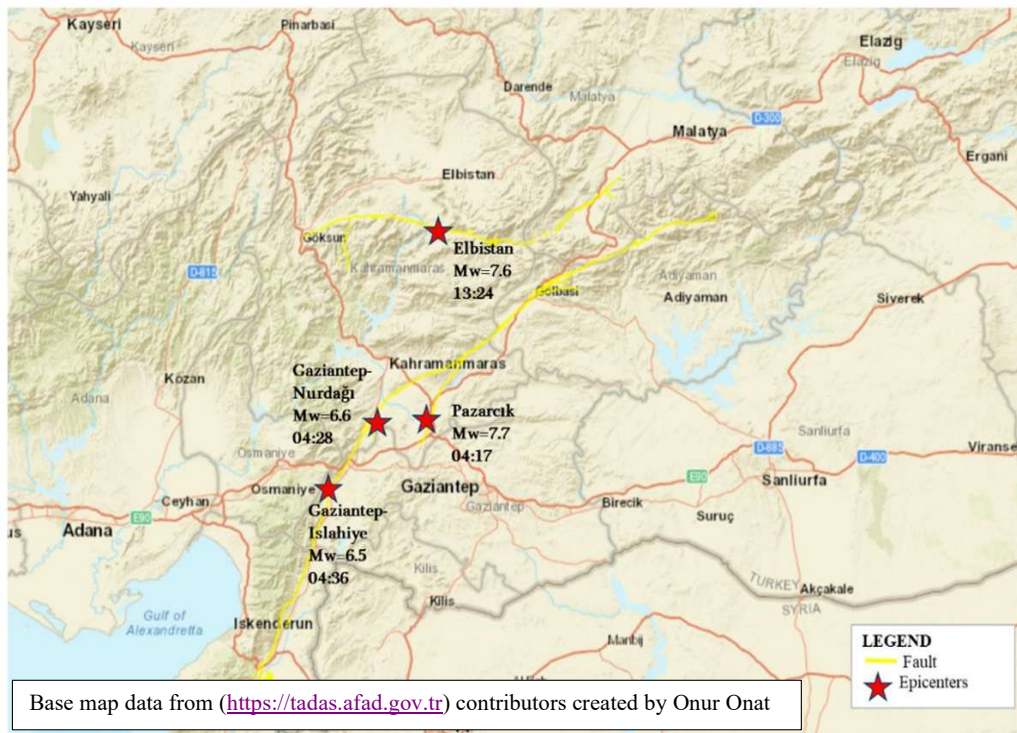




40 1. Introduction

41 The February 6, 2023, Kahramanmaraş earthquake doublet was one of the most destructive seismic events
42 in Türkiye's recent history. Involving the rupture of major fault segments across eastern and southeastern
43 Türkiye, the sequence caused widespread structural damage over a large geographic area. Its tectonic
44 setting and rupture extent underline the exceptional scale of the event and provide important context for
45 understanding the severity of the damage observed across the affected provinces (Karasin, 2023;
46 Varolgüneş, 2025). The territorial distribution of the earthquake sequence, including its epicenters and
47 ruptured fault segments, is presented in Figure 1 (Onat et al., 2026a). In addition to its exceptional
48 territorial extent, the Kahramanmaraş earthquake sequence generated extremely strong ground motions
49 in several near-fault areas. Instrumental records showed that, at some stations, the observed seismic
50 demand exceeded the highest design level defined by the current Turkish seismic code, particularly over
51 the short- and intermediate-period ranges that are most critical for low- and mid-rise reinforced concrete
52 (RC) buildings (Karasin, 2023; Sezgin et al., 2024; Altunışık et al., 2023; Atmaca et al., 2025; Aras et al.,
53 2026). These conditions make the event especially valuable for comparing recorded earthquake demand
54 with code-based design expectations and for assessing structural performance under loading conditions
55 that, in some cases, went beyond routine design assumptions.



56

57 **Figure 1.** Epicenters and ruptured faults of the February 6, 2023, Kahramanmaraş Earthquake
58 sequence (Onat et al., 2026a).

