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ORIGINAL ARTICLE

2022 Düzce, Türkiye earthquake: advances in the past 2 decades, lessons learned, and future projections

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Abstract
In the year 1999, two devastating earthquakes (M_w 7.4 Kocaeli earthquake in August and M_w 7.2 Düzce earthquake in November) occurred in Northwest Türkiye. These two earthquakes led to a very large number of casualties and building collapses. When the 1999 earthquakes occurred, most of the structures in the earthquake-impacted region were not designed according to modern seismic design codes. During the 25 years following those earthquakes, there have been significant advances in building construction in the light of earthquake engineering, including adequate seismic codes, new regulations, and effective code enforcement in the earthquake impacted region. These advances have been reflected in the construction of new structures in the region and the retrofitting of existing ones. As a result, 70–80% of the current building stock in Düzce was designed, constructed, or retrofitted after the 1999 earthquakes. Almost 23 years later, in 2022, an M_w 6.1 earthquake occurred in Düzce, with ground shaking close to the seismic design code life safety performance level. The 2022 earthquake provided a great opportunity to evaluate the effectiveness and consequences of the advances in earthquake engineering and the relevant policy-making and regulations. This paper provides a comparative overview of the 1999 and 2022 earthquakes that struck the city of Düzce in terms of hazard, vulnerability, and consequences. Furthermore, other key lessons learned from the 2022 Düzce earthquake are documented based on field reconnaissance and numerical simulations. The lessons learned are expected to provide useful guidance for the reconstruction efforts after the 2023 Kahramanmaraş Türkiye earthquake sequence or in similar efforts in other parts of the world.

Keywords Earthquake reconnaissance · Building codes · Ground motions · Seismic performance comparison · Seismic resilience

Extended author information available on the last page of the article

1 Introduction

Türkiye is located in one of the most seismically active regions in the world. It lies mostly on the Anatolian plate and is surrounded by three main tectonic plates, namely the Arabian plate, the African plate, and the Eurasian plate. Consequently, many high-intensity earthquakes have occurred in this region over the last century, including the 1939 Erzincan earthquake (M_s, 7.9), 1976 Çaldıran earthquake (M_w, 7.0), 1999 Kocaeli earthquake (M_w 7.4), 1999 Düzce earthquake (M_w 7.2), 2011 Van earthquake (M_L 6.7), 2020 Elazığ earthquake (M_w 6.8), 2020 Izmir Seferihisar earthquake (M_w 6.6) (AFAD 2022a), 2022 Düzce earthquake (M_w 6.1) (USGS 2022a), and the recent 2023 Kahramanmaraş earthquake sequence (M_w 7.8 and M_w 7.7) (Dilsiz et al. 2023).

Most of these earthquakes led to major damage, including the collapse of buildings and casualties. Two of the most devastating of these earthquakes were the 1999 Kocaeli and Düzce earthquakes. These two earthquakes led to numerous casualties and widespread building collapses (Sezen et al. 2000). Notably, the Turkish earthquake code (TEC) had already been updated in 1998 (TEC 1998), one year before these earthquakes, with modern principles of earthquake engineering. These two earthquakes resulted in further updates of TEC to include performance-based engineering principles and concepts of nonlinear analysis. Furthermore, these earthquakes resulted in significant design, construction, and code enforcement policy changes in the earthquake-impacted region (including Düzce, Kocaeli, and other cities in Türkiye). A municipal law that limited the number of stories in this region to four was enacted (Duzce 2023). Almost 20 years after the 1999 Kocaeli and Düzce earthquakes, an M_w 6.1 earthquake with a depth of 10.0 km and epicenter coordinates of 40.847°N 30.967°E struck Gölyaka, Düzce at 4:08 am local time on November 23, 2022 (USGS 2022a). This earthquake was caused by shallow strike–slip faulting in the crust (USGS 2022a), and the resulting ground motions were close to design-level shaking intended in TEC (2018). Therefore, this earthquake provides a great opportunity to evaluate the consequences of the advances in earthquake engineering and policies enacted in the region. It also provides an opportunity to make future projections, for example, related to the reconstruction after the 2023 Kahramanmaraş earthquakes in Türkiye. It is noted that the advances in earthquake engineering after the 1999 earthquakes were not very effective in reducing the devastating consequences of the 2023 Kahramanmaraş earthquakes, partly because of the issues in code enforcement and construction quality in that region, compounded by the extreme shaking that was multiple folds of the maximum considered earthquake (MCE) levels at some locations (Dilsiz et al. 2023). Furthermore, the 2023 Kahramanmaraş earthquakes once again highlighted the common deficiencies in existing reinforced concrete buildings in Türkiye, including insufficient earthquake-resistant design practices. Precast concrete and masonry structures in the region also suffered severe damage due to several reasons including inadequate engineering design, and construction deficiencies. However, this is not the focus of this paper as there were major differences in local policies and code enforcement between the earthquake-impacted regions of the 2022 Düzce and the 2023 Kahramanmaraş earthquakes. Therefore, this paper focuses on the Düzce region, where there were major advances in earthquake engineering and their implementation and adoption of relevant design, construction and city planning policies.

With this motivation, this paper provides a comparative overview of the 1999 and 2022 earthquakes in terms of hazard, vulnerability, and consequences, with a focus on the city of Düzce and its eight districts: City center, Akçakoca, Cumayeri, Çilimli, Gölyaka, Gümüşova, Kaynaşlı, and Yığılca. It is situated adjacent to the highly populated and industrialized Marmara region of Türkiye. Consequently, it has witnessed a significant population surge and substantial growth in its built environment over the past two decades. Additionally, valuable insights drawn from the 2022 Düzce earthquake are documented using field reconnaissance and numerical simulations.

The organization of the paper is as follows: Sect. 2 provides a comprehensive comparison of the 1999 and 2022 earthquakes, while Sects. 3, 4, and 5 focus on detailed comparisons of hazard characteristics, vulnerability characteristics, and consequences, respectively. Section 6 elucidates further significant lessons learned from the 2022 Düzce earthquake by discussing the performance of buildings and other infrastructure during the 2022 earthquake from the post-earthquake reconnaissance. Section 7 includes numerical simulations that shed light on the reasons for the low damage experienced during the 2022 earthquake and a comparison of the response of buildings in the 1999 and 2022 earthquakes. Section 8 lists the conclusions and discusses future projections and potential future improvements beyond the observed performance during the 2022 earthquake.

2 Overview of the 1999 and 2022 earthquakes

On August 17, 1999, a moment magnitude M_w 7.4 earthquake occurred on the North Anatolian fault in north-western Türkiye, near Izmit, Kocaeli (referred to as the 1999 Kocaeli earthquake in this paper). The hypocenter was located at a depth of 15.9 km with 40.756°N, 29.955°E coordinates, 90 km east of Istanbul (Fig. 1c). This earthquake significantly impacted the cities of Kocaeli, Sakarya, Yalova, Düzce, and İstanbul leading

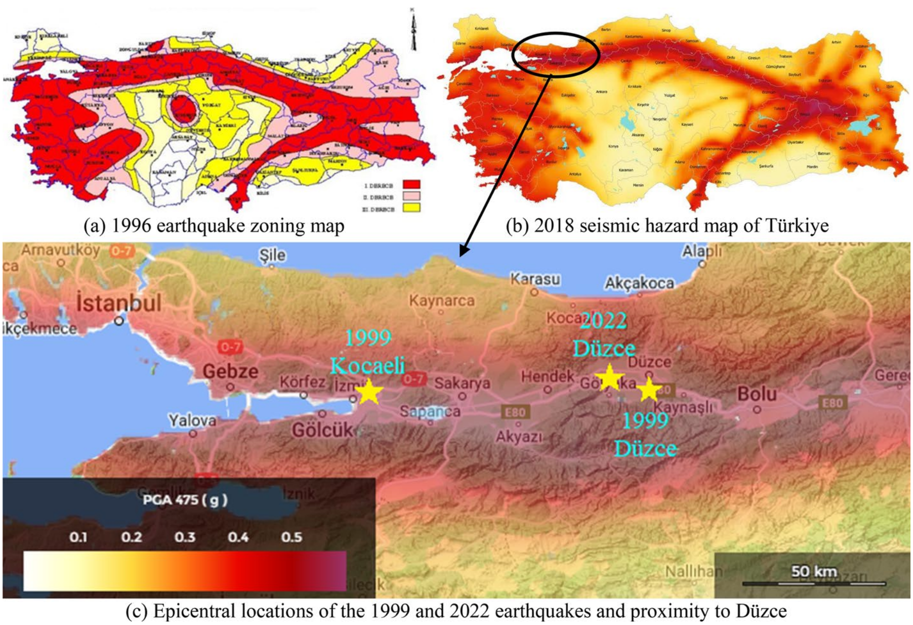

Fig. 1 Locations of the 1999 and 2022 earthquakes and seismic hazard maps of Türkiye (AFAD 2022a) providing an overview of the shaking levels in the region. **a** 1996 earthquake zoning map **b** 2018 seismic hazard map of Türkiye **c** Epicentral locations of the 1999 and 2022 earthquakes and proximity to Düzce

to 17,220 deaths and over 44,000 injuries. It destroyed 77,300 homes and businesses and damaged an additional 245,000 building units in the region (Sezen et al. 2000).

