Aegean Sea Earthquake
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PRELIMINARY VIRTUAL RECONNAISSANCE REPORT (PVRR)

Aerial view of Izmir showing building collapse dust cloud locations after the earthquake (DailyMail, 2020)

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PREFACE

The National Science Foundation (NSF) awarded a 2-year EAGER grant (CMMI 1841667) to a consortium of universities to form the Structural Extreme Events Reconnaissance (StEER) Network (see https://www.steer.network for more details). *StEER builds societal resilience by generating new knowledge on the performance of the built environment through impactful post-disaster reconnaissance disseminated to affected communities.* StEER achieves this vision by: (1) deepening structural engineers' **capacity** for post-event reconnaissance by promoting community-driven standards, best practices, and training, as well as their understanding of the effect of natural hazards on society; (2) **coordination** leveraging its distributed network of members and partners for early, efficient and impactful responses to disasters; and (3) **collaboration** that broadly engages communities of research, practice and policy to accelerate learning from disasters. StEER works closely with other extreme event reconnaissance organizations and the Natural Hazards Engineering Research Infrastructure (NHERI) to foster greater potentials for truly impactful interdisciplinary reconnaissance after disasters.

Under the banner of NHERI's CONVERGE node, StEER works closely with the wider Extreme Events Reconnaissance consortium including the Geotechnical Extreme Events Reconnaissance (GEER) Association and the networks for Nearshore Extreme Event Reconnaissance (NEER), Interdisciplinary Science and Engineering Extreme Events Research (ISEEER) and Social Science Extreme Events Research (SSEER), as well as the NHERI RAPID equipment facility and NHERI DesignSafe CI, long-term home to all StEER data and reports. While the StEER network currently consists of the three primary nodes located at the University of Notre Dame (Coordinating Node), University of Florida (Atlantic/Gulf Regional Node), and University of California, Berkeley (Pacific Regional Node), StEER aspires to build a network of regional nodes worldwide to enable swift and high quality responses to major disasters globally.

StEER's founding organizational structure includes a governance layer comprised of core leadership with Associate Directors for each of the primary hazards as well as cross-cutting areas of Assessment Technologies and Data Standards, led by the following individuals:

- **Tracy Kijewski-Correa (PI),** University of Notre Dame, serves as StEER Director responsible for overseeing the design and operationalization of the network and representing StEER in the NHERI Converge Leadership Corps.
- **Khalid Mosalam (co-PI),** University of California, Berkeley, serves as StEER Associate Director for Seismic Hazards, leading StEER's Pacific Regional node and serving as primary liaison to the Earthquake Engineering community.
- **David O. Prevatt (co-PI),** University of Florida, serves as StEER Associate Director for Wind Hazards, leading StEER's Atlantic/Gulf Regional node and serving as primary liaison to the Wind Engineering community.
- **Ian Robertson (co-PI),** University of Hawai'i at Manoa, serves as StEER Associate Director for Coastal Hazards, serving as a primary liaison to the coastal engineering community and ensuring a robust capacity for multi-hazard assessments.
- **David Roueche (co-PI),** Auburn University, serves as StEER Associate Director for Data Standards, ensuring StEER processes deliver reliable and standardized reconnaissance data suitable for re-use by the community.

ATTRIBUTION GUIDANCE

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ACKNOWLEDGMENTS

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Contributions of Özgür Özçelik and Ahmet Dindar, who provided field observations and photographs from Izmir, were especially helpful in understanding some of the observed damage and are greatly appreciated. Anastasios Sextos also communicated preliminary observations of buildings response from the island of Samos. Valuable information was also provided by Ayşegül Askan Gündoğan and Haluk Sucuoğlu regarding the presence of instrumented tall buildings in Izmir and potential earthquake early warning systems.

The sharing of logistical details, images/videos, damage reports and briefings via Slack by the entire NHERI community, including our colleagues at EERI and GEER, was tremendously helpful and much appreciated. StEER recognizes the efforts of the DesignSafe CI team who continuously supported and responded to StEER's emerging needs. Special thanks also to Spatial Networks for their ongoing partnership and generous support, making available, at no cost, the Fulcrum Community mobile platform for StEER Damage Assessments.

Finally, StEER also recognizes its student administrator, Dinah Lawan of the University of Notre Dame, for her efforts in formatting this report, as well as other members who were not able to assist in the authorship of this report but shared vital information via Slack and email.

For a full listing of all StEER products (briefings, reports and datasets) please visit the StEER website: https://www.steer.network/products

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EXECUTIVE SUMMARY

On October 30, 2020, a magnitude 7.0 earthquake took place near Izmir, Turkey and Néon Karlovásion, Greece and was felt across a large area of both countries. The main shock of the earthquake led to a small local tsunami and was followed by more than 1,250 aftershocks, 43 of which were above magnitude 4.0.

At the time of writing this report, during the first week of November 2020, at least 114 fatalities in Turkey and 2 in Greece were reported, along with 1,035 injuries. In the island of Samos, Greece, the worst damage was observed in older masonry and adobe houses. There were also partial collapses and other damages observed in several churches. Damages in Turkey were more substantial: seventeen buildings collapsed and a preliminary damage assessment conducted by Turkey's Ministry of Environment and Urbanization on 10,287 buildings in Izmir tagged 124 (1.2%), 119 (1.2%), 730 (7.1%) and 9,314 (90.5%) buildings with heavy, moderate, light, and no damage, respectively. Except for the collapses, 90.5% of buildings with no damage indicate an overall satisfactory structural response. Significant site amplification and increase in ground shaking (almost twice compared to a rock site) were observed at the Bayrakli district of Izmir, Turkey, due to soft soil conditions with Vs30 values as low as 100 m/sec. This increased shaking due to the site amplification, combined with the structural deficiencies of several medium-rise buildings, led to four complete gravity (pancake) collapses and thirteen partial or complete sidesway collapses in Izmir, Turkey. Comparison of the design and recorded spectra affirmed that the seismic hazard of the region was well-defined by all versions of the local seismic code. Regardless of the hazard level that these buildings were designed for, had they been designed according to the seismic design principles of the current or earlier versions of the governing building code, they would not be expected to collapse. Furthermore, considering that there are buildings of similar typology around these buildings, which did not collapse and were immediately reoccupied, it is quite likely that the collapsed buildings, especially those that experienced gravity (pancake) type of failure, were not designed according to the version of the code governing at the time of their construction and/or had structural/material-related deficiencies. The observed collapses moreover highlighted one more time the urgent necessity of identifying the most collapse-prone buildings and prioritizing their retrofit.

Although it is unlikely to have any structural damage due to the small tsunami inundation in Samos, Greece or the Turkish coastline around Izmir, there was extensive flooding and damage to boats and vehicles caught in the flow. This event highlights the need for public awareness that earthquakes near coastlines anywhere in the world can lead to tsunami inundation. The ground shaking is the warning to move away from the coast to high ground or to the upper floors of a sturdy building.

In terms of community resilience, there were no major interruptions in power, gas, water, telecommunication, internet, or transportation services.

The objectives of this report are: 1) to provide details of the 30 October Mw 7.0 Aegean Sea earthquake, 2) to describe local codes and building practices, 3) to compare the recorded ground shaking with the values used for design, 4) to summarize the preliminary reports of damage to buildings and other infrastructure, including the disruption to the community in terms of fatalities, downtime, and economic losses, and 5) to highlight key lessons learned, with recommendations to inform the continued study of this event by the natural hazards engineering community.

1.0 Introduction

On October 30, 2020, a magnitude 7.0 earthquake struck in the Aegean Sea near Samos Island in Greece, causing notable damage in Izmir, Turkey (AFAD, 2020a). The earthquake, referred to herein as the *Aegean Sea* earthquake, was felt across a large region of Turkey and Greece. The main shock of the earthquake was followed by more than 1,250 aftershocks, as well as a small local tsunami. At the time of writing this report, during the first week of November 2020, at least 114 fatalities were reported in Turkey and 2 in Greece (CNN, 2020). About 1,035 injuries have been reported, many associated with the 17 collapsed buildings in Izmir (AFAD, 2020b). Upon completion of search and rescue operations on November 4, 107 people were rescued from collapsed buildings (Milliyet, 2020).

The initial product of the StEER response to the 2020 Aegean Sea earthquake is this **Preliminary Virtual Reconnaissance Report (PVRR)**, which aims at:

1. providing details of the 30 October Mw 7.0 earthquake,
2. describing local codes and building practices in the affected area,
3. comparing the recorded ground shaking with the values used for design, in terms of the peak ground acceleration (PGA) and acceleration response spectra,
4. summarizing the preliminary reports of damage to buildings and other infrastructure, including disruption to the community in terms of fatalities, downtime, and economic losses, and
5. highlighting key lessons learned, with recommendations to inform the continued study of this event by the natural hazards engineering community.

2.0 Hazard Characteristics

On October 30, 2020, at approximately 2:51 pm local time (11:51 am UTC), a magnitude 7.0 earthquake (epicenter: 37.918°N, 26.790°E), with a depth of 21 km, struck 15 km NNE of Néon Karlovásion, Greece and 17.2 km SSW of Seferihisar, Turkey, as shown in Figure 1 (USGS, 2020a). The apparent duration of the earthquake was 15.7 seconds according to initial estimations. As illustrated by Figure 2, the main shock of the earthquake was followed by more than 1,250 aftershocks within three days of the main shock, 43 of which were above magnitude 4.0 (AFAD, 2020b). The main shock was also followed by a small local tsunami.

The earthquake occurred because of normal faulting at a shallow crustal depth within the Eurasia tectonic plate in the eastern Aegean Sea (USGS, 2020a). The USGS focal mechanism solution demonstrated that the earthquake occurred on a moderately dipping normal fault striking either eastward or westward. In the area near the epicenter of the earthquake, 695 earthquakes, ranging between magnitudes 4.0 and 6.8, have occurred since 1900 (AFAD, 2020a).