59 Strong near-fault earthquakes can place exceptionally high seismic demands on RC buildings, often
60 exposing vulnerabilities that are not fully anticipated by regular design assumptions. For this reason, post-
61 earthquake field evidence remains indispensable for understanding how buildings actually respond to



62 extreme ground motions and for clarifying the combined influence of seismic demand, structural
63 configuration, construction practice, and site conditions on damage patterns (Erbaş et al., 2025; Sezgin et
64 al., 2024; Isik et al., 2025; Yön et al., 2025). Numerous post-earthquake studies have documented the
65 diverse damage mechanisms associated with the Kahramanmaraş earthquakes (Yön et al., 2025; Onat et
66 al., 2026b). Extended assessments of the post-earthquake literature have also emphasized the importance
67 of linking field evidence to code revision, implementation quality, and future disaster policy (Tonyali et
68 al., 2025; Varolgüneş, 2025). At the same time, recent investigations have shown that severe damage was
69 not limited to older building stock; relatively recent buildings also experienced substantial damage when
70 structural layout, lateral load-resisting systems, construction quality, or site-related conditions were
71 inadequate (Sezgin et al., 2024; Erbaş et al., 2025; Yön et al., 2025). Despite these important
72 contributions, systematic field-based comparisons between conventional damage patterns in older RC
73 buildings and the emerging damage mechanisms observed in newer code-era buildings across the affected
74 region remain limited. In particular, the combined influence of extreme ground motion, local soil
75 conditions, structural configuration, and implementation-related deficiencies has not yet been synthesized
76 clearly at the regional scale (Erbaş et al., 2025; Sezgin et al., 2024; Yön et al., 2025). This study
77 investigates the seismic performance of RC buildings damaged during the February 6, 2023,
78 Kahramanmaraş earthquake doublet through field observations from eleven affected cities (Figure 2). The
79 main objective is to classify and compare the dominant damage mechanisms observed in older and newer
80 RC buildings and to discuss their implications for seismic design and construction practice in Türkiye.
81 Rather than focusing on isolated failures, the study emphasizes repeating field patterns across different
82 construction periods and site conditions. In doing so, it aims to provide empirical field-based evidence
83 that can support improvements in both seismic code implementation and earthquake-resilient construction
84 practice.



85
86 **Figure 2.** The effected area from 6th February Kahramanmaraş Earthquakes

87

88 2. Methods

89 This section presents methodological procedures of the study into categories.

90 2.1. Study area and earthquake features



91 The current study investigates the seismic performance of RC buildings damaged during the February 6,
92 2023, Kahramanmaraş earthquake doublet through field observations from eleven affected cities (Figure
93 2). The earthquake doublet impacted a wide region, producing extensive damage across multiple
94 provinces and generating strong ground motion records, particularly in near-fault zones. Event parameters
95 and strong-motion data were obtained from national seismological agencies (AFAD and KOERI) and
96 supported by the Türkiye Open Access Database and Analysis System (SBB, 2023; TADAS, 2023;
97 Tanırcan and Eken, 2023). The study area was selected to capture a broad range of building responses
98 under varying construction periods and site conditions. In particular, the study focuses on the contrast
99 between damage patterns observed in older building stock and those emerging in more recent, code-era
100 structures.

101 2.2. Ground motion and demand evaluation

102 Recorded ground-motion data were used to interpret the level of seismic demand experienced by the
103 building stock. Response spectra (2% and 5% damping) derived from recorded accelerograms were
104 compared with code-based design spectra at selected stations. This comparison helps to identify whether
105 design-level demand was exceeded and to relate observed damage patterns to spectral characteristics,
106 particularly in the short-period range relevant to low- and mid-rise RC buildings.

107 2.3. Field survey strategy

108 The study is based on post-earthquake field observations. Field reconnaissance was carried out across
109 affected cities to document dominant and several structural and geotechnical damage patterns in RC
110 buildings. Rather than compiling a complete damage inventory, the survey focused on identifying the
111 most representative and frequently observed damage mechanisms.