Almost three months after the 1999 Kocaeli earthquake, an M_w 7.2 earthquake struck the province of Düzce on November 12, 1999 (denoted as 1999 Düzce earthquake in the subsequent sections of this paper), which took place on the Düzce segment, with a focal depth of approximately 11 km, and the epicenter was determined as 40.806°N, 31.187°E (Fig. 1c). This earthquake had a significant impact on the cities of Düzce, Sakarya, Bolu, and Kocaeli. In the earthquake that lasted for 30 s, 763 people lost their lives, 4948 people were injured, and thousands of people were left homeless. After the 1999 Düzce earthquake, 31,197 homes and businesses were destroyed, and an additional 91,354 building units in the area were damaged (Ozmen and Bagci 2000).

At 4:08 am local time on November 23, 2022, an earthquake struck 3 km northeast of Gölyaka District and 7 km west of Düzce, Türkiye. According to the Ministry of Interior of Türkiye (AFAD 2022b), the earthquake is reported as having M_w of 5.9, a depth of 6.81 km, and an epicenter at 40.823°N, 31.025°E (Fig. 1c). According to USGS (2022a), this earthquake had M_w of 6.1 and a depth of 10.0 km. The earthquake resulted in two fatalities, minor structural damage but significant nonstructural property damage (Altunisik et al. 2022; Sezen et al. 2023).

Figure 1c shows the epicenters of the 1999 Düzce, 1999 Kocaeli, and 2022 Düzce earthquakes and their proximity to Düzce. Table 1 provides a comparative overview of these three earthquakes, considering aspects of hazard, vulnerability, and consequences. Further details are provided in the following sections for each aspect. As can be observed from this

Table 1 Comparative overview of the 1999 and 2022 earthquakes with an emphasis on Düzce (combined from Ozmen 2000; Ozmen and Bagci 2000; AFAD 2022b, 2023; Sucuoglu 2000)

Category	Characteristics	Earthquake		
		1999 Kocaeli	1999 Düzce	2022 Düzce
Hazard	PGA in Düzce station (g)	0.37	0.52	0.42
	PGV in Düzce station (cm/sec)	56.38	80.16	73.65
	Uniform duration of the motion in Düzce station (sec)	17.68	21.74	14.81
	Shaking intensity relative to design level	~DBE*	>MCE**	~DBE
Vulnerability	Application of modern seismic design principles	×	×	✓
	Strict code enforcement	×	×	✓
	Maximum 4-story regulation	×	×	✓
Consequences	Number of fatalities	271	710	2
	Number of injuries	1,163	4151	93
	Normalized number of collapsed building units***	5.1%	20.8%	0.66%
	Normalized number of damaged building units****	12.4%	32.1%	5.13%
	Total losses ($)	10B		150 M
	Recovery time	Several years		A few weeks

* Design basis earthquake, ** Maximum considered earthquake, *** Number of collapsed building units/Total number of building units, **** Number of damaged building units/Total number of building units

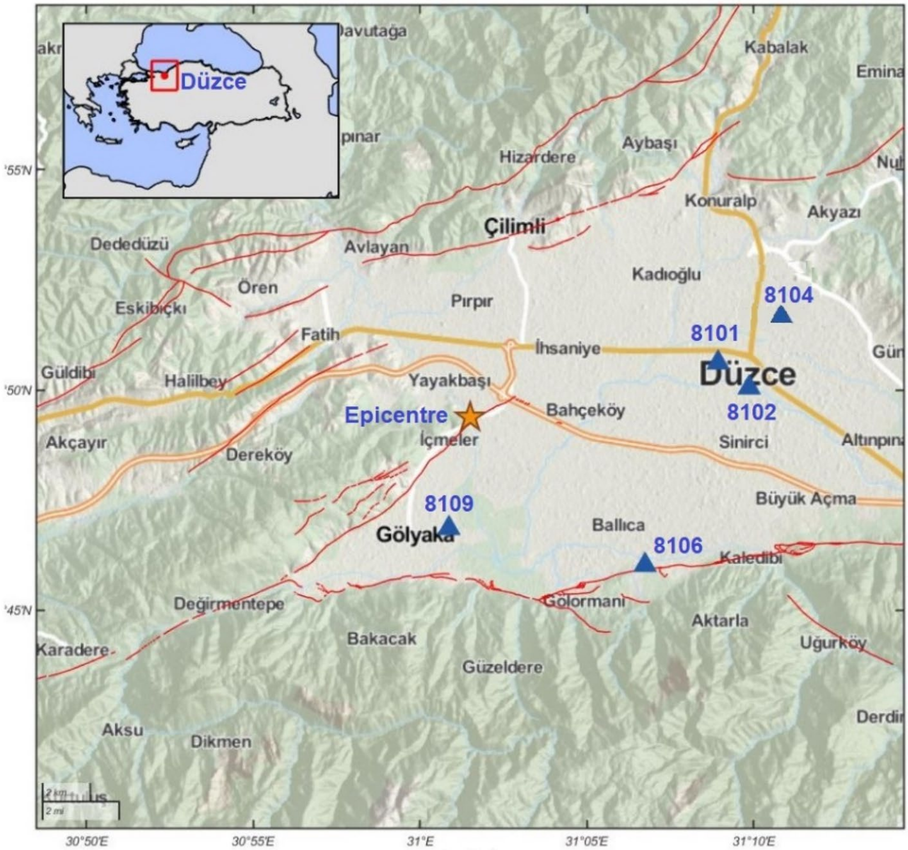

Fig. 2 Map of the five closest stations (blue triangles) to the epicenter where the ground motions in 2022 Düzce earthquake were recorded (Adapted from AFAD 2022b)

table, the design of structures using modern principles of earthquake engineering, along with strict code enforcement and effective regulations, resulted in the observed successful performance of the built environment in the 2022 Düzce earthquake, which is the expected and intended performance at this level of an earthquake, as compared to the major devastation observed in the 1999 and other earthquakes in Türkiye.

3 Hazard characteristics

This section provides a concise overview of the ground motion characteristics of the 2022 Düzce earthquake, followed by their response spectra and a comparative assessment of ground motions from the 1999 and 2022 earthquakes.

Table 2 Ground motion stations and recorded PGA values (Adapted from AFAD 2022b)

Station							Measured PGA (g)			Measured PGV (cm/s)			Measured PGD (cm)		
Code	Province	District	Latitude	Longitude	$V_{s,30}$ (m/s)	R_{epi} (km)	E–W	N–S	U–D	E–W	N–S	U–D	E–W	N–S	U–D
8109	Düzce	Gölyaka	40.7810	31.0144	183	4.75	0.36	0.27	0.24	22.81	43.99	7.58	4.39	12.01	2.28
8106	Düzce	Center	40.7670	31.1124	338	9.63	0.38	0.35	0.23	33.08	26.06	5.87	9.98	4.52	1.92
8101	Düzce	Center	40.8436	31.1489	282	10.62	0.31	0.25	0.22	36.83	29.69	8.72	10.29	10.03	1.78
8102	Düzce	Center	40.8342	31.1644	280	11.79	0.42	0.22	0.25	73.65	35.21	12.96	23.39	17.39	1.97
8104	Düzce	Center	40.8611	31.1804	398	13.74	0.37	0.36	0.23	40.82	31.09	8.89	7.56	9.34	1.75
8105	Düzce	Center	40.9028	31.1520	914	13.88	0.60	0.60	0.22	31.05	18.23	7.26	5.23	3.13	1.55

Table 3 Features of the recorded ground motions from station 8102 (AFAD 2022c)

Direction	PGA (g)	Uniform duration (s)	Significant duration (s)	Predominant period (s)
E–W	0.42	13.25	5.06	1.18
N–S	0.22	14.81	14.32	1.64

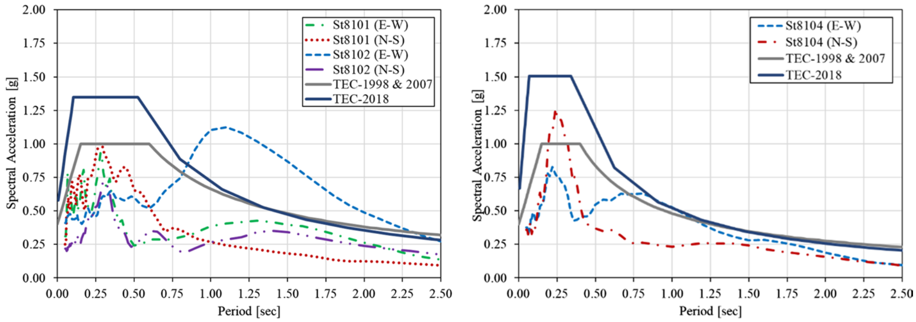

Fig. 3 Comparison of acceleration response spectra of the recorded ground motions at three stations of the 2022 Düzce earthquake with the design spectrum per TEC (1998), TEC (2007) and TEC (2018)