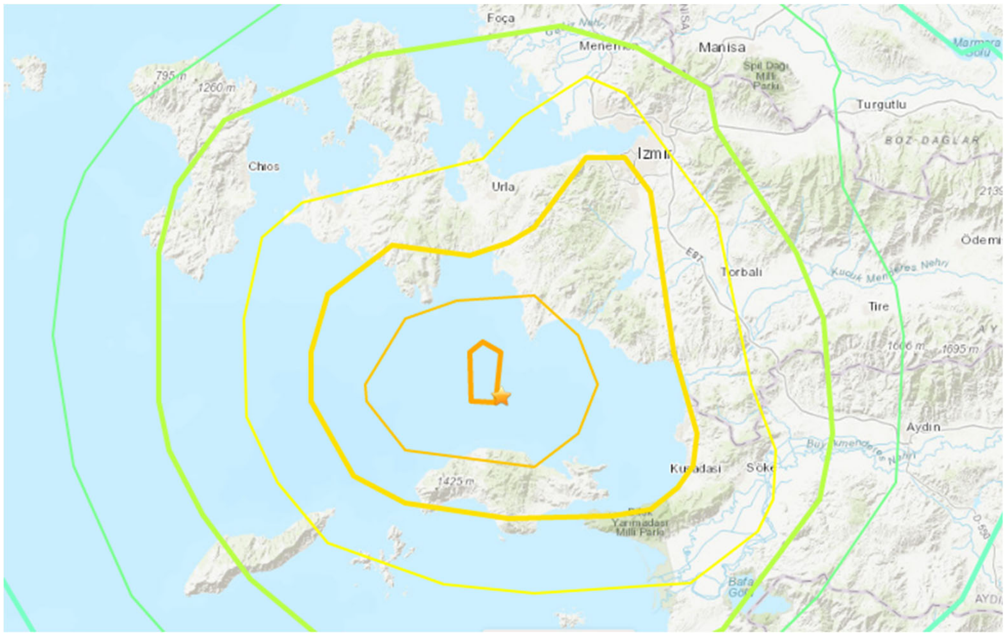

Figure 1. Epicenter of the 2020 Aegean Sea earthquake (USGS, 2020a)

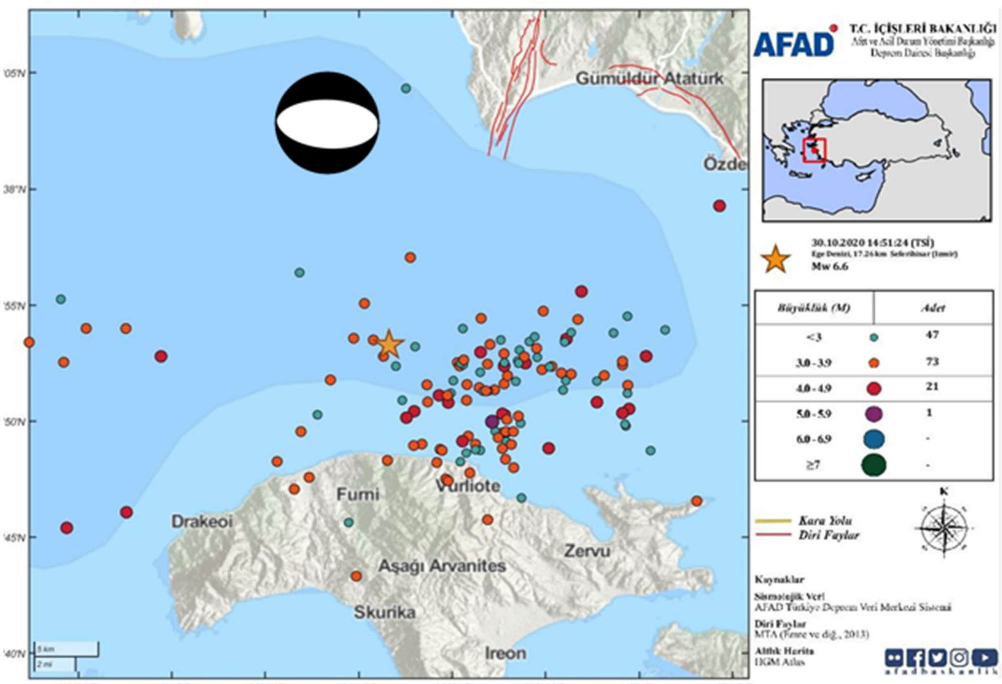

Figure 2. Aftershocks of the 2020 Aegean Sea earthquake within six hours after the mainshock (AFAD, 2020b)

2.1. Ground Motions

USGS ShakeMap contours (Fig. 3) indicate that the estimated peak ground acceleration (PGA) was as high as 0.4g, while the maximum estimated intensity is VIII (USGS, 2020a). See Figure 4 for a similar representation using the Modified-Mercalli intensity measures (AFAD, 2020a).

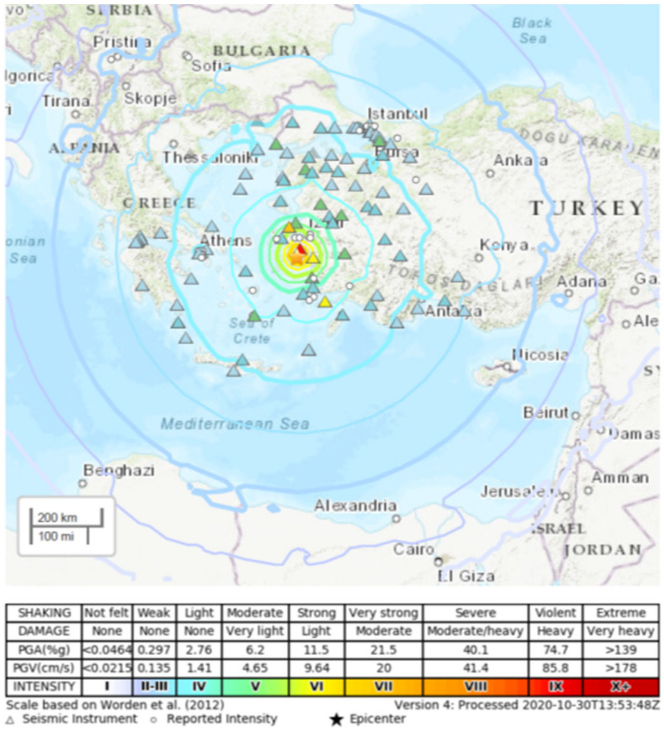

Figure 3. Intensity contours estimated from ShakeMap (USGS, 2020)

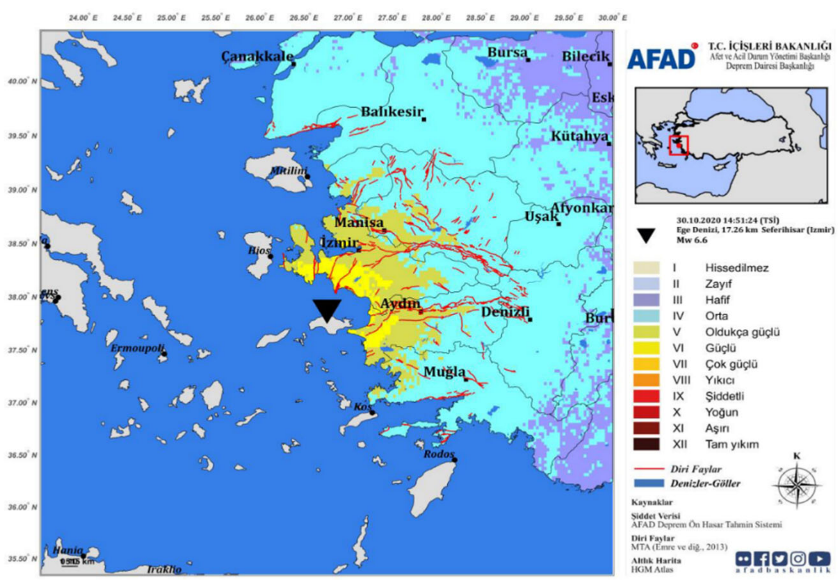

Figure 4. Expected intensity map prepared by AFAD-RED software (AFAD, 2020a). Black triangle is for the epicenter and red lines are for the active faults in the region.

2.2. Response Spectra of the Ground Motions

The maximum PGA recorded at the station marked with the red triangle in Figure 3 was 0.98g (961 cm/s^2). This acceleration was recorded in the North-South direction at the GMLD Gümüldür-IZMIR station (38.076°N, 26.875°E) of the Kandilli Observatory (KO) network, located 22.27 km away from the epicenter (Fig. 3). It is noted that this acceleration (Fig. 5) is much greater than the design basis PGA at this location, which is equal to 0.46g according to the earthquake hazard map of Turkey. Figure 6 compares the 5%-damped acceleration response spectra of the two horizontal components of the ground motion recorded at this station are compared against the design basis earthquake (DBE) and maximum considered earthquake (MCE) response spectra at this location based on Turkish Building Seismic Code (TBSC, 2018). Peaks around the 0.7-0.8 sec range of the response spectra are indicative of the soft soil conditions in this area. Spectral accelerations of the recorded ground motion are observed to be much larger than those of the DBE spectrum, especially for the medium-long period structures. The MCE spectral accelerations are also reasonably smaller than those of the recorded NS component, especially in the medium-period range. The peak ground velocity (PGV) in the North-South direction at this station was 79.14 cm/s. It is noted that the shaking intensity and response acceleration values at this station are larger than those of the other stations that are closer to the locations of the collapsed buildings, as shown in Figure 7. Therefore, further in-depth exploration of the potential reasons of the acceleration records at this station and observations related to the hazard and observed structural performances is recommended.