112 For each building, the following attributes were systematically assessed:

- 113 • Structural system type (e.g., frame, frame–shear wall),
- 114 • Approximate construction period (older vs. code-era),
- 115 • Plan and vertical irregularities,
- 116 • Damage to primary load-bearing elements (columns, beams, walls),
- 117 • Evidence of site- and foundation-related effects such as settlement, tilting, liquefaction,
118 groundwater influence, and excavation-related instability.

119 Field photographs were used as the primary means of documentation, ensuring that observations could
120 be traced and compared across different locations. Representative cases were selected to illustrate
121 repeating patterns.

122 2.4. Damage classification framework

123 Observed damage patterns were organized into three main categories to allow a structured comparison:

- 124 1. **Conventional damage in older RC buildings**, including column failures, soft-storey mechanisms,
125 pounding, torsional effects, and detailing deficiencies.
- 126 2. **Damage in newer (code-era) buildings**, typically associated with system-level issues such as
127 discontinuities in shear walls, insufficient wall ratios, interrupted load paths, and configuration-
128 related irregularities.
- 129 3. **Site- and foundation-related damage**, including liquefaction-induced effects, loss of bearing
130 capacity, differential settlement, building tilting, groundwater-related distress, and excavation or



131 retaining-system failures.

132 This classification makes it possible to distinguish between member-level failures, system-level
133 deficiencies, and geotechnical effects, while also acknowledging that these mechanisms often interact in
134 practice. It is consistent with the related field and numerical studies cited in the original manuscript,
135 including those emphasizing inappropriate reinforcement use, pounding, discontinuous framing,
136 inadequate confinement, soft-storey irregularity, and design/application defects (Ince, 2024; Kazaz et al.,
137 2024a; Kazaz et al., 2024b; Sezgin et al., 2024; Tura et al., 2024; Vuran et al., 2024).

138 **2.5. Interpretation framework**

139 Damage was interpreted by bringing together field observations, ground-motion characteristics, structural
140 configuration, construction quality, and site conditions. Rather than attributing failures to a single cause,
141 the study adopts a combined perspective in which seismic demand, design and detailing, construction
142 practice, and geotechnical effects are considered together. Special attention is given to soil–foundation–
143 structure interaction, especially in cases where liquefaction, loose bearing capacity of soil due to high
144 ground water table and ground deformation played a dominant role in building response.

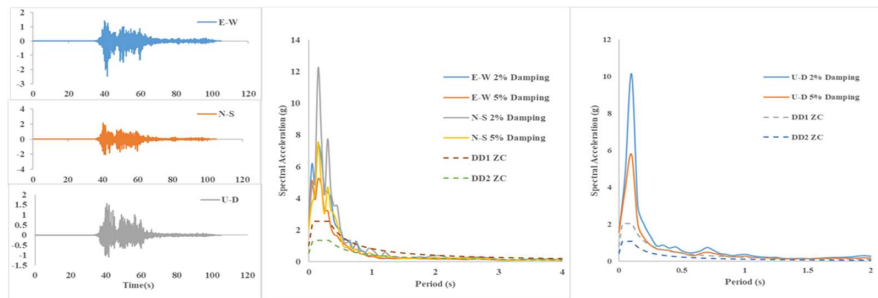
145 **2.6. Methodological scope and Limitations**

146 The study is based on qualitative field observations supported by engineering interpretation. It does not
147 include a full quantitative damage inventory, material testing, or numerical modeling. Instead, the aim is
148 to identify and interpret the dominant damage mechanisms observed in the field and to relate them to
149 seismic demand, building characteristics, and site conditions. While the findings provide consistent
150 insights into recurring damage patterns, they should be understood within the limits of observational data
151 and may be complemented by future analytical or quantitative studies.