3.1 Ground motions

Five ground motion stations closest to the epicenter of the 2022 Düzce earthquake are shown in Fig. 2 (AFAD 2022b). These stations, labeled as 8101, 8102, 8104, 8106, and 8109, are depicted in Fig. 2. Additionally, Table 2 lists the peak ground acceleration (PGA), peak ground velocity (PGV), and peak ground displacement (PGD) values recorded at these stations as well as at station 8105, which is not shown in Fig. 2. In Table 2, the maximum PGA is 0.60 g, which was recorded in the East–West direction at station 8105 (40.903°N, 31.152°E) of the AFAD network, located at an epicentral distance (R_{epi}) of 13.88 km and approximately 7 km away from the Düzce city center. The authors confirmed with AFAD authorities that the accelerations measured at station 8105 were possibly unreliable. During the on-site inspections carried out by AFAD after the earthquake, it was determined that this station's current location and state were not suitable for making reliable measurements because of the flexibility of the housing that hosted the accelerometer (Sezen et al. 2023). Therefore, it was decided to relocate the station after this earthquake. This is an indication of the importance of earthquake reconnaissance not only for evaluating the condition of structures after earthquakes, but also for assessing the adequacy of ground motion recording stations. Consequently, the recordings at station 8105 are disregarded in this study, although they are included in Table 2. Based on this assessment, it is seen in Table 2 that the largest measured PGA, was 0.42 g, at station 8102 near the Düzce city center. The recorded ground motions in terms of acceleration, velocity, and displacement at station 8102 with $V_{s,30}=280$ m/s are shown in Fig. 14. The maximum PGA values measured at that station were 0.42 g, 0.22 g, and 0.25 g in the East–West (E–W), North–South (N–S), and vertical (U–D) directions, respectively. Moreover, PGV and PGD were the largest in the E–W direction, with corresponding values of 73.65 cm/s and 23.39 cm, respectively.

The uniform duration, significant duration corresponding to the time interval between 5 and 95% of the Arias intensity and predominant period information are listed in Table 3. The East–West component of this ground motion shows a characteristic sine pulse starting shortly after 5.0 s and includes one peak in the positive direction (0.41 g at 6.05 s) and two peaks (0.26 g and 0.29 g at 5.32 and 6.55 s, respectively) in the negative direction. This typical near-field East–West motion is consistent with the East–West strike–slip fault mechanism identified by USGS (2022b). As observed from the Arias intensity plot in Fig. 14, a significant portion of the earthquake's energy has emerged in those pulses. Additionally, while Stations 8109, 8102, and 8101 are situated on soft soil, Stations 8106 and 8104 are on relatively soft soil. The stations on soft soil conditions exhibit a noticeable soil effect, influencing the amplitude, frequency, and duration of seismic waves during an earthquake. This is evidenced by their greater PGA, PGV, and PGD, particularly by the E–W PGV value in Station 8102 with a clear dominant period of 1.1 s in its frequency contents as observed by the corresponding response spectrum in Fig. 3. As a result, a correlation between damage distribution and soil conditions was observed, as more damage occurred to structures in settlements with soft soil conditions.

3.2 Response spectra

Horizontal components of the ground motions recorded near the city center of Düzce (at stations 8101, 8102 and 8104 in Fig. 2) are used to calculate the response spectra and compare with the design spectrum given in the current Turkish Earthquake Code, TEC (2018) and previous versions of it (TEC 1998 and TEC 2007), as shown in Fig. 3. The design response spectrum corresponds to the design basis earthquake (DBE) level with a corresponding return period of 475 years in Turkish earthquake codes. Stations 8101 and 8102 are located on soft soils (e.g., $V_{s,30}=280$ m/s at station 8102), which corresponds to site class ZD in TEC (2018). Station 8104 is located on soil with shear wave velocity, $V_{s,30}=398$ m/s, for the corresponding site class ZC in TEC (2018). Due to differences in soil properties, the design spectrum presented in Fig. 3 differs between the site of station 8104 and that of stations 8101 and 8102. Since these three stations are located 10.62–13.74 km away from the epicenter (Table 2) and near Düzce city center (Fig. 2), they provide good estimates for the seismic demand experienced by the structures in Düzce. Figure 3 indicates that the spectral accelerations were less than the corresponding seismic design accelerations specified in the current design code, TEC (2018), except for the ground motion measured in the E–W direction at station 8102. For this ground motion, spectral accelerations for periods between approximately 0.9 and 2.4 s are larger than those implied in the design code, which is particularly due to soft-soil conditions at this location, as discussed earlier. This motion can particularly be demanding for structures with periods greater than 0.8 s due to the high spectral accelerations in this range. As these structures experience damage, their periods elongate, leading to similar or greater demands due to the shape of the response spectrum. However, this effect did not cause any damage in the region as there are a limited number of long-period structures present.

As explained in the forthcoming sections, there was a major reconstruction effort after the 1999 earthquakes, and the majority of the buildings in Düzce are expected to be designed according to the 1998 and 2007 versions of the code, with a lower percentage designed according to the 2018 version. Furthermore, all buildings constructed in Düzce have less than four stories according to local municipal regulations, natural periods of which are expected to be smaller than 0.5 s. In light of this information, it is observed that

Table 4 Comparison of ground motion parameters at Station 8101 for 1999 Kocaeli, 1999 Düzce, and 2022 Düzce earthquakes

Parameter	Direction	1999 Kocaeli	1999 Düzce	2022 Düzce
Measured PGA (g)	E–W	0.37	0.52	0.31
	N–S	0.32	0.41	0.25
	Vertical	0.21	0.32	0.22
Measured PGV (cm/s)	E–W	56.38	80.16	36.83
	N–S	53.67	63.53	29.69
	Vertical	22.29	18.95	8.72
Measured PGD (cm)	E–W	23.17	47.79	10.29
	N–S	40.72	38.52	10.03
	Vertical	13.62	14.15	1.78
Uniform duration (s)	E–W	16.23	20.46	13.53
	N–S	17.68	21.74	12.62
	Vertical	14.91	16.59	9.44
Significant duration (s)	E–W	11.08	10.92	7.42
	N–S	11.81	11.13	7.22
	Vertical	12.61	10.92	7.19
Predominant period (s)	E–W	1.94	1.30	1.74
	N–S	3.88	0.43	0.39
	Vertical	3.02	0.12	0.07

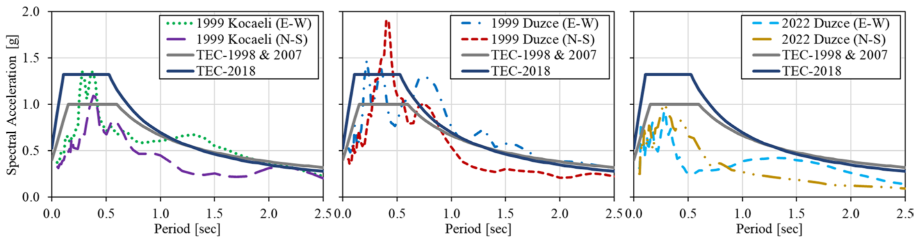

Fig. 4 Comparison of acceleration response spectra of the recorded ground motions at station 8101 with the design spectrum per TEC (1998), TEC (2007), and TEC (2018)

the spectral accelerations in the period range of interest are close to design accelerations for stations 8101 and 8102, while the East–West component of accelerations at station 8104 is higher than the design accelerations given in the TEC (1998) and 2007. Consistent with similar codes in the US and around the world, the intent of the Turkish earthquake code is to limit damage to repairable levels in design-level earthquakes. As described in the forthcoming sections of the paper, the observed structural damage was quite low, not only satisfying this objective but performing beyond that.

3.3 Comparison of motions from the 1999 and 2022 earthquakes

After the 1999 earthquakes, several other ground motion recording stations were added near Düzce. Station 8101 was the only common seismic station at Düzce during the 1999 Kocaeli, 1999 Düzce, and 2022 Düzce earthquakes; therefore, the ground motions recorded during those events are used for comparison here. The time series of horizontal and vertical components of ground motions recorded at station 8101 in terms of displacement, velocity, and displacement are shown in Figs. 15, 16, and 17 for 2022 Düzce, 1999 Kocaeli, and 1999 Düzce earthquakes, respectively. As it can be seen in the figures, the 1999 Kocaeli earthquake lasted longer than the 2022 Düzce earthquake in terms of duration. The 1999 Kocaeli earthquake energy appeared as short successive pulses. In the 1999 Düzce earthquake, although the duration of the earthquake was shorter, the earthquake energy appeared as relatively longer high-amplitude pulses. In the 2022 Düzce earthquake, similar to the 1999 Kocaeli earthquake, the earthquake energy appeared in short duration with high amplitudes. Furthermore, the 1999 Düzce earthquake experienced a larger magnitude and multiple oscillations in velocity and displacement, demonstrating typical characteristics of near-fault ground motions. In contrast, the 2022 Düzce earthquake showed comparatively less severe velocity and displacement responses.

