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Masonry building behaviors during the February 6–12, 2017 Ayvacik-Çanakkale Earthquakes

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Abstract. Masonry structures in the rural areas of Turkey often damaged due to moderate and big earthquakes. After every earthquake many scientists made field investigations on the earthquake performance of these structures and gave many useful information on construction techniques. However, the newly constructed masonry buildings are still not suitable for the suggested techniques, and they are still in danger against future earthquakes. Five moderate earthquakes of moment magnitude Mw 5.3, 5.3, 5.2, 5.0, and 5.3 struck the Ayvacik-Çanakkale District of Turkey between 6 and 12 February, 2017. More than a thousand of aftershocks were occurred and most of the masonry buildings in the villages nearby main shock epicenter were affected. The author went to the earthquake field and investigated the earthquake performances of masonry structures. This paper presents the recorded acceleration data, acceleration response spectra, and the seismological aspects of these earthquakes. Besides, case studies of damaged stone masonry buildings, and failure mechanisms are discussed with illustrated photos which were taken during the field investigations. It is concluded that the damaged masonry buildings were not designed and constructed properly in accordance with the Turkish building codes or similar specifications.

Keywords: Ayvacik-Çanakkale earthquake; field investigations; structural damage; stone masonry buildings, strong ground motions

1. Introduction

Turkey is one of the most seismically active regions in the world. Moderate or large earthquakes occur in this region nearly every decade. The 1999 Kocaeli Earthquake (M_w=7.4), 1999 Duzce Earthquake (M_w=7.2), 2003 Bingol Earthquake (M_w=6.4), and 2011 Van Earthquake (M_w=7.1) are some examples of large earthquakes that occurred in Turkey. Many people lost their lives during these seismic activities due to the poor quality of collapsed buildings. Many masonry buildings located in seismically active regions of Turkey were also damaged during these large and similar moderate earthquakes. The earthquake behaviours of masonry buildings in Turkey have been generally investigated by many researchers after large seismic events. Celep *et al.* (2011), Cetinkaya (2011) outline the failures of masonry and concrete buildings due to the March 8, 2010 Kovancilar and Palu (Elazığ) Earthquakes. They observed that most of the failures causing casualties occurred in stone masonry buildings in the rural areas that were constructed with mud mortar binder and heavy clay roofs formed on irregular wooden beams supported by two main walls of the buildings. Often, roofs having very weak support connections or very small support lengths tend to separate from the walls very easily. Similarly, Bayraktar *et al.* (2007) reported the performance of masonry buildings during the July 2, 2004 Doğubayazit (Ağrı) Earthquake. According to their survey, the walls were mainly made of irregularly shaped stones with smooth surfaces. Therefore, enough adherence was not gained between the stones and grout. Heavy earth roofs increased the lateral forces and the rotten ends of the wooden logs also made the roof highly vulnerable to collapse during the earthquake. Adanur (2010), Ural *et al.* (2012) investigated the performance of masonry buildings during the 2007 Bala (Ankara) Earthquakes based on field surveys. According to the studies, most of the masonry buildings in the affected area were not designed and constructed in accordance with Turkish Earthquake Code (2007).

However, the behaviour of masonry buildings subjected to a moderate earthquake is poorly understood or investigated. For this reason, post-earthquake reconnaissance activities that record the performance of these structures are of the same significance as research activities for researchers, engineers, policy-makers, and Turkish society, in general. The 2011 Van Earthquake was the last big earthquake, with a magnitude of 7.2, in Turkey and some researchers, such as Bayraktar *et al.* (2013), Dogan (2013), Tapan *et al.* (2013), Cakir *et al.* (2015), Damcı *et al.* (2015), Karaca *et al.* (2017), Hadzima-Nyarko *et al.* (2018), Bilgin and Huta (2018), Ranjbaran and Kiyani (2017), Polatsu *et al.* (2016), Pardalopoulos *et al.* (2016), investigated the seismic behaviour of masonry buildings. According to data released by the Republic of Turkey, Ministry of Environment and Urban Planning, 2288 buildings fully collapsed as a result of the Van earthquake. According to observations conducted in the area, a major portion of the mostly single-storey masonry buildings that were constructed in the traditional style entirely collapsed.