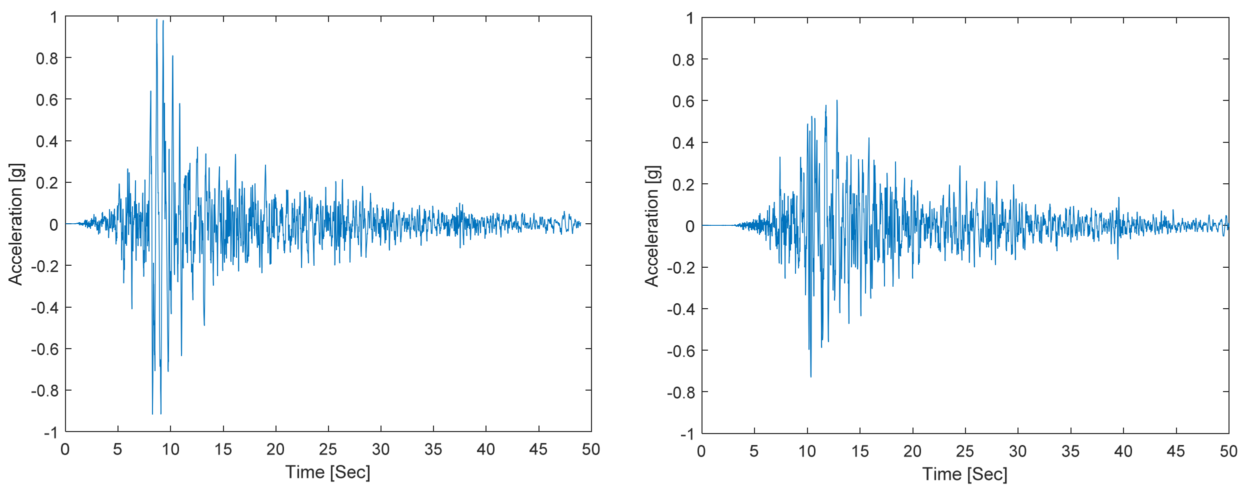

Figure 5. NS (left) and EW (right) components of the recorded accelerations in the Gümüldür station.

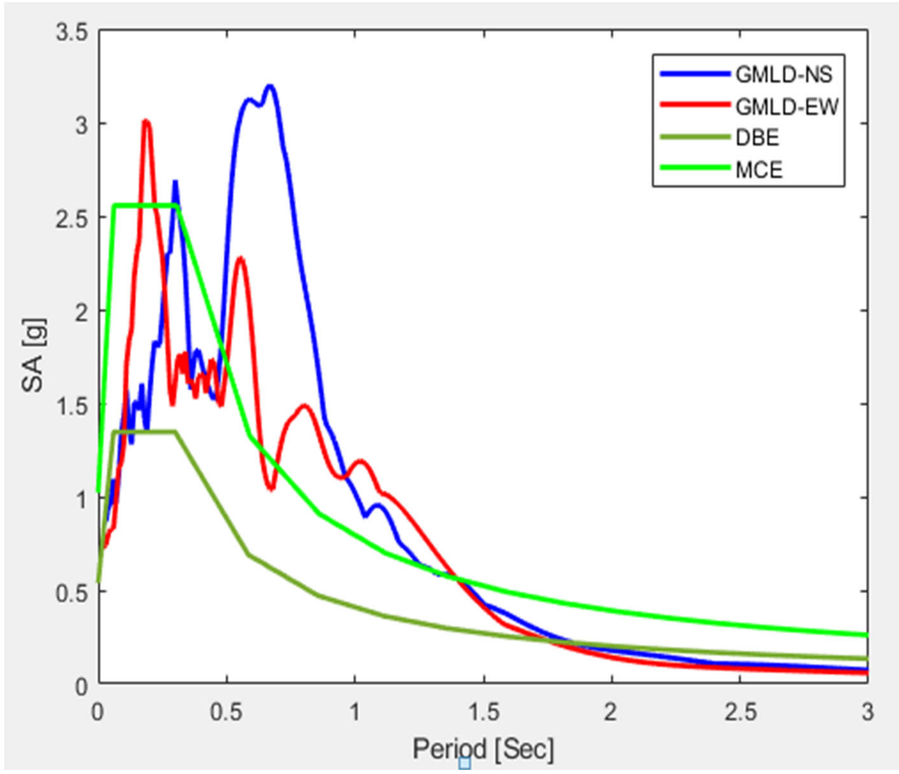

Figure 6. Comparison of the acceleration response spectrum of the recorded ground motion at the Gümüldür station against the DBE and MCE spectra at this location.

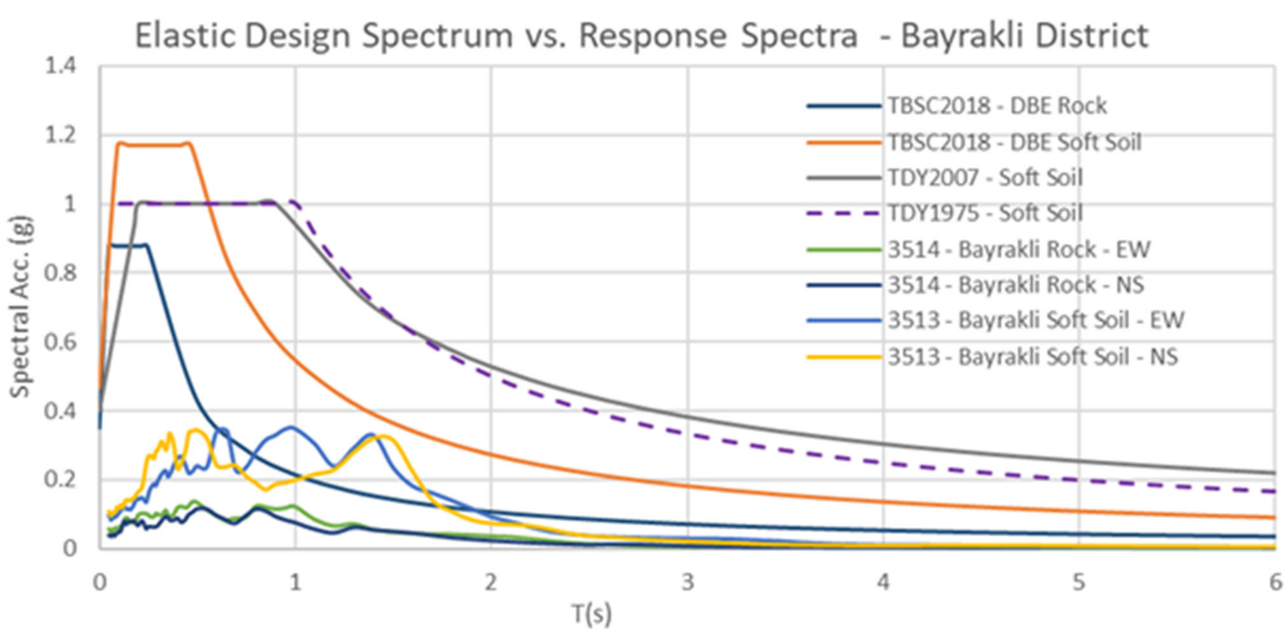

Figure 7. Comparison of the acceleration response spectra of the recorded ground motion at the two stations of AFAD in Bayrakli district against the DBE level spectra of current and earlier versions of Turkish Seismic Codes at these locations.

Figure 7 presents a comparison of design spectra from three versions of the Turkish Building Seismic Code with the response spectra of the recorded ground motions at the two stations of AFAD in Bayrakli district of İzmir. These stations are located on two different types of soil conditions, namely rock (station #3514, at 38.476°N, 27.158°E) and soft soil (station #3513, at 38.458°N, 27.167°E). Bayrakli is the area where the most severe damage to structures was observed. DBE level design spectra were computed based on the current Turkish Building Seismic Code (TBSC, 2018) and two earlier versions of the national codes for the comparison. Considering the collapsed buildings were mostly located on soft alluvial soils of Bayrakli, the comparison in Figure 7 gives an idea of the soil amplification in the region. It is observed that the PGA (spectral acceleration corresponding to zero period in Fig. 7) recorded at the soft soil is double the one recorded on the rock site. Furthermore, spectral acceleration values of the recorded ground motion for soft soils are observed to be much larger than those of the rock sites. The peak spectral accelerations are amplified up to 0.35g on soft soils from 0.14g on rock sites. Due to this amplification, spectral acceleration values were 2.5 times larger on soft soils than rock. The response spectra data are obtained from AFAD ground motion database (AFAD, 2020c). On the other hand, since the DBE design spectra for both rock and soft soil cases (Fig. 7) were much larger than the response spectra of the ground motions, MCE level was not considered for the comparison.

It is observed from Figure 7 that the spectral accelerations of the recorded motion on soft soil are smaller than the DBE spectrum of TBSC (2018) for soft soil at this location. However, considering that the collapsed buildings were designed and constructed in the 1990s, and that they were not designed using the current design spectrum that was put in effect with the 2018 version of the TBSC, the design spectra of the previous versions of the Turkish Seismic Codes are also shown in Figure 7 for comparison. The older design spectra are given only for soft soils for the sake of brevity. As it can be clearly seen from the comparison of the design and recorded spectra, the seismic hazard of the region has been well-defined by all versions of the seismic code. **Regardless of the hazard level that these buildings were designed for, had they been designed according to the seismic design principles of the current and earlier versions of the TBSC (including capacity design, confinement and adequate detailing, which aim at preventing brittle failures and ensuring large levels of ductile response at the damage locations before failure), they would not be expected to collapse.**

Furthermore, considering that there are buildings of similar typology around these buildings, which did not collapse (Section 5 has several examples of collapsed and nearby non-collapsed buildings), some of which are even re-occupied by their residents a few days after the earthquake, it is quite likely that the collapsed buildings, especially those that experienced gravity (pancake) type of failure, were not designed according to the version of the TBSC governing at the time of their construction and/or had structural/material-related deficiencies. Proper component or system-level retrofits of these buildings could have also prevented the observed collapses**.** Similar to what has been observed in many earthquakes, this event highlights the importance of identifying the most collapse-prone buildings and prioritizing their retrofits. An Urban Transformation Law was enacted in Turkey in 2012, which aimed at the transformation of high-risk areas. This transformation includes demolition of the substandard existing building stock and reconstructing new buildings, properly designed and constructed according to the recent building codes. Such efforts are expected to reduce or eliminate observed collapses and corresponding losses in future earthquakes.

2.3. Ground Motion Predictions

Figure 8 compares the recorded PGA at 30 different strong motion stations within Turkey and Greece with the one estimated by using the Boore et al. (2014) (BSSA14) ground motion prediction equation (GMPE). It is observed that most of the recorded PGAs fall within the estimated 2.5/97.5th percentiles, evidencing a good agreement between the observed and the estimated ground motion intensities. However, the closest station recorded a PGA that is over 80% greater than the estimated 97.5th percentile. This discrepancy between the recorded and estimated ground motion intensity may be explained by the lack of data in the high magnitude/low distance region for developing the GMPE, along with potential near-fault effects. Another reason is the site amplification at this location, which has a site condition different from the Vs30 = 250 m/s that these predictions use. Peak values of the accelerations recorded in other stations are listed in Table 1.