Moreover, the comparison of ground motion parameters in terms of recorded PGA, PGV, PGD, uniform and significant durations, and predominant periods at Station 8101 for the 1999 Kocaeli, 1999 Düzce, and 2022 Düzce earthquakes is reported in Table 4. The 1999 Düzce earthquake generally exhibited higher values for measured PGA, PGV, and PGD compared to the 1999 Kocaeli and 2022 Düzce earthquakes, indicating more intense ground motion. Additionally, the 1999 Düzce event showed longer uniform and significant durations, suggesting a prolonged duration of strong shaking. The predominant period varied significantly across the different events and directions, with the 1999 Kocaeli earthquake containing longer periods in the N–S and vertical directions compared to the other events. Overall, the 1999 Düzce earthquake demonstrated more severe ground motion characteristics than the other two earthquakes. Moreover, while the predominant period of the 1999 Kocaeli earthquake was around 2.0 s (expected to affect structures with longer periods more severely), it was around 0.4 s for 1999 Düzce and 2022 Düzce earthquakes in the N–S direction. Because the natural periods of the building stock in the region is closer to the latter in the 2022 Düzce earthquake, however despite this unfavorable frequency contents, buildings in the region performed well due to the reasons explained throughout the paper.

The calculated response spectra and features of the motions are illustrated in Fig. 4. Both the 1999 Düzce and 1999 Kocaeli earthquakes were longer in duration. Comparing the peak values and the response spectra of the Düzce motions from the 1999 Kocaeli and 2022 Düzce earthquakes, it is observed that while the 1999 Kocaeli earthquake motion is a bit more intense, both are close to design levels (Fig. 4). Despite the two events being close to design levels, major damage in Düzce during the 1999 Kocaeli earthquake was due to the low construction quality and the incompatible design of structures with the earthquake engineering principles (Sezen et al. 2000). The N–S components of the 1999 Düzce earthquake produced exceptionally high spectral accelerations (1.91 g), exceeding the TEC (1998) and TEC (2018) design spectral acceleration value by 91% and 44% at a period of 0.42 s. TEC (1998) had only been approved for building design prior to that earthquake. Design spectral accelerations were even lower in TEC (1975), which was used for the design of most buildings that collapsed in 1999. The intent of the earthquake code is to prevent collapse in large-intensity earthquakes and to at least meet the life safety performance level during a design earthquake. However, the 1999 Düzce earthquake was much more severe than the TEC (1998) and TEC (1975) design considerations in some period ranges, resulting in the collapse of many buildings.

4 Vulnerability characteristics

The current Turkish earthquake code was published in 2018 and became effective in 2019 (TEC 2018). Prior to this latest revision, the code had undergone seven revisions in 1947, 1953, 1961, 1968, 1975, 1998, and 2007. These revisions were based on the advancements in earthquake engineering and lessons learned from past earthquakes around the world and particularly in Türkiye.

The 1998 version of the code was the first one that introduced modern principles of earthquake engineering that are commonly used today, such as capacity design, strong column-weak beam principle, ductility concepts and others. When the 1999 earthquakes occurred, the 1998 version of the Turkish earthquake code (TEC, 1998) was in effect only for a year. Therefore, most buildings in Düzce at that time did not meet the modern principles of earthquake engineering and a significant number of collapses and major damage was observed. TEC (2007) included performance-based engineering principles and concepts of nonlinear analysis. The current version of the code (TEC, 2018) includes state-of-the-art earthquake engineering principles such as performance-based design, similar to those of ASCE/SEI 7–22 (2022) and ASCE/SEI 41–17 (2017). TEC (2018) requires a minimum of eleven ground motions like ASCE/SEI 7–22 (2022) for nonlinear analysis procedures. The requirement of TEC (2007) was seven ground motions.

There were changes in the seismic hazard maps in each code revision, which directly affected the lateral seismic design loads on the buildings. Figures 3 and 4 present the comparisons of design spectra according to the current and former seismic design codes at several sites in Düzce city center. As clearly seen in these comparisons, code-based seismic demands according to the 2018 version are significantly larger than the previous values, especially for low-rise buildings that are expected to have natural periods of less than 1 s.

Table 5 Damaged residential and commercial building units in Düzce after the 1999 Kocaeli, 1999 Düzce, and 2022 Düzce earthquakes (Ozmen 2000; Ozmen and Bagci 2000; AFAD 2023)

Damage status	1999 Kocaeli		1999 Düzce		2022 Düzce	
	Number of building units	Ratio (%)	Number of building units	Ratio (%)	Number of building units	Ratio (%)
Severe damage or collapsed	3,095	5.1	12,513	20.8	1,313	0.8
Moderate damage	4,180	7.0	9,065	15.1	18	0.01
Limited damage	3,303	5.5	10,222	17.0	24,704	14.9
No damage	49,563	82.4	28,341	47.1	139,970	84.3
Total number of building units	60,141	–	60,141	–	166,005	–

The design spectra are defined at the DBE level, which has a probability of exceedance of 10% in 50 years and a 475-year recurrence period by the former and current seismic design codes of Türkiye. However, unlike the previous codes, TEC (2018) also defines three other individual specific earthquake levels, including the MCE with a probability of exceedance of 2% in 50 years, the serviceability earthquake with a probability of exceedance of 50% in 50 years, and the frequent earthquake, with a probability of exceedance of 50% in 30 years. Unlike ASCE/SEI 7–22 (2022), rather than applying a constant multiplier (e.g., 1.5) to obtain MCE spectrum from the DBE spectrum, the mapped spectral acceleration parameters of the MCE spectrum are also specified by the hazard map. The spectral parameters for a specific location and seismic hazard level are provided by an interactive web page of AFAD.

In addition to the advances in the seismic design codes, the disaster management system and the corresponding legislation in Türkiye have also undergone a significant transformation in the past 20 years. It is noted again that this transformation was effective in the region impacted by the 1999 earthquakes and does not necessarily apply to the rest of the country, as evidenced in the 2023 Kahramanmaraş earthquake sequence.

With the seismic design code enhancements and disaster management system developments aiming at earthquake risk reduction, the newer building inventory in the Düzce region was expected to have enhanced seismic performance. Extended use of ready mixed concrete with stricter quality control and ribbed reinforcing steel with higher quality, together with the enforcement of "building supervision during construction" law and the corresponding code enforcement in the region are believed to be important factors for the performance enhancement of the built environment in the past 20 + years. The minimum concrete strength requirement of the codes has been gradually increased up to 25 MPa in TEC (2018). Formerly, this requirement was 20 MPa in TEC (2007).

In the region affected by the M_w 6.1 earthquake on November 23, 2022, the majority of the buildings were relatively new, since the devastation of the 1999 earthquakes was very extensive in Düzce region. Most buildings, including schools, hospitals and government buildings, have been either retrofitted or rebuilt in the last two decades, following the 1998, 2007 and 2018 versions of TEC. In this context, approximately 70–80% of the current building stock in Düzce was reported to be constructed after the 1999 earthquakes (Altunisik et al. 2022). The adequate seismic design of this new building stock was complemented by the efficacy of code enforcement in the region. In addition to the strictly applied seismic design codes, the zoning rule of limiting the number of stories of buildings to four in the earthquake-impacted area had a favorable impact on the seismic performance of the built environment. This is perfectly confirmed with the signal recorded at Station 8102, since the fundamental periods of the low-rise structures are lower than the predominant periods of this earthquake (as can be seen in Fig. 3 for the case of Station 8102). In

Table 6 Determination of structural damage according to DARCMBAE (2016)

Damage status	Damage to the vertical load-carrying elements	Damage to the horizontal load-carrying elements
Limited damage	0–20%	0–75%
Moderate damage	20–50%	0–75%
	0–20%	≥ 75%
Severe damage	20–50%	≥ 75%
	≥ 50%	–

summary, the low level of structural damage reported in these buildings clearly indicates the effectiveness of these reconstruction measures.

5 Consequences

For assessment of the advances in earthquake engineering, policy-making and enforcement in the Düzce region as a testbed, the general consequences of the 1999 and 2022 earthquakes are compared in this section, particularly in terms of damaged buildings. As well-known and well-documented, the 1999 earthquakes had major consequences, including a significant number of fatalities, injuries, collapse and severe damage to buildings and other infrastructure (Table 1). Table 5 presents the damaged building information, including residential and commercial units in Düzce after the 1999 Kocaeli, 1999 Düzce, and 2022 Düzce earthquakes. As shown in Table 5, After the 1999 Düzce earthquake, 52.9% of the building stock in Düzce was damaged, whereas the damaged building ratio after the 1999 Kocaeli earthquake was 17.6%. During the 1999 Kocaeli earthquake, the greatest damage occurred primarily in the city center, while during the 1999 Düzce earthquake, it affected both the city center and the Kaynaşlı district. In the 2022 Düzce earthquake, the city center, Cumayeri, Çimli, Gölkaya and Gümüşova districts experienced the most pronounced damage.