152 **3. Results**

153 **3.1. Ground motion characteristics**

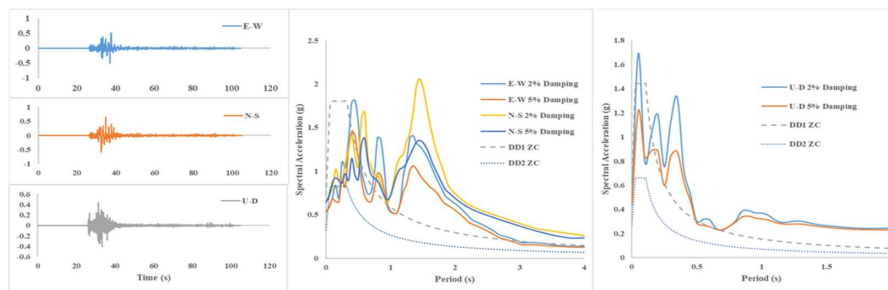
154 The February 6, 2023, earthquake sequence generated exceptionally strong ground motions over a wide
155 area, particularly in near-fault zones. Instrumental records showed that recorded response spectra at
156 several stations exceeded the design spectra defined by the current Turkish Seismic Code (TSC-2018),
157 especially within the short-period range that is critical for the seismic response of low- and mid-rise
158 reinforced concrete (RC) buildings (Karasin, 2023; Sezgin et al., 2024). Near-fault pulse-type
159 characteristics were observed in selected ground-motion records, concentrating a significant portion of
160 seismic energy within a short time interval (Figure 3). Such pulse-like motions are associated with
161 increased displacement demand and amplified structural response, particularly in buildings with limited
162 ductility or unfavorable structural configurations (Sevim et al., 2024; Erbaş et al., 2025).



163

164

a) Station 4614



165

166

b) Station 4612

167

Figure 3. Comparison of recorded and design response spectra at representative stations

168

Comparison between recorded spectra and code-based design spectra further documented marked exceedance in spectral acceleration demand. These exceedances were more pronounced in soft-soil zones and in areas affected by local site amplification and basin-related effects (Onat et al., 2024; Yön et al., 2025; Onat et al., 2026b).

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3.2. Conventional damage patterns in older buildings

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Field observations indicated that reinforced concrete (RC) buildings exhibited recurrent and well-documented damage mechanisms across both older building stock and more recently constructed code-era buildings. Severe column damage, including concrete crushing, reinforcement exposure, and loss of confinement, was observed in buildings of different construction periods (Figure 4). In older RC buildings, column failures were commonly associated with insufficient transverse

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reinforcement, weak concrete strength, and inadequate confinement (Sevim et al., 2024; Erbaş et al., 2025).

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181

182 **Figure 4.** Representative column damage observed in reinforced concrete (RC) buildings affected by
183 the February 6, 2023, Kahramanmaraş earthquake sequence.

184

185 Severe column damage observed in a relatively new RC building in Adiyaman, including concrete
186 crushing, spalling, and exposure of longitudinal reinforcement (Figure 4 a–c). Similar column damage
187 observed in an older RC building in Malatya, characterized by loss of confinement and extensive
188 deterioration of primary load-bearing elements (Figure 4 d–e).

189 The examples illustrate that severe column damage occurred in both newer code-era and older RC
190 buildings, although the underlying causes may differ. Soft-storey mechanisms were also widely observed,
191 especially in buildings with open ground floors used for commercial purposes or parking. In such cases,
192 the abrupt reduction in lateral stiffness at the ground-storey level led to concentration of drift demand and,
193 in many instances, severe damage or partial collapse (Sezgin et al., 2024). Torsional effects were
194 frequently observed together with soft-storey response, particularly in buildings with asymmetric plan
195 configurations or irregular stiffness distribution. Representative before- and after-earthquake examples
196 illustrating severe structural damage associated with soft-storey behavior and related failure patterns are
197 shown in Figure 5.