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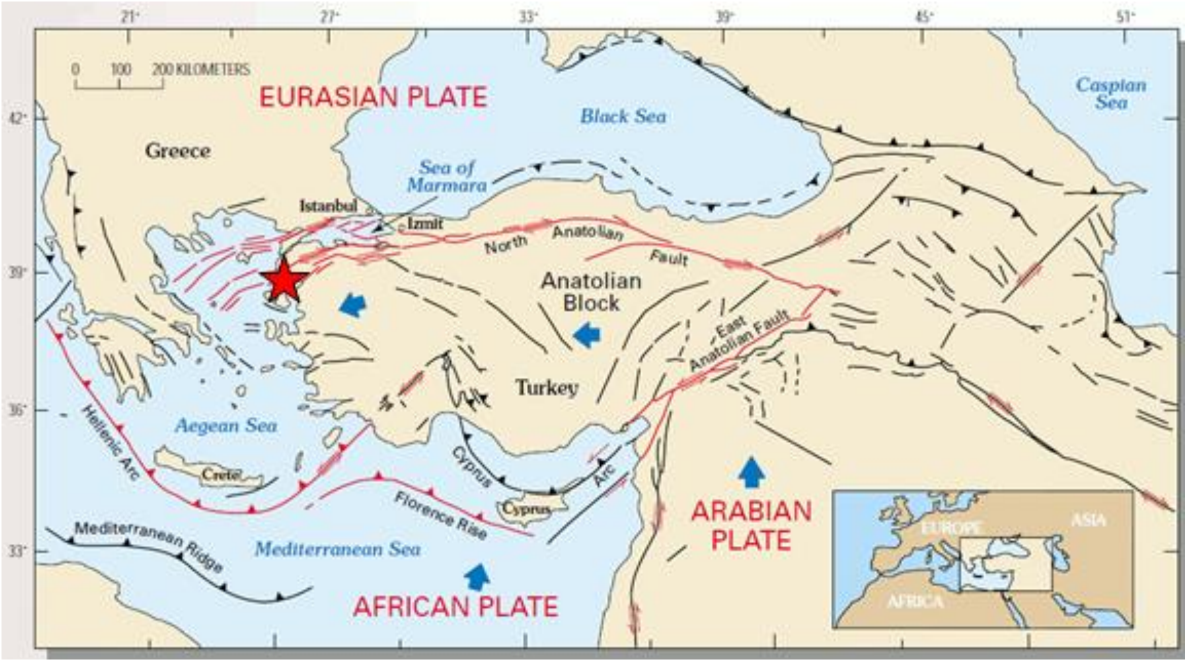

Fig. 1 Simplified tectonic map of Turkey (Adanur 2010)

Stone and lime were used in masonry structural systems because of social and economic properties and climate conditions in the area. However, the compressive strengths of these materials were very low, between 1 and 5 MPa. Therefore, the load-carrying walls were very weak. This weakness caused damage and structural collapse, even in medium magnitude earthquakes.

An earthquake storm occurred in the west of Turkey near the Çanakkale (Dardanelles) region (Fig. 1). It was started on 6th February 2017 and continued for 6 days. During this period, five moderate earthquakes and nearly a thousand aftershocks occurred. Two M_w=5.3 earthquakes occurred on 06.02.2017. Another M_w=5.2 earthquake occurred one day after the first shock. Then a M_w=5.0 struck the region on 10.02.2017. The last main shock occurred with M_w=5.3 on 12.02.2017. All these main shocks and active faults in the region can be seen in Fig. 2. A field investigation was carried out by the author immediately after this earthquake series, and the observations are reported in the present paper. The objective of this investigation was to record and analyse the damage causes in the masonry buildings. This paper discusses the seismological aspects of the Ayvacik Earthquake, describes the tectonics of the region, and elaborates on the performance of masonry buildings during these earthquakes.

2. Seismological and geotechnical aspect

The major fault systems near the epicentre of the earthquakes are known as the Kestanbol Fault and the Gülpınar Fault. The Kestanbol fault is an active fault in the west of the Biga Peninsula and extends parallel to the coast of the Aegean Sea. The fault is within the borders of Çanakkale province. It has a total length of 25 km between Geyikli and Tuzla villages. Current morphologic erosional surfaces and faulted sediments on Holocene alluvial fans are evident. The eastern block of the fault is systematically above, which reveals the fault slope component. The young fault scrolls in the Tuzla region show that the surface ruptures in the Holocene. On the south, the fault turns east and ends in the Tuzla Stream valley. Findings indicate that the Kestanbol Fault is a slippery active fault with a left directional strike component.

The Gülpınar Fault extends between Gülpınar and Babakale villages at the westernmost of the Biga Peninsula. The fault starts 1 km north of Babakale at a lineament within the Miocene volcanic along the seashore and its total length is about 9 km. It is the continuation of the Kestanbol fault. The youngest faulting unit is the Late Miocene Gülpınar formation. According to correlations in the geological units, it is a normal fault and is inclined to the west. No signs of quaternary activity were found except for the linearity that the fault created.