After the 2022 earthquake, all occupancy class buildings in Düzce have been evaluated by rapid visual assessment methods to determine their damage status. Damage assessment studies were conducted by the Ministry of Environment, Urbanization, and Climate Change, starting with initial investigations in the city center and the most affected districts. In the districts of Akçakoca, Kaynaşlı, and Ağırca, assessments were carried out only on buildings whose owners had submitted an official request letter. Moreover, some of the authors of this study played a significant role in conducting the field reconnaissance. Structural damage was classified according to the DARCMBAE (Damage Assessment of Reinforced Concrete and Masonry Buildings Affected by the Earthquake) post-earthquake rapid visual screening method (DARCMBAE 2016) developed by the Turkish Chamber of Civil Engineers Disaster Preparedness and Response Board and the PDRS (Principles

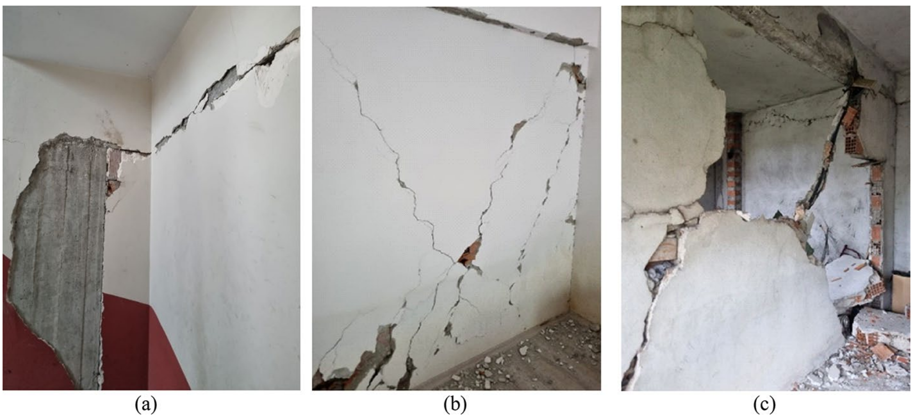

Fig. 5 Examples of **a** damage at the infill wall/RC frame interface, **b** diagonal cracks in infill walls, and **c** out-of-plane damage of infill walls

on Detection of Risky Structures) (2019) method. As can be seen in Table 6, the DARCMBAE method considers the dimensions of horizontal and vertical structural system elements and uses empirical equations to calculate the level of structural damage, where the damage to the vertical load-carrying elements is respectively classified as Low, Moderate, or Severe if < 20%, 20–50%, or > 50% of columns are damaged. In addition, the percentage of damaged beams is also taken into consideration when determining a building's damage state. For example, damage is classified as Low or Moderate if less than 75% or more than 75% of the beams are damaged. The final damage is governed by the worst of the two damage levels determined by the condition of the columns and beams. The PDRS method (2019) uses a post-earthquake rapid visual screening form to collect data for masonry and reinforced concrete (RC) structures. The form includes various parameters, such as the number of stories, plan and vertical irregularities, plinth area, diaphragm type, short column potential, roof type, site soil properties, and visual quality of construction. For RC structures, it distinguishes between RC frame structures and RC frame & shear wall structures. The method also differentiates different types of masonry structures, such as unreinforced masonry and reinforced masonry. Ministry of Environment, Urbanization and Climate Change conducted the inspections following the DARCMBAE (2016) and PDRS (2019) procedures and the results are summarized in Table 5. While most of the building stock in the region has experienced limited or no damage, a limited number of buildings (0.66% of the buildings) experienced severe damage. A few instances of complete building collapses of non-engineered buildings in rural areas were also observed. It is important to point out that the majority of buildings exposed to the earthquake performed much better than the basic Life Safety seismic performance requirement set by the design codes, according to which significant structural damage is acceptable but overall building collapse must be avoided. More specifically, the objective of the Turkish earthquake code (i.e., TEC, 2018) to limit the damage to repairable levels in design level earthquakes was met and significantly exceeded.

(a) (b) (c)

Fig. 6 Examples of **a** RC beam damage including diagonal cracks, **b** short column damage, and **c** column damage including diagonal cracks

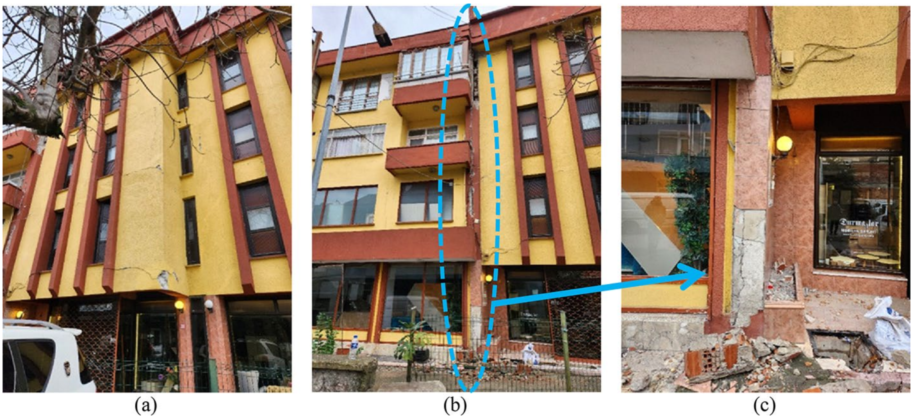

Fig. 7 Damage to an RC apartment building due to pounding

6 Performance of the built environment

In addition to the overall comparison of the consequences of the 1999 and 2022 earthquakes, which is a major objective of the paper, it is also instructive to present detailed observations regarding the structural damage patterns and causes of damage during the 2022 Düzce earthquake based on the collected field data. This section documents such observations, and more details are provided in Sezen et al. (2023). Similar detailed information for the 1999 earthquakes is well-documented; therefore, it is not repeated here.

6.1 Residential buildings

For residential buildings, the reported damage was typically localized in the infill walls in the form of in-plane and out-of-plane separations or failures and damage to non-structural components. Figure 5 shows examples of wall separation from the RC frame and diagonal shear failure of infill walls, which were mainly caused by in-plane loading. This type of

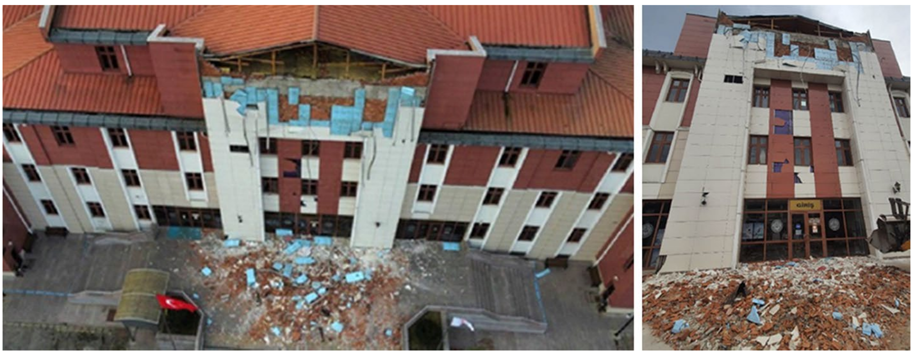

Fig. 8 Facade damage and gable collapse in the Düzce courthouse (Sources: Deutsche Welle (2022) (left), Aydin Demir (right))

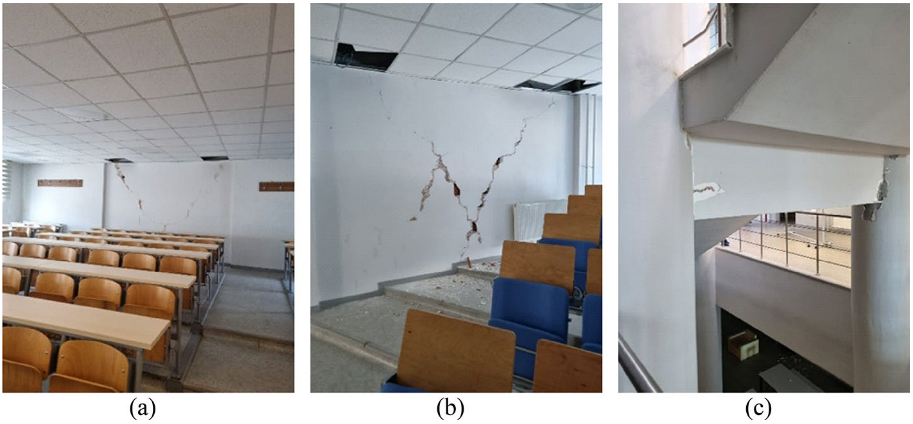

Fig. 9 Damage to infill walls and stairs in a school in Düzce

damage and diagonal strut in the masonry infill is due to the different deformation patterns of the much stiffer infill wall and the surrounding frame. The first phase of this behavior is cracking at the perimeter of the infill, leading to its separation from the frame (Fig. 5a), which can be followed by damage introduced to the frame members due to the forces transferred by the diagonal strut (Fig. 5b). This separation also makes the infill wall vulnerable to the seismic load perpendicular to the wall (out-of-plane loading). In some cases, in-plane damage weakened the out-of-plane capacity of infill walls, resulting in their out-of-plane failure and/or collapse (Fig. 5c). This kind of failure of infill walls due to the interaction of in-plane and out-of-plane loading has been also observed in other earthquakes (Braga et al. 2011; Marinković et al. 2022) and jeopardizing the escape routes (Lu et al. 2020). In-plane/out-of-plane interaction has been investigated both experimentally (Butenweg et al. 2019) and numerically (Kadysiewski and Mosalam 2009; Mosalam and Günay 2015), with main conclusions that its effects on the reduction of infill wall capacity has to be taken into account.

