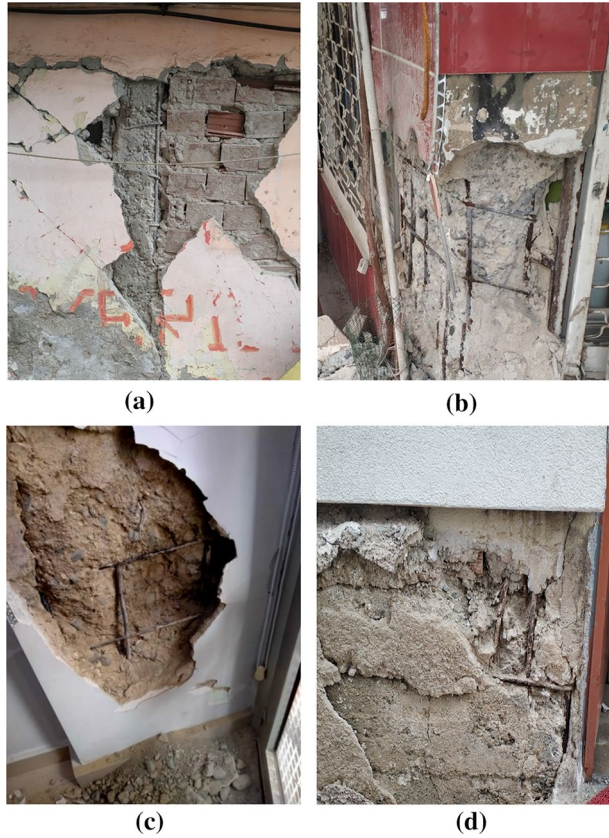


plastic hinges occur at the ends of the beam and brittle failure prevents. But this situation had not been seen at observed buildings which damaged seriously.

5.5 Poor concrete quality and corrosion

Concrete compressive strength is one of the main factors required for reinforced concrete structures to show expected performance against earthquakes. But during the field observations, it was seen that many damaged buildings had not sufficient concrete quality. In Turkey, using of ready-mix concrete became common after 1999 Kocaeli earthquake. Before this earthquake, handmade concrete was generally used without using a vibrator. Because of this wrong application, a homogenous mixing could not be obtained, and the expected compressive strength could not be provided. TSC-2007 requires that compressive strength of concrete should be minimum 20 MPa in all buildings, while this value is required to be minimum 25 MPa for all buildings according to new seismic code, TBEC-2018. In addition, inadequate concrete cover caused corrosion in reinforcement bars, leading to diminishing diameters of these bars. Figure 25 shows poor quality of concrete and corroded reinforcement bars in various buildings that existed in the earthquake region. Moreover, Provincial Directorate of the Ministry of Environment and Urban Planning declared that the compressive strengths of the concrete cored from collapsed and damaged structures were around 7–10 MPa.

Fig. 25 Failure of column due to poor concrete quality during the Elazığ-Sivrice earthquake (a Rüstempaşa district; b Mustafapaşa district; c Ulukent district; d Sürsürü district)



5.6 Failures of gable walls

Existing gable walls were weak against the out-of-plane mechanism during the earthquake because these walls were constructed without bond beams. This type of failure is not a structural damage but falling parts of wall can be cause loss of lives and properties. The main reason of damages to such walls is the large unsupported wall lengths. It was determined that poor wall-to-wall, wall-to-floor connections, and absence of lateral supporting walls were the other reasons of these damages. Reinforced concrete vertical and inclined bond beams should be used to prevent such damages. Gable walls of investigated buildings were built without bond beams. Figure 26 demonstrates the out-of-plane failures of gable walls of various reinforced concrete buildings in the affected region.