The north of the acidic-neutral volcanic community developed over the granitic activity in the Biga peninsula consists of felsic compound lavas and the south group consists of pyroclastic units with acid-medium composition. There are rhyolitic-rhyodacitic lava flows on the volcanic community. These rocks have changed with the factors they are influenced by. (Bozkurtoğlu *et al*, 2005)

The current Turkish Earthquake Code (TEC 2007) specifies four seismic zones in Turkey. Zone 1 is the most hazardous and Zone 4 is a no hazard zone. Ayvacik is located in Zone 1. The code requires a design acceleration of 0.4×g for load-carrying walls and buildings located in Zone 1 (g is gravitational acceleration). According to AFAD (2017), large earthquakes that occurred in this region during the last century are: 1900 (M_w=5.2) Ayvacik-Çanakkale, 1912 (M_w=7.4) Şarköy, Mürefte-Tekirdağ, 1912 (M_w=5.2) Gelibolu-Çanakkale, 1935 (M_w=6.3, M_w=5.2)

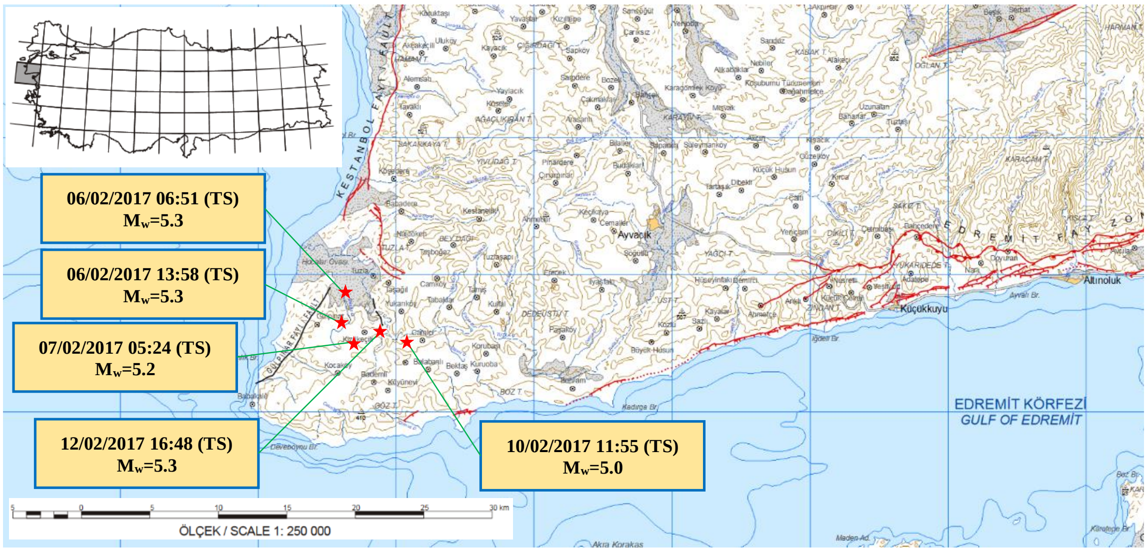

Fig. 2 Map of the region with 5 main shocks and active faults (MTA 2017)

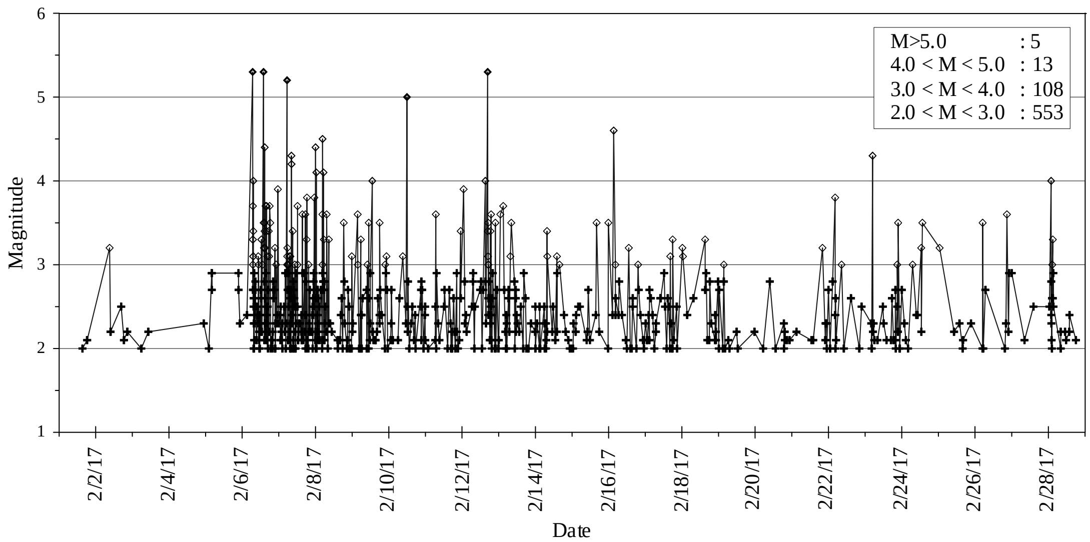

Fig. 3 Seismic activity from February 01 to 28, 2017 (DAD 2017)