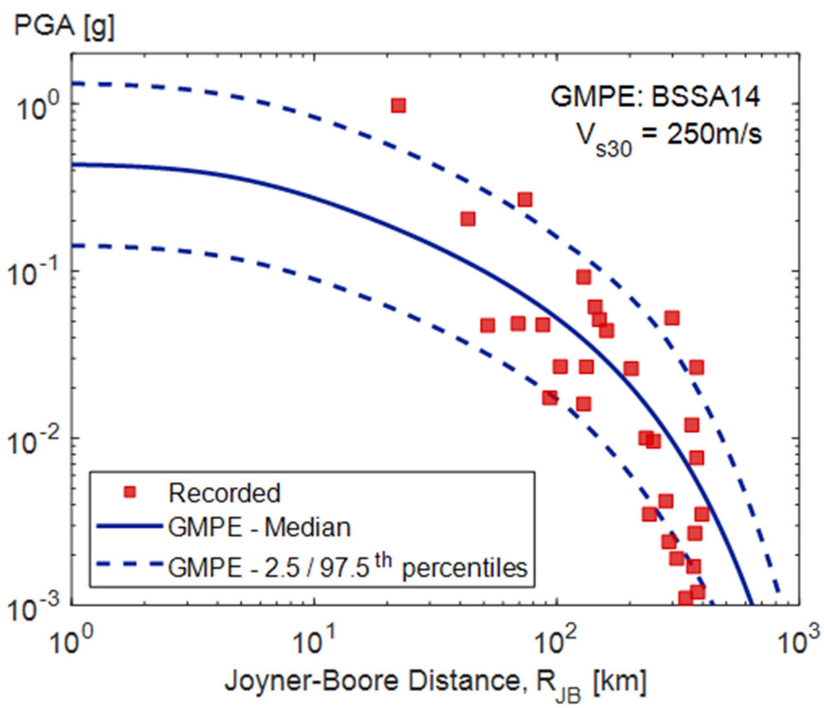

Figure 8. Comparison of recorded and estimated PGA using the Boore et al. (2014) ground motion prediction equation for the Mw 7.0 Aegean Sea earthquake.

Table 1. Ground motion stations and recorded peak acceleration values (gal)

Stations			Measured PGA (gal)			R_{epi}*
AFAD Code	**Province, District**	**Coordinates**	**N-S**	**E-W**	**Vert.**	**km**
3536	Izmir, Seferihisar	38.197, 26.838	50.2	79.1	32.8	34.75
0905	Aydin, Kuşadasi	37.860, 27.265	180.8	144.2	81.0	42.95
3523	Izmir, Urla	38.328, 26.771	80.3	63.6	36.9	48.94
3533	Izmir, Menderes	38.257, 27.130	73.6	45.9	37.5	51.38
3516	Izmir, Güzelbahçe	38.371, 26.891	47.3	48.4	32.1	54.57

*R_{epi} = epicentral distance

3.0 Local Codes and Construction Practices

Earthquake-resistant design of buildings in Turkey is regulated by the Turkish Building Seismic Code, TBSC (2018). Prior to this revision, TBSC has undergone seven revisions in 1947, 1953, 1961, 1968, 1975, 1998, and 2007. Most of these revisions were based on the advances in earthquake engineering and lessons learned from earthquakes around the world and particularly in Turkey. For example, the 2007 version of the code has been highly influenced by the observations made after the 1999 Izmit and Düzce earthquakes (Sezen et al., 2000, 2003). The current version of the code includes state-of-the-art earthquake engineering principles such as performance-based design. Moreover, seismic hazard maps are available for the entire country at DBE and MCE levels.

The most common structural type in the most heavily affected areas of Izmir from the earthquake is medium-rise multistory reinforced concrete (RC) buildings. This type of construction is not only common in Izmir, but also houses most of Turkey's urban population. According to the statistics on urban housing compiled from State Institute of Statistics sources, over 50% of the buildings in existence today in the largest three cities of Turkey (Istanbul, Ankara, and Izmir) are of RC frame construction, and over 75% of these are of more than three stories (World Housing Encyclopedia, 2000). A vast majority of the RC buildings have unreinforced masonry (URM) infill walls, generally built of hollow clay tiles. Therefore, the strength of these URM infills is relatively low, but they provide high stiffness contribution to the lateral force resisting system prior to their disintegration. This eventually leads to soft or weak story mechanisms because of the brittle failure of these URM infills. In several previous large earthquakes in Turkey, including the 1999 Izmit and Düzce earthquakes, this phenomenon led to partial or complete collapses of RC buildings with URM infill walls. It is also possible that several of the partial collapses observed during the 2020 Aegean Sea earthquake are initiated by infill wall failures. Additional studies are needed to confirm this speculation.

4.0 Impacts

This section presents various measures of impacts to the affected community. First-hand accounts of these impacts have been compiled, in the form of amateur videos, in the Appendix of this report.

4.1 "Did you feel it?" Reports

Did You Feel It? (DYFI) is a system developed by the USGS to make use of reports provided by people who felt the earthquake. By taking advantage of the vast number of Internet users, it is possible to get a more complete description of what people experienced during the earthquake, the effects of an earthquake, and an empirical estimate of the spatial distribution of intensities (USGS, 2020b). The USGS DYFI Map and related products are created within minutes of each earthquake of magnitude 1.9 or greater. The origin information (location and time) of each earthquake is provided by the Advanced National Seismic System (ANSS) and its regional and national network partners in the USA.

For this event, the DYFI survey available at the USGS website had over 600 responses within the first 5 hours after the seismic event. The evolution over time of these responses is shown in Figure 9. A map of intensities inferred from DYFI responses and the spatial variation of intensity for the 2020 Aegean Sea Mw 7.0 earthquake are plotted in Figure 10. It is observed that there are intensity levels up to VIII registered close to the epicenter. This large intensity is consistent with the observed damage in the epicentral region. The attenuation of intensity with increasing hypocentral distance shows large dispersion as observed in Figure 11. The large intensities of shaking due to the soil amplification at Bayrakli, 70 km away from the epicenter, are also observed in the attenuation plots of Figure 11.

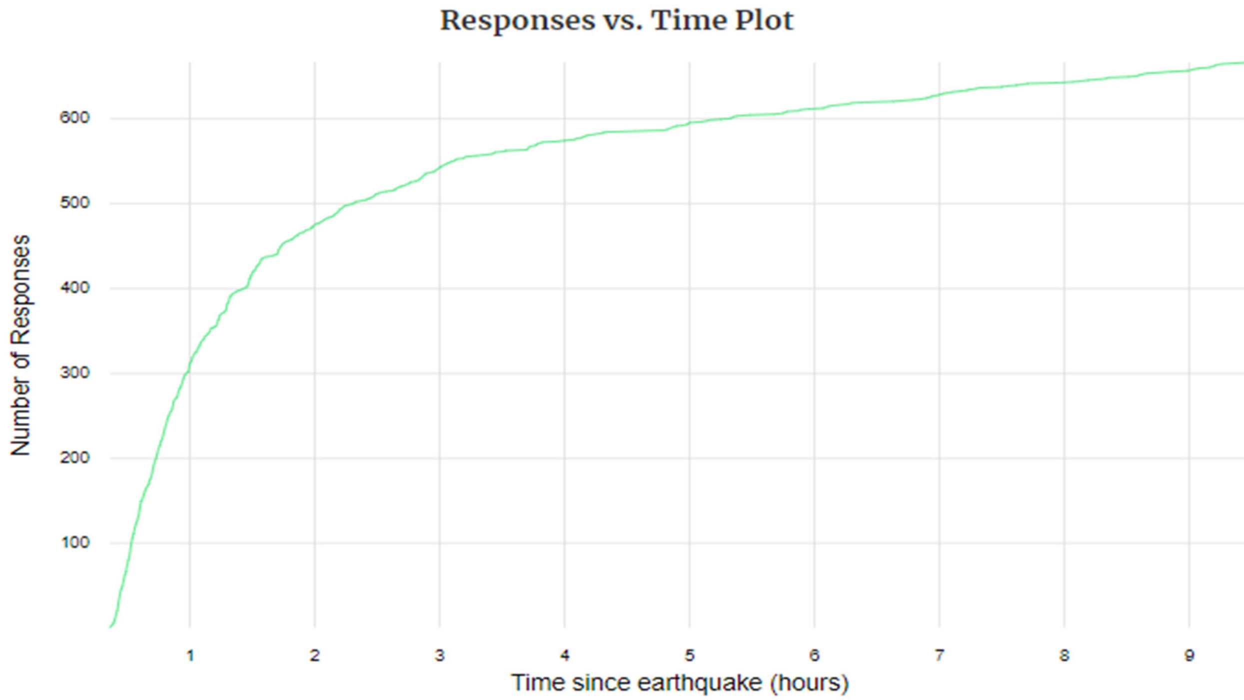

Figure 9. Time-evolution of DYFI responses collected by the USGS (USGS, 2020a).