5.7 Damages to infill walls

Different types of infill damages were ran across during the field observations. In-plane and out-of-plane interaction is overly complicated and completely depends on the load transferring mechanism of the infill wall and the RC interaction. In infilled RC buildings, firstly ground story walls are expected to fail because the walls are subjected to the highest

Fig. 26 Damages to gable walls at Sivrice township during the Sivrice-Elazığ earthquake



(a)

(b)



(a) In-plane damage (Ulukent district)



(b) Disconnection of wall from the frame (Sivrice township)



(c) Partial out-of-plane damage (Sivrice township)



(d) Total out-of-plane damage (Abdullahpaşa district)

Fig. 27 Various failure mechanism of infill walls

in-plane demands. Hence shear cracks are generated in the plane (Fig. 27a) However, exposed to the effect of in-plane and out-of-plane loading, where the E–W and N–S components of acceleration are important, infill walls of upper stories may fail under the combination of in-plane and out-of-plane effects. The in-plane resistivity decreased bearing capacity and out-of-plane loading increased owing to the continuous time history loading (Onat et al. 2018; Onat 2019; Yön et al. 2019). Hence partial or total out-of-plane mechanism was developed (Fig. 27c, d). The other damage type in the infill wall was disconnection of wall from the frame. Poor detailing of wall-to-frame or wall-to-floor connection caused this kind of damage (Fig. 27b).

5.8 Well-Performed RC Buildings

Despite damaged and failed buildings, well-performed RC structures are also available at the epicentre of the earthquake in Sivrice district as presented in Fig. 28.

6 Response of masonry structures

Masonry dwellings are constructed as a single (or double) story building in the villages of Turkey owing to easy workmanship, available materials, economic reasons and providing thermal insulation. These types of dwellings are constituted with adobe, brick and stone walls and mostly vulnerable to intensive seismic motions. However, these buildings had been lost their strength and durability due to their old age (Calayır et al. 2012; Sayın et al. 2013, 2014; Yön et al. 2017; Göçer 2020; Adhikari and D’Ayala 2020). Damages of the bearing elements of masonry dwellings observed by the technical crew can be listed as follows:

- Earthen roof damages
- Corner damages
- Out-of-plane mechanism
- In-plane mechanism

6.1 Earthen roof damages

In the rural areas of the Elazığ city, one- and two-story masonry buildings are common because they were built using local materials, require an easy workmanship and, built with traditional techniques. These buildings are usually built using thick adobe and stone walls and mostly do not require engineering services. Earthen roofs are generally used in the masonry buildings in the rural areas to provide water and thermal insulation.

Fig. 28 Well-performed RC School Buildings



Fig. 29 Damages due to heavy earthen roof at Sivrice township

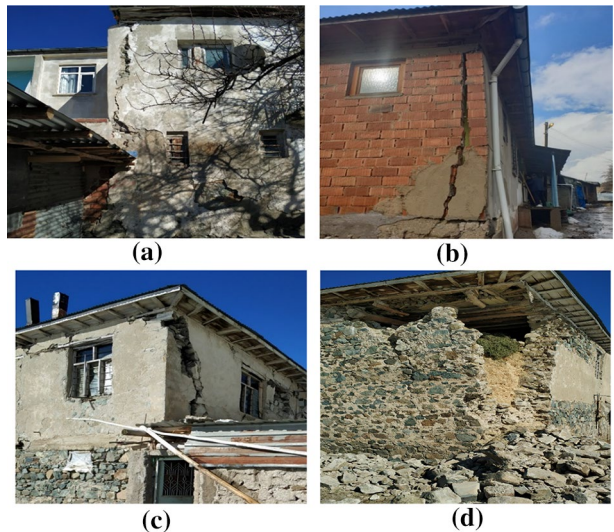


They are usually constructed over wooden logs and lose their capabilities owing to weather conditions, like snow and rain. Homeowners cover a new earthen layer on the existing roof to avoid the percolation of water. Therefore, mass of the roof increases during the years. This situation can cause large inertial forces during an earthquake. Structural walls cannot carry the heavy mass and roof is demolished partially or totally. This situation was observed during the January 24, 2020 Sivrice-Elazığ earthquake. Figure 29 illustrates this type of collapses.