Table 1 Ayvacik-Çanakkale Earthquakes information reported by AFAD (2017)

Date and Time (GMT)	Magnitude	Depth (km)	Latitude (North)	Longitude (East)	N-S (gal)	E-W (gal)	U-D (gal)
06/02/2017 03:51:40	5.3 M_w	14.16	39.54950	26.13700	103.16961	70.914196	30.387937
06/02/2017 10:58:02	5.3 M_w	8.72	39.53030	26.13510	101.53524	86.550735	22.398279
07/02/2017 02:24:04	5.2 M_w	6.24	39.52050	26.15100	64.551368	90.844943	23.213773
10/02/2017 08:55:26	5.0 M_L	7.01	39.52360	26.19460	39.679060	39.648914	14.388090
12/02/2017 13:48:16	5.3 M_w	7.00	39.53360	26.17000	71.388472	87.082964	30.324527

Biga-Çanakkale, 1953 (M_w=7.2) Yenice-Çanakkale, 1968 (M_w=5.2) Ezine-Çanakkale, 1983 (M_w=5.2) Ayvacik-Çanakkale, and 1983 (M_w=5.8) Biga-Çanakkale.

Seismic activity from February 01 to February 28, 2017 can be seen in Fig. 3. The earthquakes above magnitude 5.0 in the chart are the main earthquakes that are marked on the map in Fig. 2. According to the seismic activity graph, there were 13 more earthquakes with a magnitude of 4.0 and 5.0, 108 earthquakes with magnitudes between 3.0 and 4.0, and 553 earthquakes with magnitudes between 2.0 and 3.0 after the first main shock.

2.1 Ground motions of the main shocks

The location of the epicentre, magnitudes, three components of the ground acceleration records, and focal depths of the main shocks in the region were reported by AFAD (2017) and are summarized in Table 1. All these values are taken from recorder No.1716 at Çanakkale Ayvacik station located in the Forest Management Directorate building at 39.59965N-26.40761E. The maximum PGA values for North-South (NS), East-West (EW), and Vertical (UD) directions are measured as 0.1 g,