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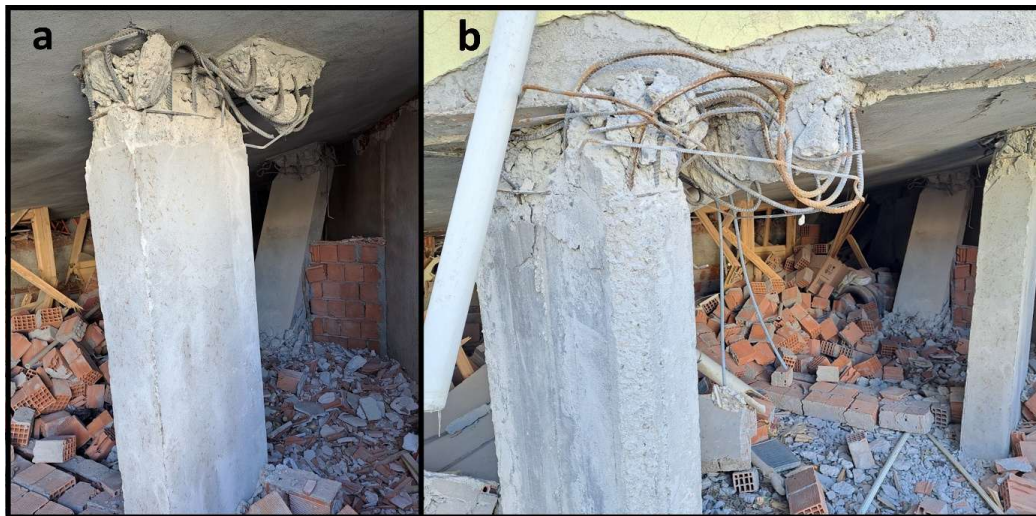


199

200 **Figure 5.** Before- and after-earthquake conditions of RC buildings affected by the February 6, 2023,
201 *Kahramanmaraş earthquake sequence.*

202

203 Pre-earthquake views of a relatively new, code-compliant RC building in Adıyaman with an open ground
204 storey used for commercial purposes are presented in Fig. 5a,b. The post-earthquake condition of the same
205 building (Fig. 5c) shows collapse and severe damage, primarily concentrated at the ground-storey level.
206 Similarly, Fig. 5d illustrates the pre-earthquake condition of an older RC building in Malatya with an open
207 ground floor, while Fig. 5e shows the post-earthquake state, characterized by widespread damage and
208 partial collapse. Another older RC building in Malatya is shown before the earthquake in Fig. 5f and after
209 the event in Fig. 5g, where severe damage to the main load-bearing elements is evident. In addition to
210 these observations, detailing-related deficiencies, such as inadequate lap splice regions, insufficient
211 anchorage lengths, and improper reinforcement arrangement, played a significant role in the progression
212 of damage. These deficiencies markedly increased the vulnerability of older building stock under the
213 extreme seismic demands imposed by the earthquake sequence (Varolgüneş, 2025). Examples of torsional
214 response in buildings with asymmetric plan configurations are presented in Fig. 6, while representative
215 cases of detailing deficiencies and poor material quality observed in older RC buildings are shown in Fig.
216 7.



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Figure 6. Torsional damage patterns observed in RC buildings affected by the February 6, 2023, Kahramanmaraş earthquake sequence



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Figure 7. Reinforcement detailing deficiencies and material-quality-related damage observed in older RC buildings following the February 6, 2023, Kahramanmaraş earthquake sequence.