6.2 Corner damages

This failure type commonly occurs due to weak connections of wall-to-wall when forced by the out-of-plane mechanism. This mechanism requires subjects to intersect of the walls. Thus, vertical cracks develop, and wall corners are separated. Serious damages are caused because of weak connections among adjacent walls and the absence of bond beams. Similar failures are seen at the corners of the roof level because of reduced compression stress and increased seismic acceleration at upper stories. Top corners are more vulnerable to failure due to cantilever-like behavior when there is no slab in-plane rigidity at the roof level. The corner damages at different buildings are shown in Fig. 30.

Fig. 30 Corner damages of masonry buildings in Sivrice township



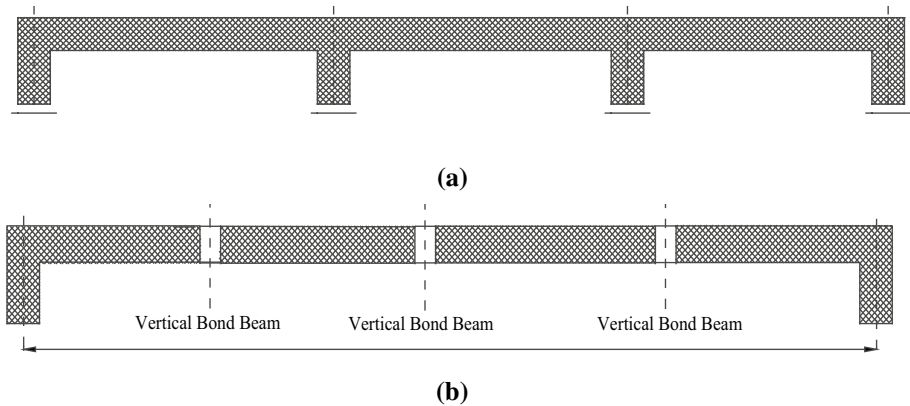


Fig. 31 Limitation of unsupported wall by **a** perpendicular walls and **b** vertical bond beams

6.3 Out-of-plane mechanism

This type of failures can be arisen from several factors such as large unsupported walls, weak wall-to-floor connections or poor wall-to-wall connections, and absence of bond beams which should provide structural integrity to prevent out-of-plane failure damage to walls. These deficiencies cause partial or total wall failure during an earthquake. Furthermore, to prevent these damages in masonry buildings, the unsupported length of a wall should be limited by using perpendicular walls and vertical bond beams. Figure 31a, b shows this type application. Reinforced concrete vertical bond beams should be built along the full story height at the corners and near the openings.

In the earthquake region, wooden beams bearing the weight of the floor of the masonry buildings are placed on load-bearing walls only in one direction. Hence, the dynamic loads are transferred to perpendicular walls by these wooden beams. Thus,

Fig. 32 Out-of-plane mechanism at **a–c** Sivrice township and **d** Elazığ city center