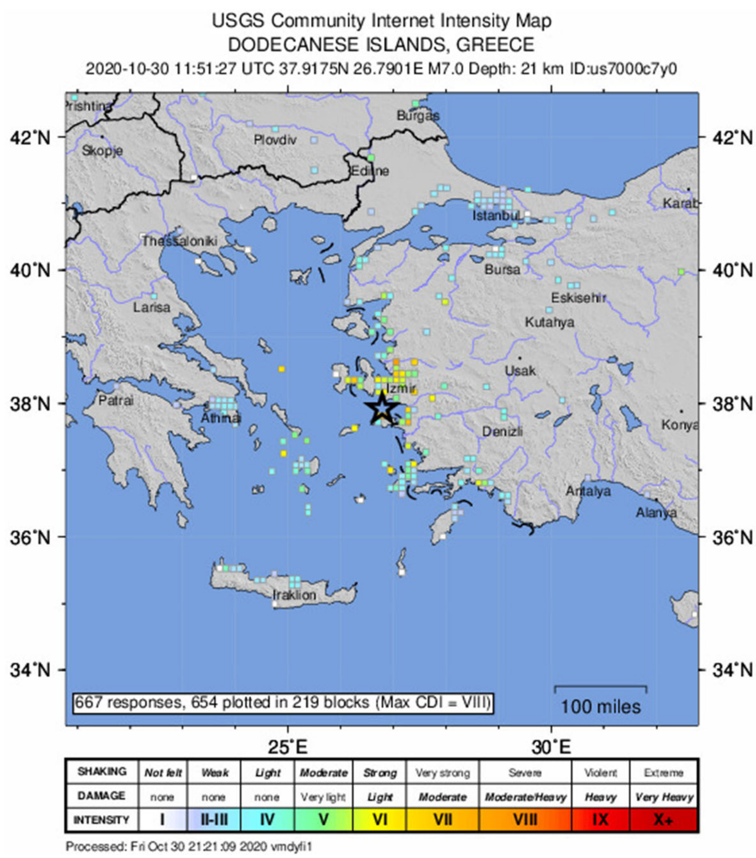

Figure 10. Intensity map inferred from DYFI responses (USGS, 2020a).

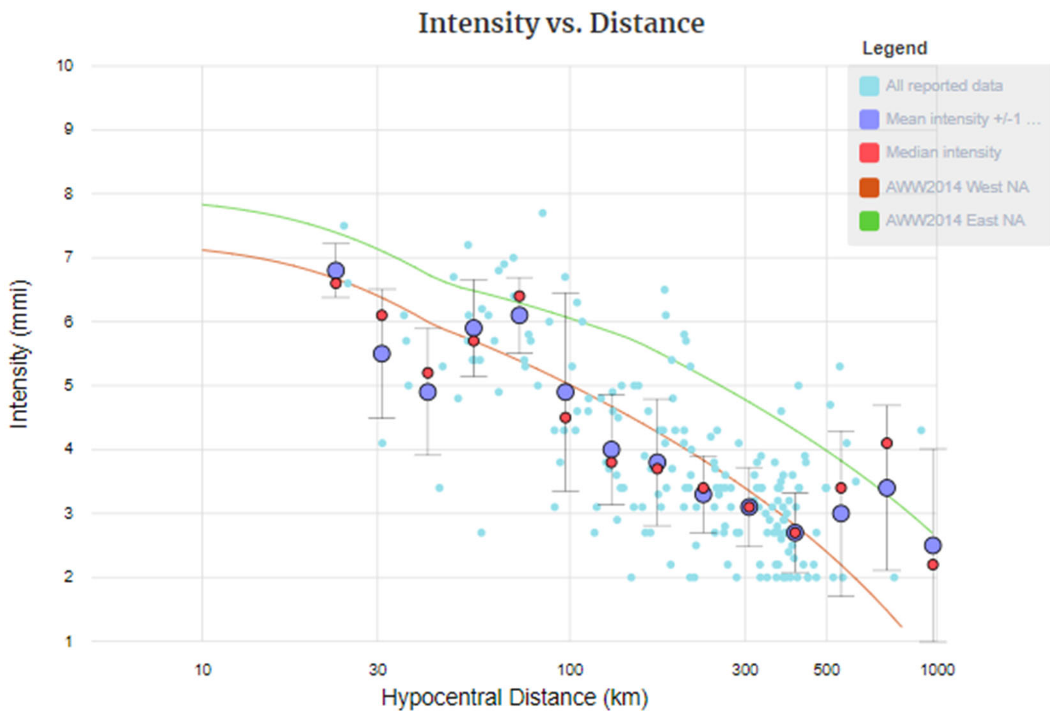

Figure 11. Attenuation of intensities inferred from DYFI responses (USGS, 2020a).

4.2 Estimated Population Exposed

PAGER (Prompt Assessment of Global Earthquakes for Response) is a product of the USGS that produces automatic reports on estimates of the possible impacts of large earthquakes. It combines information from the spatial distribution of population and isoseismals of Modified Mercalli intensity (MMI). A summary of exposed population centers according to USGS PAGER is given in Table 2, organized by shaking intensity in terms of MMI. Table 3 reports the proximity and population of the five settlements closest to the epicenter of the earthquake, which occurred at 23.38 km from the closest settlement, namely Doğanbey Payamli village, Seferihisar district of Izmir.

Table 2. Population centers exposed to the 2020 Aegean Sea earthquake
(From PAGER, USGS 2020 & GeoNames Database of Cities with 1,000 or more residents)

MMI	City	Population	MMI	City	Population
VII	Neon Karlovasion, Greece	7,000	VI	Izmir, Turkey	2,501,000
VII	Kokkari, Greece	1,000	III	Ankara, Turkey	3,517,000
VII	Seferihisar, Greece	20,000	III	Istanbul, Turkey	11,174,000
VII	Mytilinioi, Greece	2,000	II	Alexandria, Egypt	3,812,000
VII	Vathy, Greece	2,000	II	Cairo, Egypt	7,735,000
VII	Samos, Greece	2,000			

Table 3. Closest settlements to the epicenter of the 2020 Aegean Sea earthquake

Province	District	Village	Distance (km)
Izmir	Seferihisar	Doğanbey Payamli	23.38
Izmir	Seferihisar	Ürkmez	26.44
Izmir	Menderes	Gümüldür	29.74
Izmir	Seferihisar	Kavakdere	31.66
Izmir	Seferihisar	Seferihisar Mrkköy	33.84

4.3 Estimated Fatalities and Economic Losses

PAGER produces approximate estimates of the probability density functions of the number of fatalities and economic losses in U.S. dollars. More specifically, these probability density functions provide estimates of the fatalities and economic losses by providing probabilities within specific ranges.

The number of shaking-related fatalities in this event was projected to be low to intermediate according to the USGS, which is a smaller than typical predictions compared to previous earthquakes with similar magnitude. As shown in Figure 12, the USGS PAGER tool estimated fatalities to be 0, 1 to 10, 10 to 100, and over 100 with probabilities of 5%, 29%, 46%, and 18%, respectively, for this event. At the time of writing this report, at least 114 fatalities have been reported. The PAGER estimated economic losses due to damage to be less than $1 million, between $1 and $10 million, between $10 and $100 million, between $100 and $1,000 million, between $1,000 and $10,000 million, and between $10,000 and $100,000 million with probabilities of 6%, 22%, 35%, 26%, and 8%, respectively. No published estimates of actual losses were available at the time of this report.

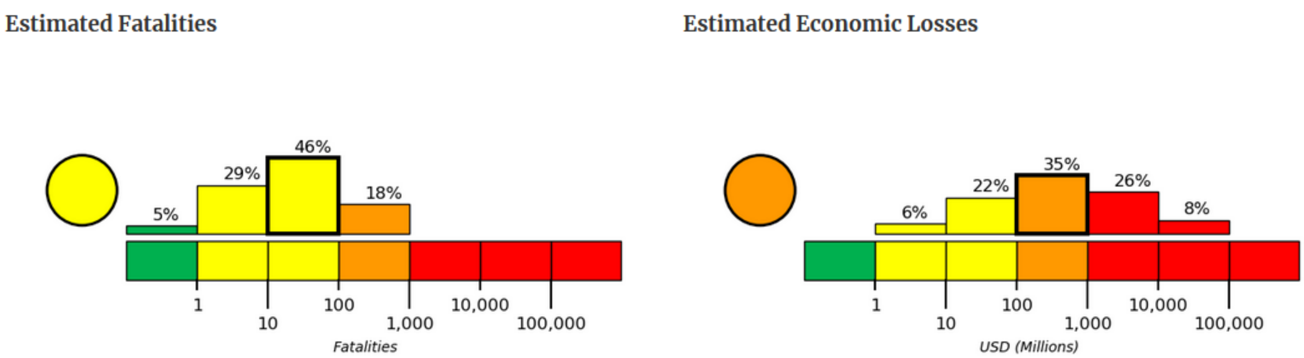

Figure 12. PAGER estimated probability of fatalities and economic losses for the 2020 Aegean Sea earthquake (USGS, 2020a)

4.4 Community Resilience

Authorities warned residents in Izmir not to return to damaged buildings, saying they could collapse in strong aftershocks. Many people spent the few nights after the earthquake out in the streets, too frightened to return to their homes, even if they sustained no damage as reported by the Demirören News Agency (DHA) news agency.

Most of the services, including power, gas, water, telecommunication, and internet remained operational after the earthquake, except for several planned power and gas outages to facilitate rescue operations. Despite the damage in several bridges, there were not significant transportation interruptions because of the availability of alternative routes. Therefore, the community as a whole showed sufficient resilience to this event. To avoid any potential effects of the earthquake consequences on students, a one-week break in education at all levels was announced in the province of Izmir.

5.0 Damage to Buildings

Information provided in this section and Section 6.0 was gathered from various public websites, news services, and social media. Section 7.0 provides limited field observations by local teams. As the earthquake resulted in damage to a number of building types/occupancies, this section is organized into subheadings for different building classes.

5.1 Residential Buildings

This earthquake led to significant residential building damage in a large area including Turkey and Greece. Since construction practices in these regions varied considerably, due to the level of urbanization and population density, the two geographies are separately analyzed.

5.1.1 Turkey

The city of Izmir was severely hit with reports of at least 20 buildings heavily damaged or collapsed, cars being crushed and people in the streets following the quake (CNN, 2020). Izmir Mayor Tunc Soyer indicated that 17 multi-story buildings collapsed (Figures 13-16), all older RC buildings located in the Bayrakli district of Izmir, around 70 km away from the epicenter in an area characterized by soft soil with Vs30 as low as 100 m/sec. As shown previously in Figure 7, site amplification occurred in this area, which is one of the reasons for the observed collapses, along with potential structural and material deficiencies of these buildings. Of these 17 collapses, 13 were sidesway collapses, and the remaining four were gravity (pancake) collapses (Haberturk, 2020). Sidesway collapse occurs due to lateral dynamic instability at excessive lateral displacements, when the lateral strength of the structure significantly degrades. However, for gravity failure, non-ductile RC buildings mostly collapse by losing gravity load carrying capacity, far before reaching these excessive lateral displacements (Mosalam and Günay, 2014). Turkey's Minister of Interior Affairs Suleyman Soylu indicated there were small cracks in some buildings in six other provinces (LATimes, 2020).