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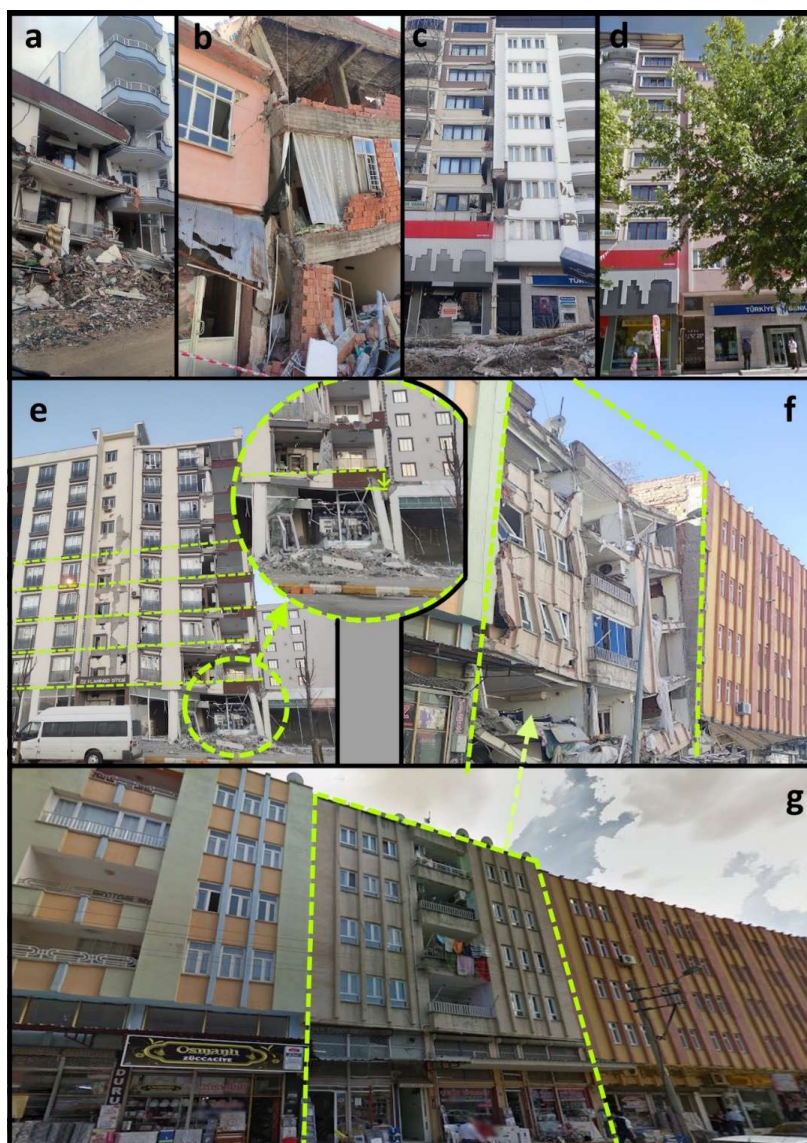
234

The pounding effect can be clearly observed in both older buildings constructed in accordance with previous seismic codes and in more recently designed structures built under current regulations such as the 2018 Turkish Seismic Code (TSC-2018). As shown in Figure 8, field observations following the earthquake, together with the corresponding pre-event conditions, clearly highlight the widespread occurrence of the pounding effect in closely spaced buildings. Figure 8a) presents a representative case from Adiyaman, where severe structural damage is observed after the seismic sequence. The comparison between pre- and post-earthquake conditions in Figures 8 c) and 8 d) further illustrates the extent of structural deterioration, ranging from extensive damage to partial collapse. A particularly critical case is depicted in Figure 8 e), where the missing of an adequate seismic separation gap, combined with a ground-floor commercial extension characterized by a relatively short dynamic period, resulted in a pronounced



235 pounding interaction. This interaction primarily affected the corner column located at the building edge,
236 leading to severe local failure and near-collapse conditions. In this instance, the impact demands arising
237 from dynamic incompatibility between adjacent structures were further amplified by stiffness
238 irregularities at the lower storey. Finally, Figures 8 f) and 8 g) present the pre- and post-earthquake
239 conditions of adjacent mid-rise residential blocks arranged in a row configuration. The observed damage
240 pattern in Figure 8 f) confirms that pounding was not an isolated phenomenon but rather a recurrent failure
241 mechanism in densely built urban areas, particularly where adequate separation joints were either absent
242 or insufficiently detailed.