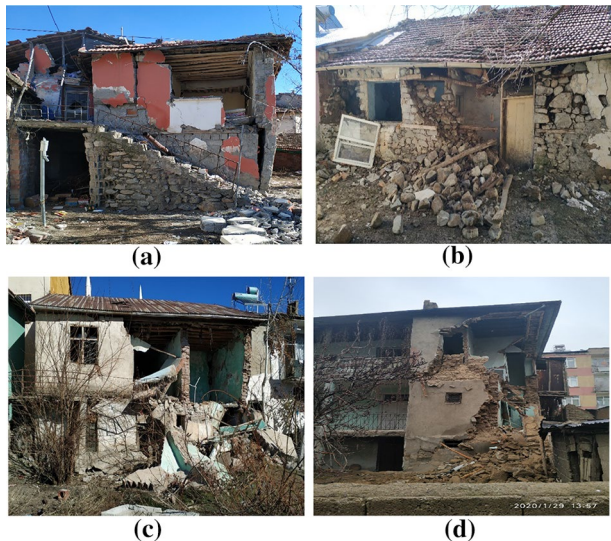


Fig. 33 In plane mechanism in Sivrice township

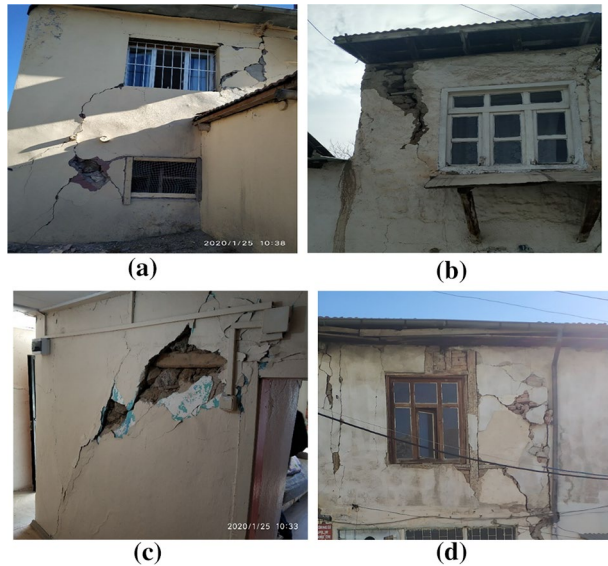
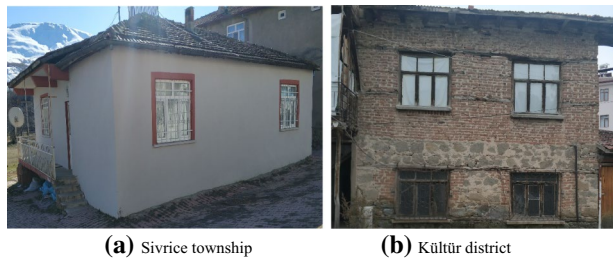


Fig. 34 Well-performed masonry buildings



the walls that are not supported by wooden beams and then can be overturned in the out-of-plane direction. In the affected region, the out-of-plane mechanism is typically observed. Figure 32 illustrates this type of damages for different dwellings.

6.4 In-plane mechanism

The seismic response of masonry structures is related to in-plane stiffness of the walls. In-plane mechanism is generally observed in many masonry structures by shear cracking. Shear forces enhance because of earthquake loads and can damage walls and their connections. These damages generally occur near openings owing to the lack of bond beams that add lateral strength to walls. In the earthquake region, many masonry buildings did not have sufficient, proper vertical and horizontal bond beams to increase the lateral seismic performance of the walls. Figure 33 shows in-plane mechanism of the masonry buildings in the earthquake region.

7 Well-performed masonry dwellings

Apart from damaged and failed buildings, well-performed masonry dwellings were also available after the main shock at the epicenter of the earthquake in Sivrice township. These dwellings were demonstrated at Fig. 34 below.

8 Non-residential structures

Performance, failure and damage of non-residential structures were evaluated under this section. Damage of elevated water reservoir and masonry minaret are presented in Fig. 35.

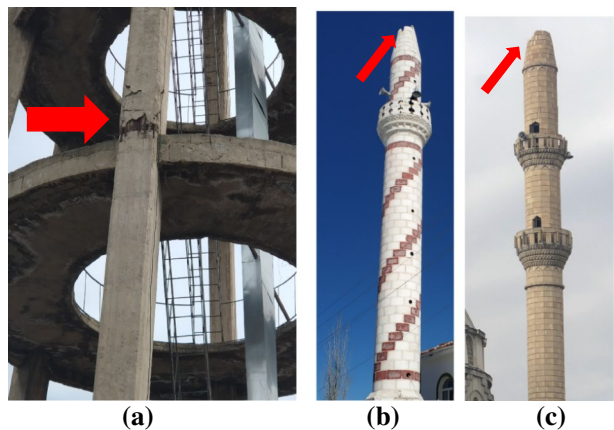
Water towers are sensitive structures under the influence of the earthquake. The bearing elements of these structures should be well detailed. However, poor detailing caused damage to the structure in this earthquake (Fig. 35a). However, since the minarets are tall and thin structures, they are frequently affected by earthquakes (Atmaca 2020). Local damages were seen at the top of the conical portion of minarets (Fig. 35b).