Several partial collapses were also observed as shown in Figures 17-20. In one of these examples (Fig. 17), a quarter of an eight-story building with a rectangular plan collapsed. It is likely that this failure started from the corner columns at the collapsed location because of the increased axial forces due to the overturning moments acting along both horizontal axes of the building. These large axial forces' interaction with biaxial bending could have started a partial collapse initiated by one of the lower story corner columns. Although there is no visible plan irregularity, it is also possible that the increased shear failures due to accidental torsional eccentricity or any other torsion irregularity not visible from the photographs in Figure 17 could have led to a column failure. Fortunately, the collapse progressed along only a quarter of the building and did not lead to a full collapse, which indicates the presence of sufficient redundancy and redistribution capacity in the structural system. Figure 18 illustrates a similar partial collapse of one side of a building. Figure 19 documents another partial collapse, which led to failure of the bottom three stories, resulting in a rigid body tilting of the remaining upper stories.

Figure 13. Aerial view of Izmir showing building collapse dust cloud locations (DailyMail, 2020)

Figure 14. Still capture of a video showing a multi-story building during collapse in Izmir (AA, 2020).

Figure 15. Images from collapsed buildings in Bayrakli district of Izmir (CNN, 2020; AA, 2020).

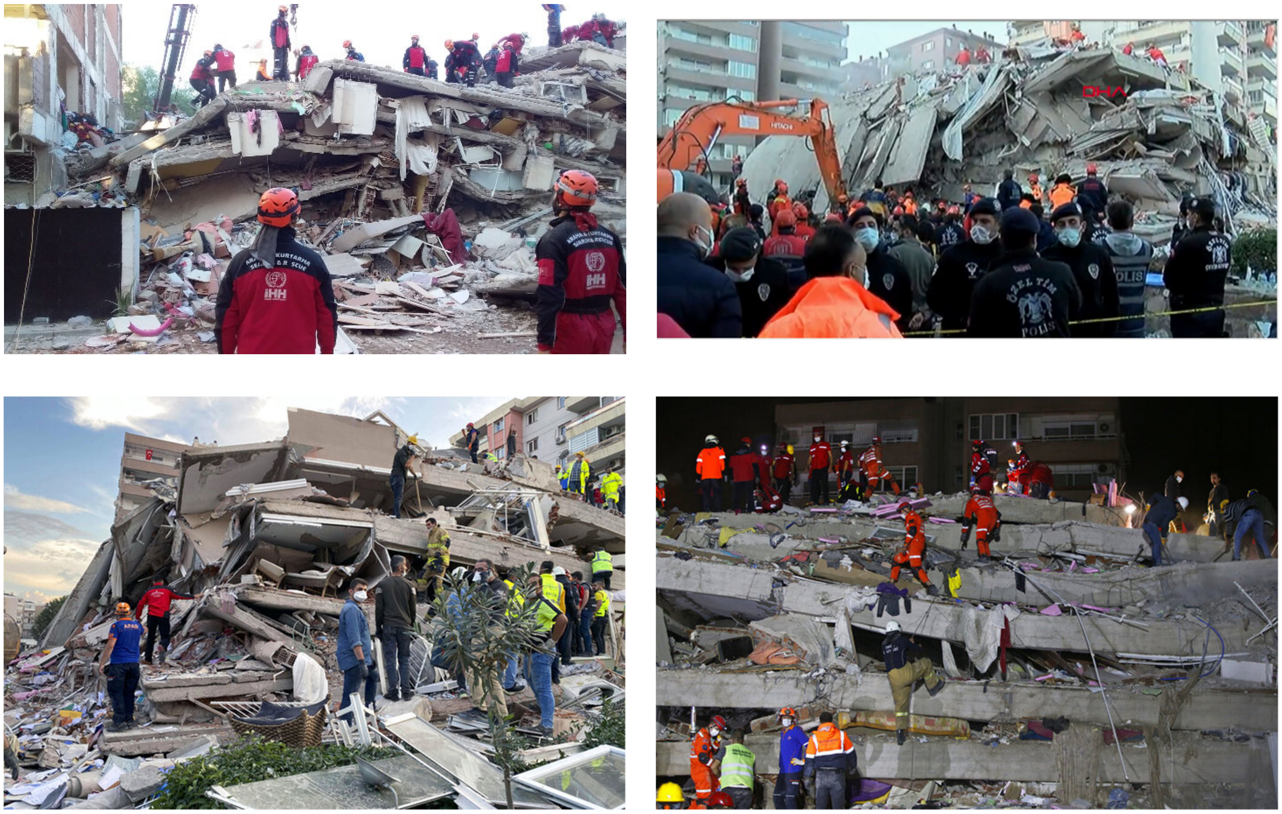

Figure 16. Images from gravity (pancake) collapse of buildings in Bayrakli district of Izmir (CNN, 2020; AA, 2020; AP, 2020; BBC, 2020).

In those buildings that did not collapse, common reported damage included in-plane diagonal and horizontal cracking of hollow clay masonry infill walls (Fig. 20). It is noted that several tall buildings, designed according to the current TBSC (2018) and currently under construction, performed well.

Table 4 summarizes Turkey's Ministry of Environment and Urbanization's preliminary damage assessment of 10,287 buildings. Some of the buildings with heavy damage are not in a condition that allows repair and are being demolished.

Table 4. Ministry of Environment and Urbanization Preliminary Damage Assessments (N=10,287) (NTV, 2020)

Heavy	Moderate	Light	Undamaged
124 (1.2%)	119 (1.2%)	730 (7.1%)	9,314 (90.5%)

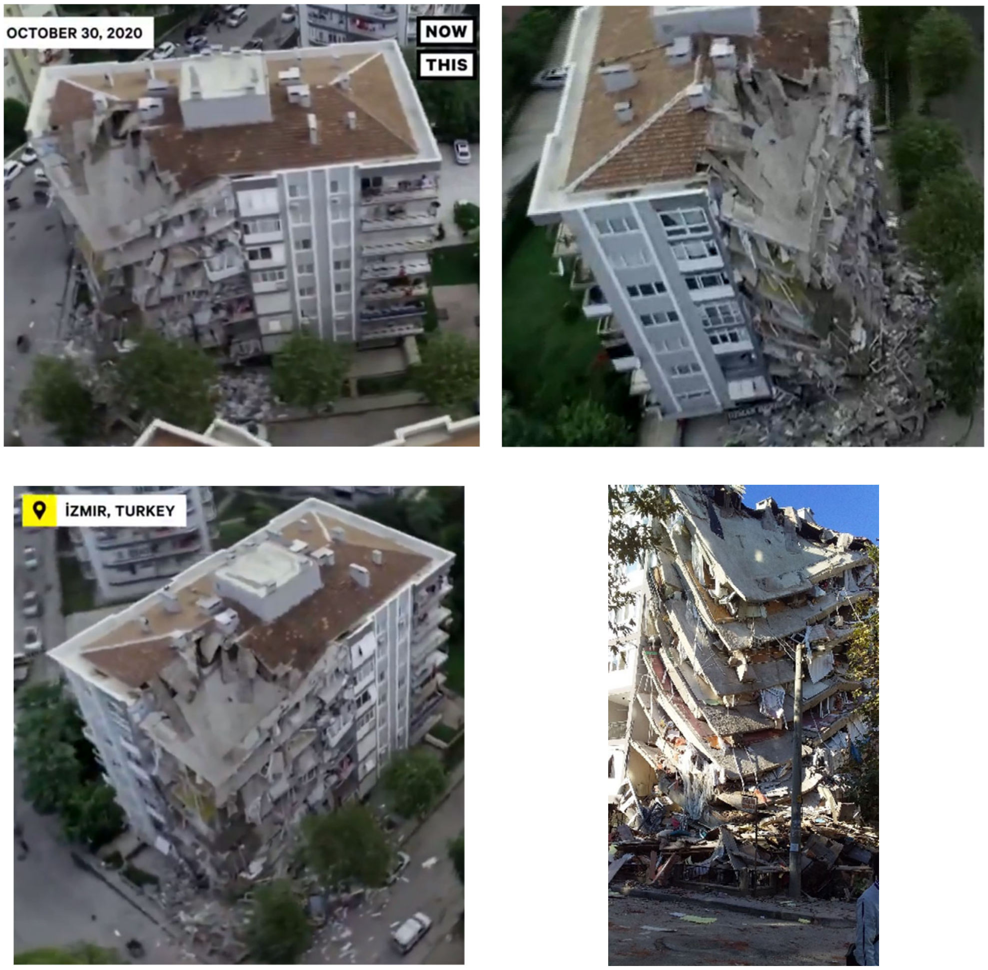

Figure 17. Eight-story building partial collapse in Manavkuyu area, Bayrakli district, Izmir (Twitter, 2020; Fox19, 2020).

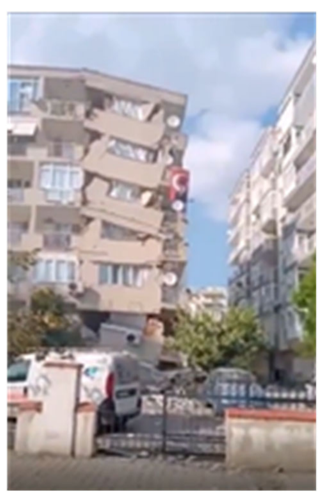

Figure 18. Partially collapsed Karagul building in Manavkuyu area, Bayrakli district, Izmir (Hurriyet, 2020).

Figure 19. A partially collapsed building in Bayrakli district of Izmir, where first three floors above the ground collapsed (Twitter, 2020b; Haber7, 2020; Fanatik, 2020).

Figure 20. Damage in building façades (CNNTurk, 2020).

5.1.2 Greece

Most damage in Greece was reported in older masonry and adobe houses in the towns of Pythagorio, Karlovasi and Vathy on Samos island (Fig. 21). Well-maintained masonry buildings generally performed in an acceptable way, with minor to moderate damage resulting from expected modes of failure. Part of the Church of the Assumption of the Virgin Mary in Karlovasi also collapsed, fortunately while no one was inside. Reinforced concrete buildings demonstrated satisfactory structural performance.