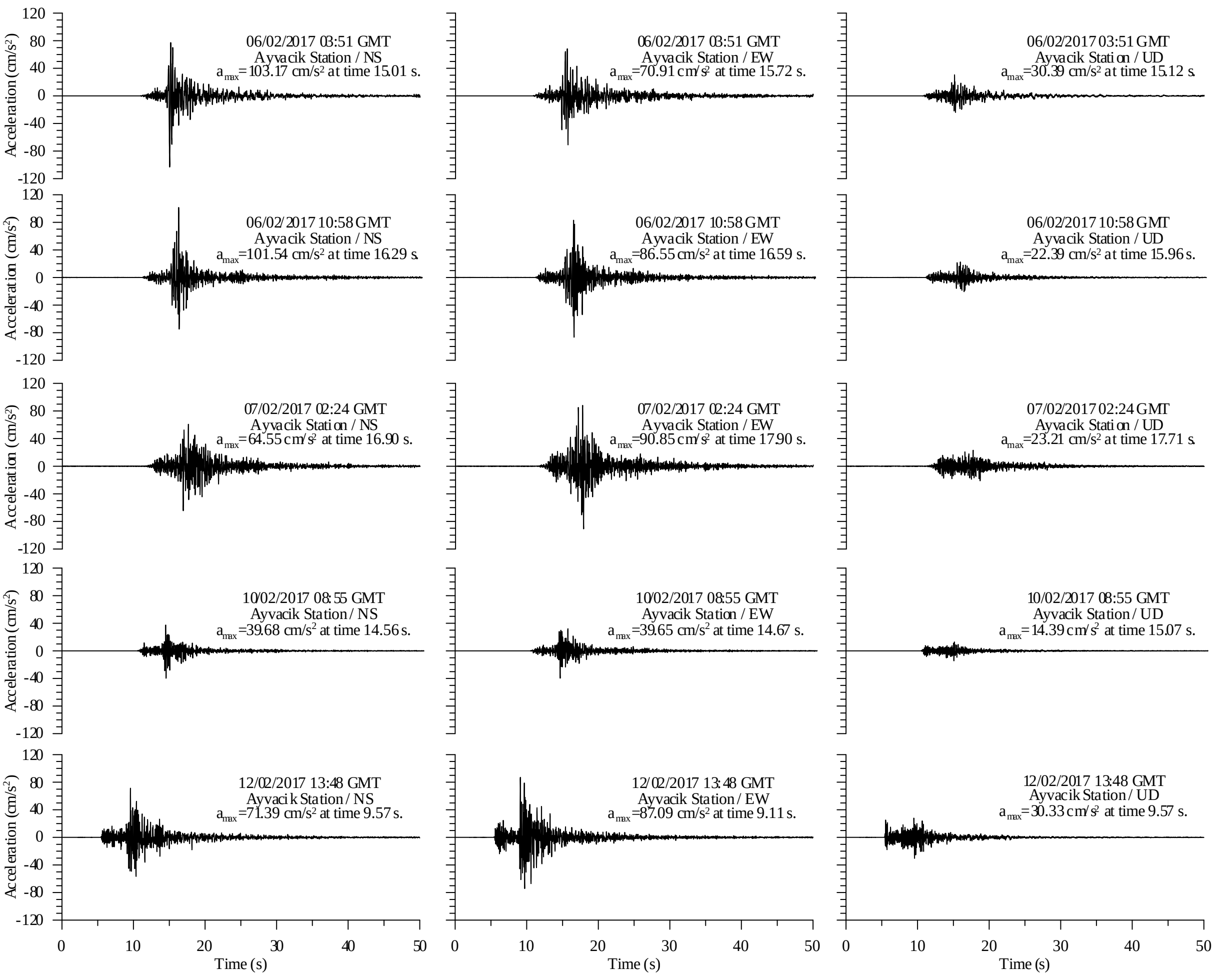

Fig. 4 Acceleration records of five big earthquakes with NS, EW and UD components occurred in Ayvacik-Çanakkale.

0.07 g, and 0.03 g for the first earthquake that occurred on 06/02/2017. According to the Turkish Earthquake Code (2007), the expected maximum PGA is around 0.3-0.4 g for this region. Fig. 4 shows the time histories for the earthquake acceleration records.

Acceleration-time records for the major earthquakes are given in Fig. 4 in NS, EW and UD directions. In the plot legends, date, time, recording station, direction, maximum acceleration value and earthquake creation time are given. According to the information in Fig. 4, the NS component of both earthquakes that occurred on February 6 and the one on February 10, and the EW component of the other two earthquakes were effective. All earthquakes occurred in about 10 seconds.

Elastic response spectra were calculated using the north-south component of the ground acceleration recorded at the Ayvacik station (Fig. 5). For the response spectra shown in Fig. 5, the damping ratio varied from 0 to 20%. A maximum 5% damping should be considered for masonry and adobe structures according to Turkish Earthquake Code. Fig. 5 also shows the design acceleration limit (3.675 m/s^2) specified in the Turkish Earthquake Code. This design acceleration is calculated from Eq. (1).

$$S_{ie} = \frac{A_o \cdot I \cdot S(T_1)}{R_a(T_1)} g \qquad (1)$$

Table 2 Spectrum characteristic periods (T_A and T_B)

Local Site Class	T_A (second)	T_B (second)
Z1 (very rigid soil)	0.10	0.30
Z2	0.15	0.40
Z3	0.15	0.60
Z4 (very soft soil)	0.20	0.90

where A_o is the effective ground acceleration coefficient. For seismic Zone 2, the specified value of A_o is 0.3. I is the importance factor and is equal to 1.0 for residential or other ordinary masonry buildings.

In TEC (2007), the spectrum coefficient S is defined in Eq. (2) for short periods, constant acceleration and constant velocity ranges.

$$\begin{aligned} S(T) &= 1 + 1.5\,\frac{T}{T_A} && (0 \le T \le T_A) \\ S(T) &= 2.5 && (T_A < T \le T_B) \\ S(T) &= 2.5\left(\frac{T_B}{T}\right)^{0.8} && (T_B < T) \end{aligned} \qquad (2)$$

Spectrum characteristic periods, T_A and T_B, in Eq. (2) are specified in Table 2, as a function of the local site class.