9 Conclusions and suggestions

The aim of this paper is to reveal brief and mechanism focused technical data of January 24, 2020 Sivrice (Elazığ) earthquake. In addition, it summarizes the past and present seismic characteristic of the earthquake region. Moreover, the general characteristics of the main shock, and after-shocks and the structural damage caused by the earthquake, observed during the site investigations. Also, geotechnical observations were carried out in the earthquake region. Soil deformations and lateral spreads were observed, especially due to liquefaction. As a result of these deformations, damages were seen on the dock and asphalt pavement. Beside these deformations, rockfalls were seen after the mainshock and aftershocks. The observed damages were classified for reinforced concrete (RC) structures and masonry dwellings. All distinguished earthquake induced failures and damages were discussed. After a detailed study, following conclusions attracted attention and were listed below.

Reinforced concrete buildings;

Fig. 35 Damage to elevated water reservoir (a) and masonry minarets (b, c)



- Using plain bar and insufficient spacing of transverse reinforcement caused considerable damage. In addition, the ends of the stirrups were not bent 135° and thus, this application had reduced the wrapping effect of the stirrup. To avoid damage to structural members, attention should be paid to detailing of transverse reinforcement, and close-spaced stirrups should be used.
- Existing short columns caused serious damages especially to basement floors of buildings. It is possible to avoid this kind of damages such as increasing of shear strength of this part of the column by building a wall around the column in this area.
- Each building has different natural vibration periods due to their structural and material properties. During the earthquake, hammering effect occurs between attached buildings or buildings which have insufficient gap. This effect can be devastating for buildings. To avoid this kind of damage, proper gaps should be left between the attached buildings.
- If rigid and deep beams are built with weak columns as compared with the beams, plastic hinge occurs at the end of such columns. This situation causes brittle failures and then total collapses can be seen. To prevent this type of damage, columns should be stronger than beams and plastic hinges should be designed to be on beams firstly.
- Material quality and workmanship is one the main factors affected the earthquake performance. Our field observation shows that, poor concrete quality and/or corrosion of reinforcement bars reduce the structural performance of load bearing elements. Hence, expected performance against earthquake cannot be provided. To prevent damage arising from this situation, selection and application of materials and workmanship should be paid attention.
- The reason of infill wall damage is lower strength of infill materials and weak connections to frames. To avoid this kind of damage, sufficient connection and high strength mortar should be used between wall and frame.

Masonry buildings;

- The field observations show that existing of earthen roofs create heavy masses on the top of buildings. Hence, the seismic effect forced the structural walls during the earthquake caused partial or total collapses especially in adobe dwellings. According to the results obtained, adobe structures and this type roofs should not be constructed.
- It was seen that weak wall-to-wall connections and absence of vertical and horizontal bond beams created structural corner failures. Using of sufficient bond beams and proper wall-to-wall or wall-to-bond beam connections can eliminate this type of damage.
- Out-of-plane mechanism is one of the main structural damages to masonry buildings. The main mistakes that caused this damage are the absence of vertical and horizontal bond beams, weak connections between the walls, and large unsupported walls. This type of damage can be prevented by using sufficient wall-to-wall and wall-to-roof connections. Also, large unsupported walls should not be constructed, and horizontal and vertical bond beams should be implemented.
- Absence of bond beams and presence of large openings that reduce the lateral rigidity of the load bearing walls weaken the structural performance walls. Increased shear force with ground motion develop in-plane damages. To prevent in-plane failures, it should be abstained from the construction of large openings, and vertical bond beams should be built near the openings.

Suggestions from Lessons and Learned of damaged/failed structures.

- The structures have shear walls showed satisfied performance.
- During the design phase, torsional irregularity and short column effect should be eliminated with suitable solutions.
- As presented above, damage and failure of the earthquake proved that collapsed and heavily damaged structures are not fulfill any code requirements when constructed.
- The masonry buildings, have vertical and horizontal bond beams, do not have severe damage.
- Strengthening techniques should be evaluated and applied for less damaged and existing masonry buildings like shotcrete, FRP, CFRP, wire mesh.
- Also, construction workers should be educated about earthquake and construction retrofitting. Application on site should be strictly controlled by engineers.

Finally, observed poor performance, in this earthquake, is in fact in accordance with observations from other earthquakes and similar construction practices. This performance and failures are in fact expected, since practitioners have not learned any lessons from past earthquakes.

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