5.2 Hospitals

Patients in Buca Seyfi Demirsoy hospital in Izmir (Fig. 22) were evacuated because of damage to the hospital (GlobalNews, 2020). Similar damage was observed in several other hospitals around Izmir. Base isolation of hospitals in seismic regions is required by law in Turkey to provide functionality and continued operation after earthquakes. Notably, base-isolated Turkish hospitals performed well during the 6.7 Mw Elazig earthquake in 2020 (Günay et al., 2020). Unfortunately, the hospitals damaged in this earthquake were designed and built before this law came into effect. Damage and evacuation of the Buca Seyfi Demirsoy hospital thus demonstrated the importance of requiring base isolation for hospitals.

Figure 21. Damage to masonry and adobe houses on Samos island, Greece (CNN, 2020).

Figure 22. Fallen debris and damage observed in the interior walls of the Buca Seyfi Demirsoy hospital in Izmir (Habererk, 2020; Oda TV, 2020).

5.3 Government Buildings

Nonstructural damage was observed in the windows, exterior and interior infill walls and staircases of the Courthouse in Izmir. Several of these nonstructural damages are shown in Figure 23 (Yurt Gazetesi, 2020). Although such damage is not significant from structural point of view, they cause significant disruption to operation and functionality of the facility.

5.4 Religious Buildings

The roof and a wall of the Orthodox Church of Kimisi Theotokou (also known as the Church of Dormition or the Assumption of the Virgin Mary Church) in Neo Karlovasi on the Greek Island of Samos collapsed during the earthquake (Fig. 24). The two bell towers of the Agios Nikolaos Orthodox Church, also in Neo Karlovasi, were damaged in the earthquake (Fig. 25), as well as the Orthodox Church of Agios Nikolaos in Kokkari on the Island of Samos (Fig. 26) (MSN, 2020). All three churches were designed by the architect Angelos Angelidis in the late 19th to early 20th century. There were also reports of damage to the Orthodox Chapel of Agia Anna in Chora, Samos (Orthodoxia, 2020).

Figure 23. Nonstructural damage observed in windows, exterior and interior infill walls, and staircases of the Courthouse in Izmir (Yurt Gazetesi, 2020).

Figure 24. Façade of the Karlovasi Church on the Greek island of Samos: (a) before the earthquake (MBP, 2020a), and (b) frontal (Liferight, 2020), (c) lateral, and (d) interior views of the partial collapse after the earthquake (Orthodoxia, 2020).

(a)

(b)

(c)

Figure 25. Agios Nikolaos Orthodox Church on the Greek island of Samos: (a) before the earthquake (WC, 2020), (b) view of the left-side damaged bell tower after the earthquake (Orthodoxia, 2020), and (c) view of the right-side damaged bell tower after the earthquake (Protothema, 2020a).

Figure 26. Damage to the Orthodox Church of Agios Nikolaos in Kokkari on the Greek island of Samos (MSN, 2020).

5.5 Museums

Damage to pottery collections was reported at the Archaeological Museum of Pythagorion, on the Greek island of Samos (Fig. 27a-b) and at the Archaeological Museum of Agios Kirykos, Ikaria, Greece (Fig. 27d); the latter museum also reported cracks to the museum walls. The Archaeological Museum in Chios, Greece similarly documented damage to its terracotta and ceramics collections (Fig. 27c). At the Archaeological Museum of Vathy on the Island of Samos in Greece, developed a crack in the leg of a large statue of a kouros (Fig. 27e).

5.6 Archeological and other heritage sites

Parts of the wall of the Castle of Lykourgos Logothetis in Pythagorion on the island of Samos in Greece collapsed (Fig. 28). At the archaeological site of Heraion of Samos, minor damage to the building that supports the activities of the site was also reported (Protothema, 2020b).

(a) (b) (c) (d) (e)

Figure 27. Damage to: (a, b) pottery collection of the Archaeological Museum of Pythagorion (AVGI, 2020), (c) terracotta and ceramics collection of the Archaeological Museum in Chios (AVGI, 2020), (d) pottery collection of the Archaeological Museum of Agios Kirykos (AVGI, 2020), and (e) leg of the kouros at the Archaeological Museum of Vathy (ATHENS9.84, 2020).

Figure 28. Damage to the wall of the Castle of Lykourgos Logothetis in Pythagorion (Dikastiko, 2020; Protothema, 2020b).

5.7 School Buildings

Out of the forty-four schools on the island of Samos, eleven reported damage (mostly nonstructural) and could not be immediately re-occupied. Seven of these schools are in the Municipality of East Samos. Damaged schools (Fig. 29) were identified in Karlovasi, Chora, Paleokastro, Ano Vathi, and Pythagorion (Documentonews, 2020). Damage was also reported to schools on the island of Chios, where six schools remain closed, namely the Primary Schools of 5th Chios, 1st Livadia, 2nd Vrontadou, the Primary School and Kindergarten of Kalamoti, the Vocational High School of Chios, and the Evening High School-Unified Special Vocational High School - Lyceum (efsyn, 2020). In addition, damage was also reported to the Mazí Educational Centre (Fig. 30), which supports children and adolescents living in the Samos refugee camp located in the island (Still I Rise, 2020).

Figure 29. Damage to the Porphyriada school in Karlovasi (Documentonews, 2020).

Figure 30. Damage to the Mazí Educational Centre (Still I Rise, 2020).

6.0 Damage to Infrastructure

A few highway bridges in Izmir experienced damage, including the precast girders of a bridge under construction, which fell to the ground and crushed several parked cars (Fig. 31).

Figure 31. A collapsed girder of a bridge under construction fell to the ground and crushed parked cars in Alsancak district of Izmir, Turkey (HaberTurk, 2020).

7.0 Tsunami Observations

The earthquake source was a submarine normal fault, which typically results in downward movement of the ocean floor on one side of the fault, with possible upward movement on the other side. This displacement of the ocean floor leads to similar movement in the sea surface above the fault, which must return to horizontal by means of gravity driven waves, or tsunamis. There are a number of video recordings of the effects of the resulting tsunami waves on the Greek island of Samos and the Turkish coastline around Izmir. Although there is unlikely to be any structural damage due to the tsunami inundation, there was extensive flooding and damage to boats and vehicles caught in the flow.

In some areas, the tsunami arrived as a negative wave resulting in drawdown prior to inundation. The resulting drop in sea level exposes the near shore bathymetry as shown in Figure 32. This drawdown is also evident in a video taken on the Izmir coast showing a number of yachts that have broken free from their moorings and are moving out to sea at Teos Marina, Seferihisar, Turkey (Fig. 33). Several boats were also washed aground at Teos Marina (AU News, 2020).

Although there are no reports of injuries due to the tsunamis, there is video evidence (Fig. 34) of people ignoring the warning signs of ground shaking, the ocean receding, and even staying dangerously close to the shoreline during inundation. Figure 35 shows still images from a video captured from the second story of a building, believed to be in Seferihisar, as the incoming tsunami flooded the street and ground floor level below. Flooding was observed in Cesme and Seferihisar in parts of Turkey's wider Izmir province, as well as on the Greek island of Samos. Authorities referred to the flooding that occurred in Seferihisar as a “mini-tsunami” (CNN, 2020).

Figure 32. Tsunami drawdown exposing the ocean floor at two locations along the coast of Turkey (Source: https://www.youtube.com/watch?v=a6h68yy76rM&feature=youtu.be).

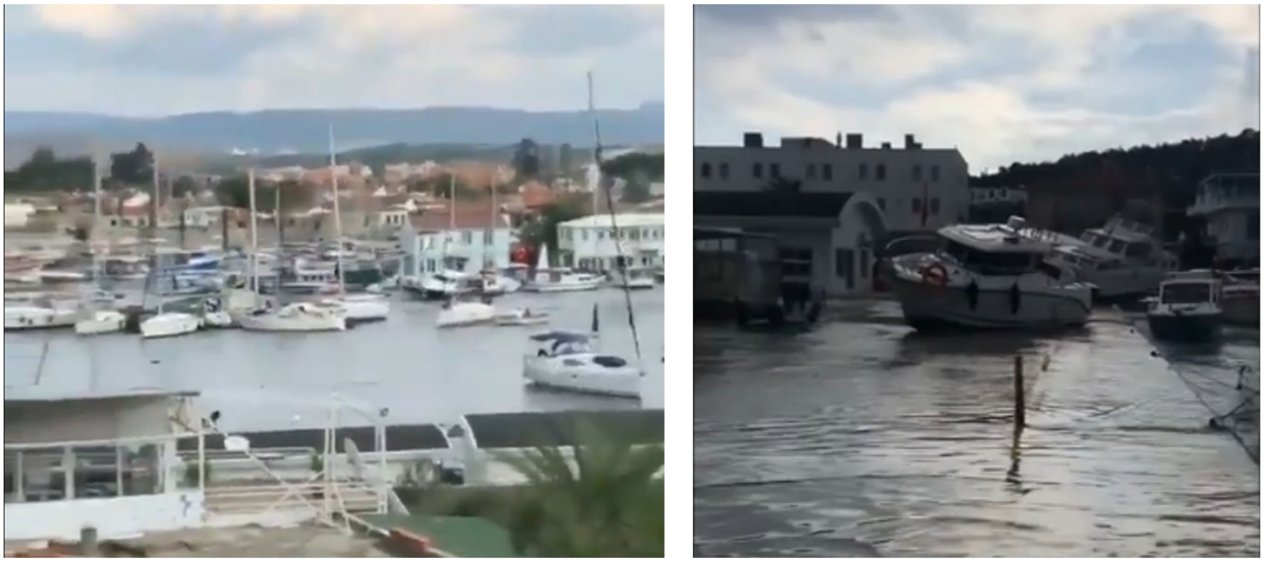

Figure 33. Yachts at Teos Marina, Seferihisar on the Turkish coast moving out of harbor due to tsunami drawdown (left) and washed onto the dock (right) (38.1947N, 26.7821E) (Source: https://www.youtube.com/watch?v=a6h68yy76rM&feature=youtu.be).