It is noted that these common types of infill damage documented in Fig. 5 were not major and limited as presented by the ratio of damaged buildings in Table 5. Therefore the 2022 Düzce earthquake is an earthquake where the infill walls contributed to the strength of the buildings in the form of overstrength. The effect of this overstrength on the dynamic response is discussed in the Numerical Simulations section.

Fig. 10 Damage on the dome (left) and walls (middle) of Kiremitoğlu mosque, and damage to the interior of Düzce Cedidiye mosque (Anadolu Ajansi 2022)

Fig. 11 Property damage in stores (Sources: Daily Sabah (2022) (left) and Tasdemir (2022) (right))

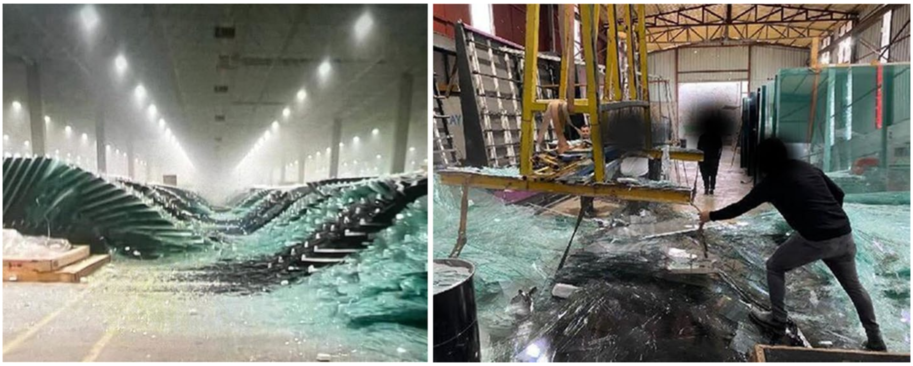

Fig. 12 Damage in a glass manufacturing facility (Sources: Ensonhaber (2022) (left) and DHA (2022) (right))

Some representative examples of observed damage in RC beams and columns are shown in Figs. 6. Shear cracks in beams likely occurred due to insufficient spacing and detailing of stirrups. Inadequate reinforcement detailing where bent-up longitudinal bars are often used to provide shear resistance to gravity loads as well as negative moment resistance at supports can be one of the reasons for observed cracks in beams. This was also the case in the 1999 Kocaeli earthquake (Sezen et al. 2000). As mentioned earlier, the majority of the buildings in Düzce are either new or retrofitted buildings, however there is still a small percentage of buildings which experienced these issues and need to be repaired and retrofitted.

Figure 6b and c show typical column shear failures. A “short column” effect (Fig. 6b) occurred in the case of non-structural partial-height masonry infills, when infill walls were constructed not to the full height of the column due to openings, e.g., windows. The infill wall caused a decrease of the effective column height and the corresponding increase of shear forces in the portion of the column which is not in direct contact with the infill.

Several buildings suffered minor damage in the earthquake due to pounding, which was caused by insufficient size or absence of seismic gaps. Figure 7a shows a four-story RC building constructed in 1988. Due to insufficient gap between the two buildings, pounding of the neighboring structures caused damage in the RC columns over the entire height of both buildings, including the parapet wall of the building located on the left in Fig. 7b.

Table 7 Summary of performance by infrastructure class

Power and telecommunication	After the earthquake, electricity was cut off in a controlled manner for ~ 2 h. Phone lines and the internet were unaffected
Roads and bridges	No significant damage observed on roads and bridges
Other lifelines	Water and natural gas were cut off in a controlled manner for ~ 2 h

The building shown in Fig. 7a also experienced infill wall damage in the second and third stories above the overhangs.

Stairs, together with elevators are critical elements because they enable evacuation from the damaged buildings after an earthquake. Furthermore, they are critical for functionality as they are key for access and regress. They should not be excluded from the design since interaction of stairways with the primary structure can cause severe damage both in the primary structures and in the stairways, thus impeding post-earthquake evacuation of buildings and hindering their functional recovery (ATC-138, 2022). In addition to Fig. 9c, examples of damage in many staircases or stairwells are provided in Sezen et al. (2023).

6.2 Government facilities and schools

No significant structural damage was observed or reported in the region's government buildings, schools, and hospitals, other than the damage in non-structural elements including infill walls, facades, etc. An example of damage to a government building is provided in Fig. 8. The Düzce courthouse was heavily damaged during the two 1999 earthquakes and therefore demolished 23 years ago. The construction of the new courthouse started in 2006 and was completed in 2008. The façade, including the gable end of the roof, was damaged in the November 23, 2022 earthquake (see Fig. 8). Broken façade materials were a falling hazard near the entrance and could have led to fatalities or injuries if the earthquake did not occur at 4:08 am when no one was in front of the building. This is a reminder that the non-structural component failures not only result in issues regarding functionality or economic loss, but they can lead to injuries or fatalities. Therefore, care should be exercised while designing the non-structural elements, such as façades or suspended ceilings.

Figure 9 shows representative examples of observed damage in school buildings. Typical damage in these multi-story RC structures with unreinforced masonry infill walls include: i) diagonal shear cracks in infill walls and separation from the surrounding beam-column frame (Fig. 9a and b), ii) cracks in the staircases (Fig. 9c), and iii) other non-structural damage including damage to suspended ceilings (Fig. 9b).

6.3 Mosques

The November 23, 2022 Düzce earthquake caused substantial damage in multiple mosques, including Kiremitoğlu Mosque in downtown Düzce, Sarıdere Village Mosque in Gölyaka, Cedidiye Mosque in Düzce, Ayşe Metin Neighborhood Mosque in Cumayeri, Yaka Neighborhood Mosque in Cumayeri, and Saz Village in Kaynaşlı. Kiremitoğlu Mosque in downtown Düzce was built in 1968 and includes unreinforced brick masonry load-bearing walls with many window openings. The mosque's central dome experienced a vertical displacement of approximately 100 mm. Major diagonal cracks were observed on the entrance

Table 8 Computed ductility demands of the SDOF systems subjected to different motions

Building		Station 8101 NS Component			Station 8101 EW Component		
		Earthquake			Earthquake		
T (sec)	V_y/W	2022 Düzce	1999 Düzce	1999 Kocaeli	2022 Düzce	1999 Düzce	1999 Kocaeli
0.2	0.125	22.6	46.9	18.6	14.4	58.9	35.1
0.2	0.375	2.1	3.2	1.6	1.5	8.6	3.0
0.3	0.125	13.8	30.8	13.1	6.1	41.2	24.0
0.3	0.375	3.1	4.8	2.0	2.1	4.1	4.7
0.4	0.125	6.9	22.6	9.2	3.9	29.2	16.1
0.4	0.375	1.8	4.2	2.3	1.2	5.1	2.0

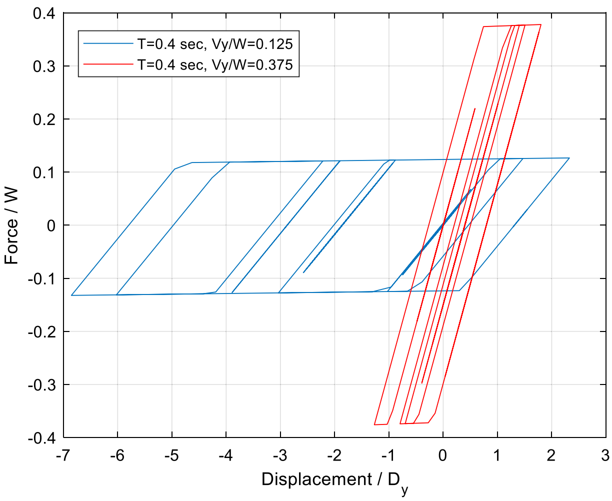

Fig. 13 Comparison of the force–displacement response of the T = 0.4 s SDOF systems with $V_y/W = 0.125$ and $V_y/W = 0.375$ subjected to Station 8101 NS acceleration component during the 2022 Düzce earthquake (D_y: yield displacement)

walls around the windows, as shown in Fig. 10. Figure 10c shows damage to the pulpit inside Düzce Cedidiye mosque. During the November 12, 1999 earthquake two minarets of this mosque collapsed and rebuilt afterwards.