The spectrum coefficient, $S(T_1)$ is constant and equal to 2.5 for masonry buildings. The maximum spectral amplification S is specified as 2.5 in the constant

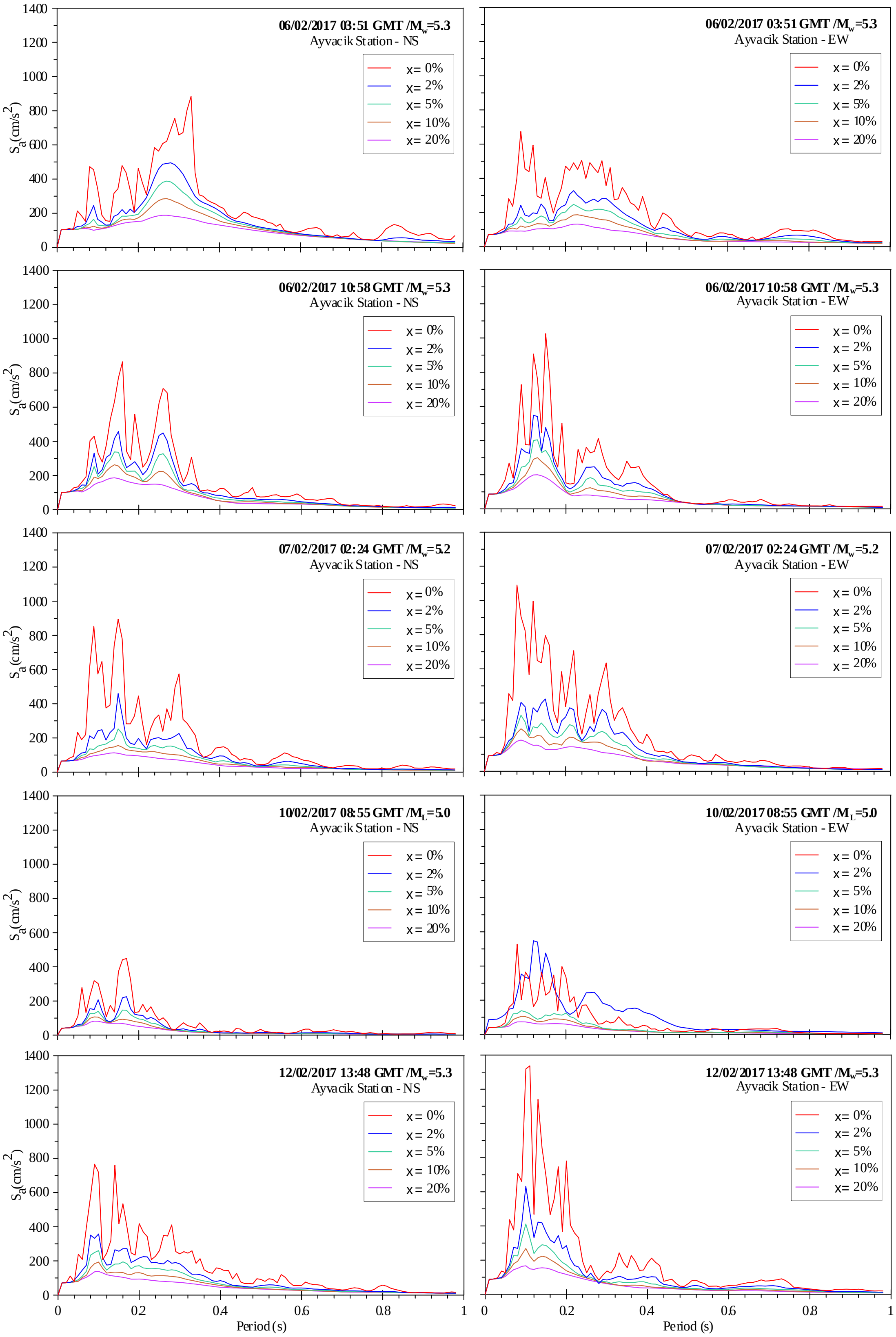

Fig. 5 Response spectra of five big earthquakes with NS and EW components occurred in Ayvacik-Çanakkale

acceleration range, where the structural period is moderately low. By specifying a constant $S(T_1)$ of 2.5, the Turkish Earthquake Code implies that masonry buildings are relatively rigid and will have relatively small structural periods. $R_a(T_1)$ is the seismic load reduction factor indicating the level of ductility of the structural system and varies between 4 and 8 for reinforced concrete structures. For masonry structures, $R_a(T_1)$ is set at 2. This very low R_a

Fig. 6 Joints without binding properties

Fig. 7 Use of rubble and cut stone

Fig. 8 Use of cut stone around corners and outer parts of the walls

value specified in the earthquake code is a recognition of very low or no displacement ductility observed in most masonry structures.