Figure 34. Vehicles and pedestrians taken by surprise as the tsunami inundates a coastal town square in Samos (37.756N, 26.9765E) (Source: https://youtu.be/g74_2ojH24o (right) and https://www.youtube.com/watch?v=a6h68yy76rM&feature=youtu.be (left)).

Figure 35. Flooded residential area in Seferihisar after the earthquake (Twitter, 2020c).

8.0 Observed Geotechnical Failures

Although there was no formal reporting of liquefaction at the time of the writing this report, there was liquefaction potential in several districts of Izmir. This includes the most affected Bayrakli district (Altun et al., 2012).

9.0 Field Observations

Though not formally activating a Field Assessment Structural Team (FAST) for this earthquake, StEER was fortunate to collaborate with colleagues and members in the area to compile some field observations. RC frames with URM infill walls are a common structural typology used for buildings in Turkey. Infill walls can provide beneficial or detrimental contributions to the structural response (Mosalam and Günay, 2015). Damage to this typology after the 2020 Aegean Sea earthquake has been documented during field reconnaissance conducted by StEER members (Fig. 36). The left photograph in this figure shows corner crushing of an infill wall, a common in-plane damage pattern observed in URM infill walls. The right picture in Figure 36 shows the heavy damage at the top of a column characterized by core concrete crushing, longitudinal reinforcing bar buckling, and transverse reinforcing bar yielding accompanied by possible fracture. Presence of inclined failure surfaces and diagonal cracks, due to the large shear forces transferred to the infill because of its in-plane high stiffness, indicates the contribution of the infill wall to the lateral force resistance up until the corner crushing failure of the infill wall. Increased shear demand on the column after the infill wall failure and the development of a short column due to the corner crushing of the infill wall resulted in the observed severe damage. Diagonal cracking of exterior and interior infill walls of other buildings have also been documented by StEER members in the field (Figs. 37-38).

Typical structural and material deficiencies that could have played a role in the damages observed in different districts of Izmir are shown in Figure 39: relatively large spacing of transverse reinforcement and potential corrosion of the longitudinal reinforcing bars.

StEER members also documented damage to nonstructural components and infill walls of the Courthouse in Izmir (Fig. 40), discussed previously in Section 5.3 of this report.

Figure 36. Heavy damage in a RC frame building with URM infills (Credit: Ozgur Ozcelik).

Figure 37. Diagonal cracks in exterior infill walls (Credit: Mauricio Morales-Beltran).

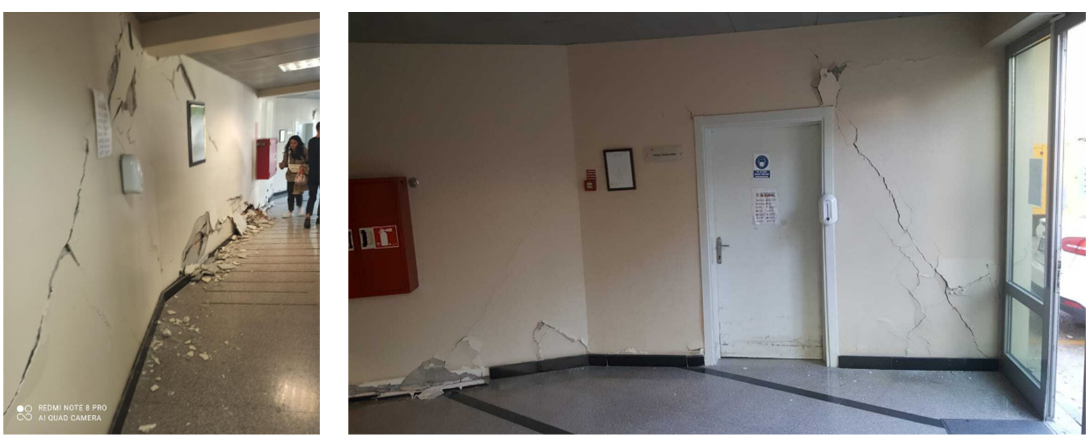

Figure 38. Diagonal cracks in interior infill walls of a building (Credit: Ahmet Dindar).

Figure 39. Large transverse reinforcement spacing (left) and corrosion of reinforcing bars (right) (Credit: Ozgur Ozcelik).

(a) (b) (c) (d)

Figure 40. Damage observed in the Courthouse in Izmir: (a) fallen suspended ceiling, (b) toppled shelves, and (c, d) extensive damage to infill walls (Credit: Ozgur Ozcelik).

10.0 Recommendations for Further Study

Based on the information gathered by the team of this Preliminary Virtual Reconnaissance Report (PVRR), StEER offers the following recommendations for future study:

Theme 1: Recorded Ground Motions and Effects on the Structural Response

1. At the time of the writing of this report, it is unclear why the level of shaking at Gümüldür, Izmir station of the Kandilli Network, with 0.98g PGA, is much larger than the recorded ground motions at all other stations. The reason for this extremely large PGA value requires further exploration.
2. The effects of site amplification on tall building response should be explored properly in this region for potentially larger future earthquakes. It is observed from the recorded motions of this earthquake that the acceleration-sensitive region in the acceleration spectrum at soft soil sites can extend to natural periods of almost 1.5 s and the acceleration amplitudes can be amplified by up to a factor of 2.

Theme 2: Systematic On-Site Damage Assessment

1. It was speculated that several of the partial collapses observed in Izmir were initiated by infill wall failures. Additional investigation is warranted to confirm the role of masonry infill in instigating any of these collapses.
2. The main information collected and discussed in this report focused on collapsed or partially collapsed buildings as the damage assessment was still ongoing in many buildings. Although some preliminary assessment totals were included in this report, causes of damage at all levels should be explored further.

Theme 3: Instrumented Buildings and Earthquake Early Warning (EEW)

1. There are several tall buildings in Izmir that were instrumented according to the regulations of the TBSC (2018). Data from these buildings are quite valuable in terms of understanding tall buildings response and informing their analytical model development.
2. The main damage occurred at a distance of 70 km from the epicenter, which could lead to an early warning of around 15 s, if an earthquake early warning (EEW) system was in effect. Currently, only Istanbul and the surrounding metro area benefits from an EEW system. The cost-benefit analysis of an EEW system could be conducted for other populous cities like Izmir in preparation for future earthquakes.

Theme 4: Reconstruction & Retrofit

1. Some of the heavily damaged buildings are not in a repairable condition and need to be demolished and reconstructed. For the design and construction of these new buildings, the feasibility of using protective systems (base isolation, supplemental damping, etc.) need to be evaluated, which may have significant benefits in the medium-long term. In earthquake engineering literature, such lifecycle comparisons have been conducted by several researchers for buildings designed according to seismic codes and with enhanced performance using base isolation (e.g., Terzic et al., 2012).
2. As also noted previously, observed collapses highlighted the need to identify and propose feasible retrofit strategies for collapse-prone buildings.

Despite the impacts documented in this PVRR, and recommendations for further study articulated above, travel restrictions and safety concerns associated with the ongoing pandemic prohibit StEER from deploying a Field Assessment Structural Team (FAST) from the United States for this event. However, StEER remains interested and willing to coordinate with colleagues in the affected region to support the ongoing collection of data locally and encourages the consideration of the above recommendations in the currently ongoing assessments and response to this event. StEER data collection workflows and the Virtual Assessment Structural Team (VAST) remain available to local researchers and will support the authorship of an Early Access Reconnaissance Report (EARR) by any local FAST, if warranted.

Appendix: Videos for Live Earthquake Shaking and Damage

1. Examples of live building collapses (Warning: graphic content)
   a) https://video.twimg.com/ext_tw_video/1322156476761280513/pu/vid/720x1280/9FpncoilFJqjKAAd.mp4?tag=10
   b) https://video.twimg.com/ext_tw_video/1322159725358714880/pu/vid/638x360/3IshtVsIN1P-F9CT.mp4?tag=10
   c) https://www.youtube.com/watch?v=VHKZNZBuTtU
   d) https://youtu.be/huEGefqJOgQ
   e) https://www.ntv.com.tr/video/turkiye/riza-bey-apartmaninin-yikilma-ani,OrMnbvfG00u-RFoP_resZw
   f) https://www.ntv.com.tr/turkiye/izmirde-hasar-tespit-calismalari-124-bina-acil-yikilacak,WHG7B7p1v0ecQaZVoEC4Gw

2. Aerial footage of damaged building sites
   a) https://www.wfmz.com/news/cnn/top_stories/turkey-aerial-footage-of-damage-in-izmir-after-quake/video_ed92d0ba-77dc-5a3d-b7f1-f4141b745722.html
   b) https://youtu.be/ifRH1yXnH0Y
   c) https://youtu.be/W86dDMjYq_U
   d) https://youtu.be/pdiG_wyjDeI
   e) https://www.youtube.com/watch?v=Z4gaIncwHNw (Karlovasi Church, Samos)

3.Tsunami flooding
   a) https://youtu.be/QOiB9unEmHk
   b) https://video.twimg.com/ext_tw_video/1322193447349063681/pu/vid/480x848/txD3rR9JLhkM-F4H.mp4?tag=10
   c) https://twitter.com/i/status/1322163744621973504
   d) https://twitter.com/i/status/1322166681431646208
   e) https://twitter.com/i/status/1322158146949926912
   f) https://youtu.be/eXpQLfG9xxU
   g) https://www.youtube.com/watch?v=g74_2ojH24o&feature=youtu.be

4. Indoor shaking and non-structural damage
   a) https://youtu.be/zW7oZxzVZ9o
   b) https://www.facebook.com/watch/?v=658807325028216

5. Live shaking and façade structural and non-structural damage
   a) https://video.twimg.com/ext_tw_video/1322149914185506817/pu/vid/352x640/cK9uJDKM9tBKaUJO.mp4?tag=10

6. Bridge damage
   a) https://www.haberler.com/izmir-de-meydana-gelen-depremde-viyaduk-yikildi-13703079-haberi/

7. General live shaking and combined videos
   a) https://video.twimg.com/ext_tw_video/1322292528150945794/pu/vid/224x400/iJeURp2J90KL4e1u.mp4?tag=10
   b) https://youtu.be/_DyckxJo_Ks

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