6.4 Commercial buildings

A significant loss was reported due to non-structural damage in the commercial areas of Gölyaka and Düzce. In most cases, shelves collapsed, or items fell in the stores during the strong shaking as shown in Fig. 11. Although the commercial buildings did not experience severe structural damage during the earthquake, the economic loss due to damage to the assets, goods, and products appeared to be relatively high in certain cases, such as the glass manufacturing factory in Fig. 12. In this factory, significant losses occurred as the vertical stacks of ready-to-ship glass products were shattered. Although there was no reported structural damage in some shops and stores, due to non-structural damage in the area, they had to be closed for a period of time until cleanup was complete.

6.5 Infrastructure performance

No damage was observed in power, telecommunications, water, and other infrastructure or lifelines. There was no interruption of internet and telephone services. No road or bridge damage was observed, although there was one incident of road pavement cracking reported in early media coverage. Overall infrastructure performance is summarized in Table 7 indicating quick recovery and community resilience.

7 Numerical simulations

This section provides insights about the reasons for low levels of structural damage experienced during the 2022 Düzce earthquake using dynamic analyses of inelastic single-degree of freedom (SDOF) models. Similar analyses are also conducted using the 1999 earthquake motions (Figs. 15, 16, and 17) to compare the demands in the 1999 and 2022 earthquakes.

After enacting a municipal law after the 1999 earthquakes, construction of buildings with more than four stories have not been allowed in Düzce in the last two decades. Therefore, natural periods of these buildings are expected to be smaller than 0.5 s. Figure 3 shows that the spectral accelerations of these buildings under the 2022 Düzce earthquake ground motions are less than the 1.3 g or 1.5 g spectral acceleration indicated by the TEC (2018) design spectrum in the short period range. However, considering that the forces used in design are obtained by dividing these accelerations of 1.3 g or 1.5 g by the response modification factors, R as large as 8, seismic force demands are larger than the seismic design forces.

Despite the demands being larger the design forces, very limited or no damage was observed in recently constructed buildings during the earthquake. Reasons for the overall low levels of observed damage can be attributed to the presence of overstrength available in the buildings due to various factors; including nominal strength values, presence of infill walls, strength increase due to minimum design requirements, load redistribution and other factors. Among these factors, the infill walls are known and have been observed to provide additional strength and add to the overstrength up to a certain intensity of earthquakes (first category), while they result in the formation of soft and weak stories prior to or during large intensity (e.g., the Maximum Considered Earthquake level) earthquakes (second category) (Mosalam and Günay 2013). The 2022 and 1999 earthquakes are earthquakes that are in the first and second categories respectively. Very limited or no damage during the 2022 Düzce Earthquake is likely due to increased base shear capacity from overstrength. For demonstration of this observation with numerical results, SDOF analyses are conducted as detailed below.

In TEC (2018), an overstrength factor D of 3.0 is used for well-detailed ductile reinforced concrete (RC) buildings. An overstrength factor close to 3.0 is also documented in several other publications, which report an overstrength value of 2.5–3.0 for low- and mid-rise buildings in Türkiye designed to various versions of TEC (e.g., Akkar et al. 2005; Cetindemir and Akbas 2017; Guler and Celep 2020). Considering this typical value of 3.0 as the overstrength for buildings in Türkiye, a design spectral acceleration of 1.0 g (specified in the 1998 and 2007 versions of TEC in the short period range at locations with the most significant earthquake hazard as shown in Fig. 3) and a strength reduction factor R of 8, the expected yield base shear V_y normalized by the building weight (V_y/W) is 0.375 ($V_y/W = D/R = 3/8$). It is assumed that the number of buildings in Düzce designed according to the 1998 and 2007 versions of the TEC is larger than those designed according to the 2018 version, therefore SDOF analyses are conducted for systems with periods of 0.2 s, 0.3 s, and 0.4 s, and with V_y/W values of 0.125 and 0.375, corresponding to cases of without and with overstrength, respectively. In all analyses, a damping ratio of 5% is utilized. Similar to FEMA P-2139-1 (2020), which explored the performance of short period buildings and provided updates on their collapse performance, a bilinear system is used in these analyses. This is deemed sufficient as the objective here is not to provide detailed results, but rather to provide explanations and insights for the observed response with basic simulations. Furthermore, all the considered ground motions are near-fault motions with pulses and do not result in many cycles that would lead to stiffness and strength degradation and several studies (e.g., Miranda and Bertero 1994) showed that the type of hysteresis has an insignificant effect on the strength reduction factors.

Table 8 shows the ductility demands of each of the six systems subjected to Station 8101 North–South and East–West components during the 2022 Düzce and 1999 Düzce and Kocaeli earthquakes (Figs. 15, 16, and 17). Figure 13 shows the normalized force–displacement response of the T = 0.4 s system as an example. Several observations are as follows:

1) Overstrength dramatically reduces the ductility demands due to the sensitivity of ductility to strength at short periods. This observation is consistent with lower probabilities of collapse for higher values of overstrength indicated in FEMA P-2138-1 (2020).
2) The ductility demands of the SDOF systems in the order of 2 ~ 3 in the 2022 Düzce earthquake is consistent with the observed low levels of damage. If there were no overstrength, some buildings could have experienced major damage.
3) To truly benefit from overstrength in earthquakes even with larger shaking levels, the mechanisms/sources that contribute to overstrength should be maintained in the entire range of response. For example, infill walls in buildings in Türkiye greatly contribute to overstrength up to small levels of drift, however if they lead to formation of soft/weak stories due to design mistakes or due to the formation of soft/weak stories during the earthquake because of the failure of infill walls, not only their contribution to overstrength is lost, but also further detrimental effect is provided by this source of overstrength. Therefore, contribution of infills should not be considered as beneficial, without doing their detailed design or applying protective measures.
4) The ductility demands of the 1999 Düzce earthquake are at least two times larger than those of the 2022 Düzce earthquake, demonstrating the severity of the 1999 earthquake. The low strength of buildings combined with nonductile characteristics (leading to insufficient ductility capacities) was the main reason for the collapse of many buildings in the 1999 earthquakes. The ductility demands of the systems with $V_y/W = 0.125$ in the 1999 earthquakes are well beyond the ductility capacities of buildings with nonductile characteristics, also explaining the sheer number of observed collapses numerically.
5) These observations from the 2022 Düzce earthquake may have implications for the future of seismic codes and performance design practices worldwide. There are ongoing discussions for potential updates of the building codes around the world to achieve certain functionality objectives (e.g., achieving re-occupancy, functional recovery, and full recovery within target times) beyond the collapse prevention and basic life safety intent of the codes. One of the proposed changes to achieve these objectives is to increase the

importance factors to increase the design forces. The observations from the 2022 Düzce earthquake show that this may be one potential reasonable approach to achieve functional recovery (at least for buildings with fundamental periods within certain period ranges) to reduce the impact of earthquakes on the public as quickly as possible.

8 Conclusions and future projections

Düzce was struck with two earthquakes in 1999 and one in 2022, and 70–80% of the current building stock in Düzce was either designed, constructed, or retrofitted after the two 1999 earthquakes. With an effort to evaluate the consequences of the advances in earthquake engineering and relevant policy making and regulations in the city of Düzce after the 1999 Kocaeli and Düzce earthquakes, this paper provides a comparative overview of the 1999 earthquakes and the 2022 Düzce earthquake in terms of hazard, vulnerability, and consequences, with an emphasis on the city of Düzce. Furthermore, other key lessons learned from the 2022 Düzce earthquake are documented using field reconnaissance and basic numerical simulations. Conclusions of the study and future projections based on these conclusions are listed below:

- During the field reconnaissance of the 2022 Düzce earthquake, it was found out that one of the ground motion recording stations was not suitable for making reliable measurements, and it was decided to relocate the station after this earthquake. This demonstrated the importance of earthquake reconnaissance not only for evaluating the condition of structures after earthquakes, but also for assessing the adequacy of ground motion recording stations.
- Low level of structural damage and limited non-structural damage was observed after the 2022 Düzce earthquake. The objective of the Turkish earthquake code (and similar modern codes) to limit the damage to repairable levels in design level earthquakes was met and significantly exceeded.
- Despite minor non-structural damage and meeting/exceeding code objectives, the economic losses due to non-structural damage and business interruption were significant. It should be explored how these economic losses can be reduced in future earthquakes with the use of protective systems and other technologies.
- Several reasons of the good structural performance of the built environment are as follows:
  - The adequate seismic design, construction, or retrofit of the new building stock (70–80% of the current buildings in Düzce) per 1998, 2007, and 2018 versions of TEC was complemented by the efficacy of code enforcement in the region.
  - In addition to the strictly applied seismic design codes, the zoning rule of limitation of the number of stories of buildings to four in the earthquake-impacted area had a favorable impact on the seismic performance of the built environment. This is supported by the ground motion recorded at Station 8102, since the fundamental periods of low-rise structures are lower than the predominant period of this ground motion caused by local soft soil conditions (refer to Fig. 3). This motion could particularly be demanding for long period structures as explained in Sect. 3.2
  - The presence of overstrength available in the buildings due to various factors; including nominal strength values used in design, presence of infill walls, strength

increase due to minimum design requirements, load redistribution, and other factors, reduced the ductility demands significantly.