Fig. 5 shows that for this ground motion, the spectral acceleration values start decreasing at about 0.35 s, and for 0.5 s or longer periods, all spectral accelerations are very low. The code specified spectral acceleration value is exceeded for masonry buildings with periods between 0.25 and 0.40 seconds for 5% damping ratio. If the damping ratio in such structures is lower than 5%, larger spectral accelerations and hence larger seismic forces are expected.

3. Masonry structures and observed damages

The author investigated the effects of 5 major earthquakes in the region on February 18, 2017. The investigation took place in four villages, in which the Republic of Turkey Prime Ministry Disaster & Emergency Management Authority declared that the most destruction occurred. These villages are Çamköy, Taşağıl, Yukarıköy and Gülpınar. People who live in the villages are dealing with livestock and are very poor. The most damage occurred at the village of Yukarıköy. The distance between the villages is at most 5 km. In villages, there are usually single or maximum 2-storey masonry buildings.

Almost all damaged structures do not comply with the requirements of the Turkish Earthquake Code (TDY, 2007). Even though the earthquakes were moderately intense, they caused damage to the stone masonry structures. The disaster area was surveyed, and detailed studies were carried out on the damaged structures to understand the reasons for their poor performance. The main reasons are discussed in detail with the examples of damaged buildings.

When looking at the masonry construction that is damaged in the region, the common feature of all is formed from rubble stone walls. The stones used in the load-carrying walls were andesite type, which is abundant in the region. When the collapsed or damaged walls were examined, these stones had no apparent size or shape. Additionally, usually having no binding property to fill the joints between the masonry units, mud was used. Adherence between the masonry units and the mortar layer in the joints is important in masonry wall behaviour. As a result of on-site observations, the author did not find any use of adherence-providing cement or lime-like material on most of the damaged structures. In Fig. 6, a damaged wall from a masonry building as described above is seen. In this way, the size differences between the masonry units and the state of the mortar joints are clearly visible.

Wall thicknesses in damaged buildings exceed 50 cm in some places. Although the walls are so thick that they are heat-insulated, this thickness caused the moment of inertia on the walls under the lateral effects. The fact that there is no element inside the wall or corners which provides continuity between the perpendicular walls is also causing damage. A picture of this situation is given in Fig. 7. According to this figure, the damage occurred in the form of out-of-plane overturning. It is also seen that the cut stones are used in the perpendicular wall.

When the walls of some damaged buildings were examined, it was seen that the inner parts of the walls were covered with rubble and the outer parts are covered with cut stone. However, in some buildings, cut stone was only used around the corner points. Photos of damage related to this situation are given in Fig. 8. Cut stone used parts made a positive contribution to the overall behaviour and making the structure survive.

In the Turkish Earthquake Code, there are some criteria that can be considered important regarding unsupported wall length. In the present code, the maximum unsupported wall length between the load-carrying wall axes connecting perpendicular to each other is 5.5 m. In some buildings damaged in the area, although the outer parts of the walls are rubble, the inner walls are made of bricks or woods. These walls could not support the outer rubble stone wall perpendicularly and led to the failure compatible with the criterion of earthquake codes. The pictures related to this situation are given in Fig. 9. Although the outer walls were built with rubble stone, the inner walls were made of bricks (Fig. 9(a)) and earth plastered wooden wall (Fig. 9(b)). The

Fig. 10 The effect of door window lintels

main load-carrying system in both buildings is only outer walls.

The positions of the door and window spaces in the buildings are generally arranged according to the Turkish Earthquake Code. Lintels are often used in these door and window spaces using large stones, and wood. In some structures, these sections have been given arch forms from the stones. This situation has prevented it from being completely destroyed. Fig. 10 shows the effects of the lintels.

Minarets are built as tower structures attached to or near mosques and are used by the Muezzins who call out the adhan (ezan in Turkish) to invite people to mosques. These slender structures are vulnerable to seismic and wind

Fig. 11 Mosque and minaret damages

loadings. In the Turkish style, the parts of a minaret are the footing as a base; pulpit, transitional segment, cylindrical or polygonal body as a shaft; a balcony; the upper part of minaret body; cone and flag. The damages caused by an earthquake or wind in the minarets usually occur in the transitional segment or in the cone part. The most important reason for the damage in the transition zone can be explained as the decrease of lateral stiffness due to the sudden decrease of the cross-section. The main reason for the damage that occurs in the cone part is that the upper part of the cone is filled with concrete for the assembly of the flag. For this reason, inertia forces occur at the top of the cone. Many studies have been carried out on minaret damages in earthquakes such as (Doğangün *et al.* 2008, Oliveira *et al.* 2012, Turk and Cosgun 2012, Ural and Firat 2015). It was determined that there was damage in the mosque and the cone of the minaret of the Yukarıköy village during the earthquake region investigation. This damage is given in Fig. 11.

4. Turkish earthquake code requirements and implications of field data and observations

Seismic design requirements were developed and earthquake code standards were published in Turkey in 1944, 1949, 1953, 1962, 1968, 1975, 1998 and 2007. The 1968 code provisions included lateral load calculations with coefficients applicable for masonry and adobe structures. The 1975 earthquake code included more detailed lateral load methods with specific requirements for masonry and adobe structures. The 1998 and 2007 codes provided more detailed design and load calculation methods for these structures. The 2007 earthquake code also included stress limits for masonry walls as a function of reinforcement, masonry block and other material properties. Construction of one-story adobe structures is allowed and design requirements are provided in the current code. Generally, the existing buildings surveyed as part of this research did not comply with the requirements of the 2007 earthquake code requirements.

The 2007 Turkish Earthquake Code includes requirements to prevent damage in masonry buildings. Some of the critical requirements are summarized below. Following each requirement, the authors' observations are also provided.

• Mortars to be used in load-bearing walls shall be lime mortar enhanced with cement (cement/lime/sand volumetric ratio=1:2:9) or cement mortar (cement/sand volumetric ratio=1/4). The author found that mortar with much lower cement ratios was commonly used in the region. In some cases, such as in barns, mud was used instead of mortar.

• The minimum compressive strength of masonry structural material shall not be less than 5 N/mm^2 on the basis of gross compression area. Compressive strength of natural stones to be used in basements shall be at least 10 N/mm^2. Compressive strengths of stones used in the region seem to meet this requirement. However, tests of adobe bricks collected from a collapsed building showed a compressive strength of approximately 0.65 N/mm^2, which is much smaller than the specified minimum value of 5 N/mm^2. It should be noted that no clay bricks or masonry units were tested.

• The ratio of the total length of masonry load-bearing walls in each of the orthogonal directions in the plan (excluding window and door openings) to gross floor area (excluding cantilever floors) shall not be less than 0.25I (m/m^2), where I represent the Building Importance Factor varying between 1.0 and 1.5. The author could not check this condition because wall dimensions, window and door openings, and building plans varied greatly.

• Load-bearing wall segment plan length between the corner of a building and the nearest window or door opening to the corner shall not be less than 1.5 m in the first and second seismic zones and 1.0 m in the third and fourth seismic zones. For the most part, this condition was satisfied in the surveyed buildings.

• Excluding the corners of buildings, plan lengths of the load-bearing wall segments between the window or door openings shall not be less than 1.0 m in the first and second seismic zones and 0.8 m in the third and fourth seismic zones. This requirement appeared to be satisfied in most buildings while a few exceptions were noticed by the reconnaissance team.

• Excluding the corners of buildings, the plan length of a load-bearing wall segment between the intersection of the orthogonal walls and the nearest window or door opening shall not be less than 0.5 m in all seismic zones. Otherwise, reinforced concrete confining elements shall be made on both sides of the openings along the height of the storey. The author observed no vertical confining elements or concrete tie columns in masonry buildings in the area affected by the earthquakes.

5. Conclusions

An earthquake storm occurred in the west of Turkey near the Çanakkale (Dardanelles) region. It started on 6th February 2017 and continued for 6 days. During this period, five moderate earthquakes and nearly a thousand f aftershocks occurred. The most affected area of these earthquakes was Yukarıköy village. The buildings in the neighbourhood were stone masonry buildings, and nearly half of the buildings in the region have major damage. A field investigation was carried out by the author immediately after this earthquake series, and the observations are reported in the present paper. The conclusions below were reached in light of the structural damages detailed above.

- All of the structural damage occurred in unreinforced rubble masonry buildings. It is known that masonry structures built without any reinforcement exhibited the worst performance in the earthquake.
- The rubble stone system was used on the bearing walls of the damaged structures. The sizes of the stones used in these walls are very different from each other. In some buildings, a wall was properly made from cut stone while the other wall was constructed as a rubble stone wall. For this reason, significant differences in lateral rigidity occurred.
- Damage due to not using cement or lime-based mortar as a binder in the walls became inevitable. During the investigations in the region, it was determined that cement mortar was used in the walls of some buildings. These buildings were either collapsed or able to survive with little damage during the seismic actions cited before.
- When the damaged buildings in these earthquakes were examined, it was found that the buildings were not built according to regulations or standards. In addition, the importance of meeting regulations and standards in the construction of buildings has once again emerged.

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