- Unreinforced masonry infill walls are known to provide additional stiffness and strength to the structure and decrease the displacements. However, this is valid only up to a certain intensity of earthquakes, while they have detrimental effects in large intensity earthquakes like the 1999 Düzce and Kocaeli earthquakes.
- The observations from the 2022 Düzce earthquake related to overstrength may have implications for the future of seismic codes and performance design practices around the world and the reconstruction efforts after the 2023 Kahramanmaraş earthquake sequence in Türkiye.
  - Increasing the importance factors to increase the design forces in ASCE/SEI 7–22 (2022) or Eurocode-8 (2004) or TEC (2018) may be one potential reasonable approach to achieve functional recovery (at least for some low-rise buildings with fundamental periods within certain period ranges). Although grocery stores or other commercial service buildings are not considered essential buildings for design purposes, their importance factors can be increased in the codes because they are critical for the recovery of the cities and regions after disasters.
  - One of the structural systems used for new construction in the earthquake-affected region after the 2023 Kahramanmaraş earthquake sequence is the so-called tunnel form shear wall buildings, which are known to provide larger strength compared to moment-resisting frames. An improved structural response can be expected due to the use of these buildings.
- The lessons learned about the design and retrofit of buildings in Düzce, using the modern principles of earthquake engineering, and proper code enforcement, and city planning, as documented by the improvements from 1999 to 2022 should be carefully considered for the reconstruction efforts after the 2023 Kahramanmaraş earthquake sequence or in similar efforts in other parts of the world.

Appendix 1

See Figs. 14, 15, 16, and 17.

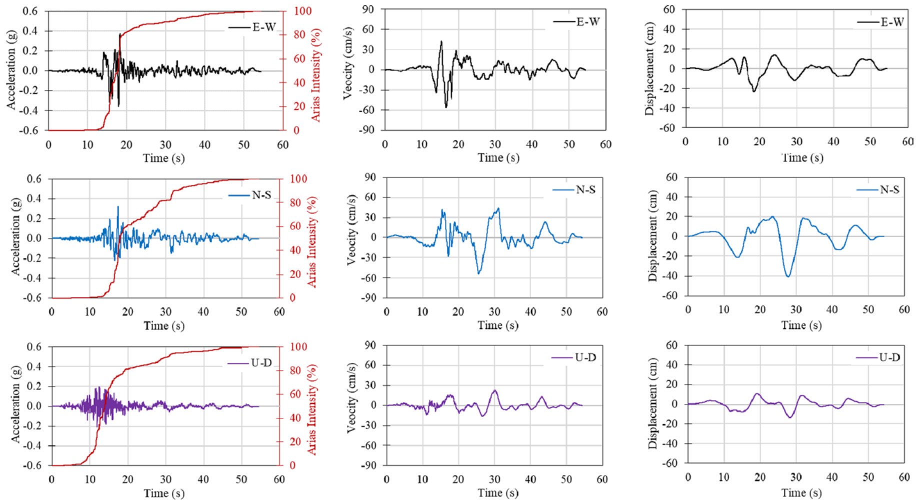

Fig. 14 2022 Düzce Earthquake (Mw = 6.1), Station 8102 (Düzce/Center), Acceleration vs Arias Intensity, Velocity and Displacement time histories (Vs,30 = 280 m/s)

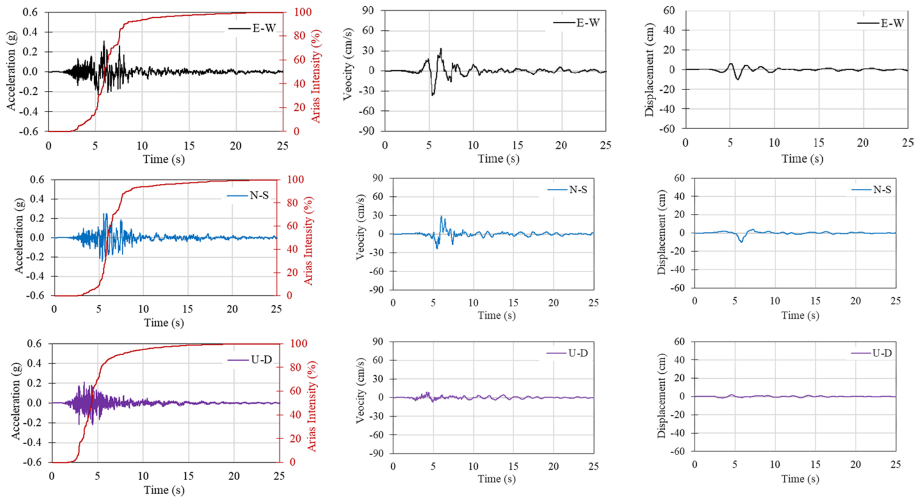

Fig. 15 2022 Düzce Earthquake (M_w = 6.1), Station 8101 (Düzce/Center), Acceleration vs Arias Intensity, Velocity and Displacement time histories ($V_{s,30}$ = 282 m/s)

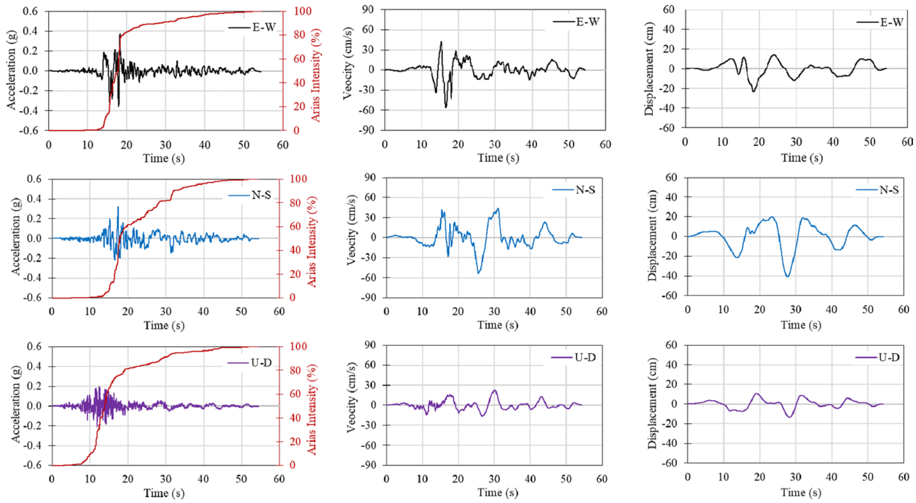

Fig. 16 1999 Kocaeli Earthquake ($M_w = 7.4$), Station 8101 (Düzce/Center), Acceleration vs Arias Intensity, Velocity and Displacement time histories ($V_{s,30} = 282$ m/s)

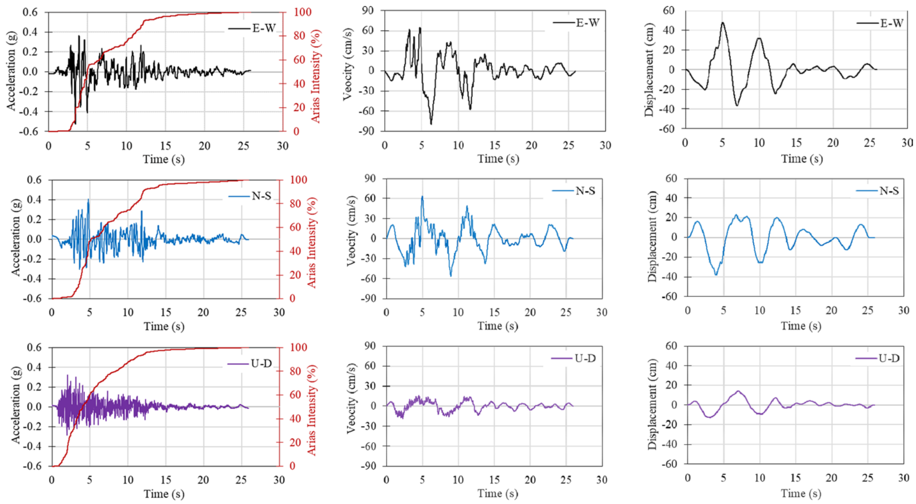

Fig. 17 1999 Düzce Earthquake ($M_w = 7.2$), Station 8101 (Düzce/Center), Acceleration vs Arias Intensity, Velocity and Displacement time histories ($V_{s,30} = 282$ m/s)

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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