243



244

245 **Figure 8.** Seismic damage observations and corresponding pre-earthquake conditions of adjacent and

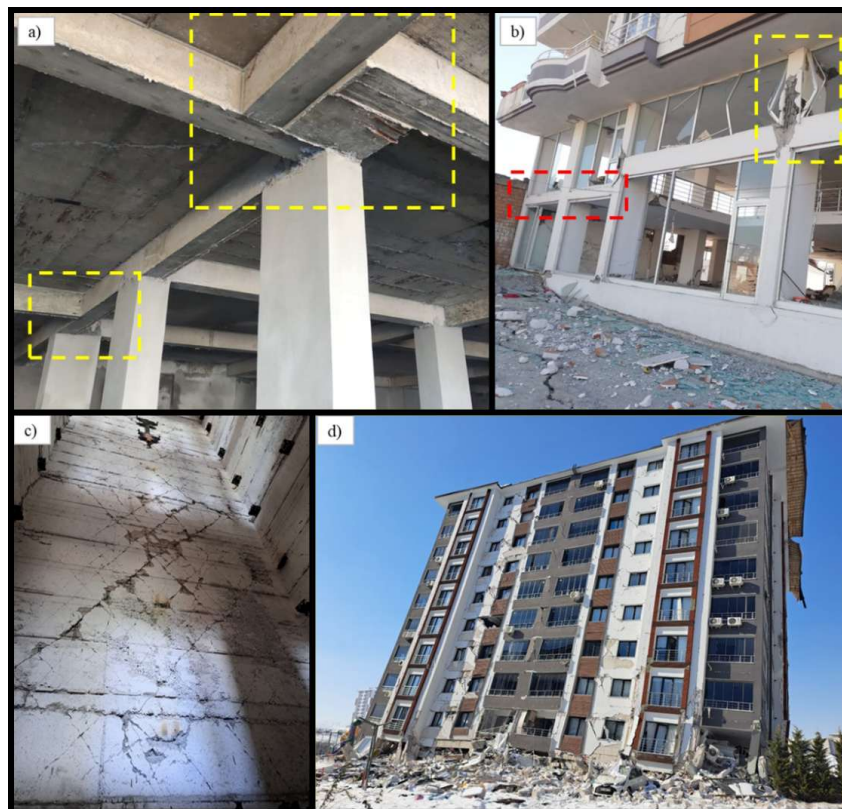


246 *mid-rise buildings: (a) Adıyaman; (b–c) member collapse; (d) pre-earthquake of (c); (e) localized*
247 *collapse by pounding; (f–g) comparison of pre- and post-earthquake conditions.*

248 **3.3.Damage mechanisms in newer code-era buildings**

249

250 Although seismic regulations in Türkiye have progressively improved by utilizing past earthquake field
251 studies (Sayın et al., 2017; Yon et al., 2019; Yon et al., 2020; Sayın et al., 2021;), these field investigations
252 showed that some relatively recent RC buildings also sustained severe damage. In contrast to older
253 buildings, the damage observed in newer structures was not predominantly associated with poor material
254 quality, but rather with structural system inadequacy and implementation-related shortcomings (Erbaş et
255 al., 2025; Yön et al., 2025). A representative example of such damage, presented in Malatya Province, is
256 demonstrated in Figure 9b). Field observations indicated that low shear-wall ratios and unfavorable
257 distribution of shear walls within the structural plan reduced the effectiveness of lateral load-resisting
258 systems. As a consequence, seismic demands tended to concentrate in frame members, increasing the
259 susceptibility of these buildings to severe damage under strong ground motions (Onat et al., 2024; Sezgin
260 et al., 2024; Yön et al., 2025) . Representative examples of such damage are presented in Figures 9 c) and
261 9 d), which include photographs taken in Malatya Province illustrating the observed deficiencies in the
262 field. In addition, deviations between the intended design and the as-built structural system were
263 documented in several damaged buildings. These deviations included deficiencies associated with
264 construction quality, inadequate site supervision, and execution-related inconsistencies. Such factors
265 contributed to unsatisfactory seismic performance even in buildings designed in accordance with modern
266 seismic code provisions (Erbaş et al., 2025; Yön et al., 2025). In this context, a field photograph taken in
267 Adıyaman Province, illustrating representative examples of these deficiencies, is presented in Figure 9 a).



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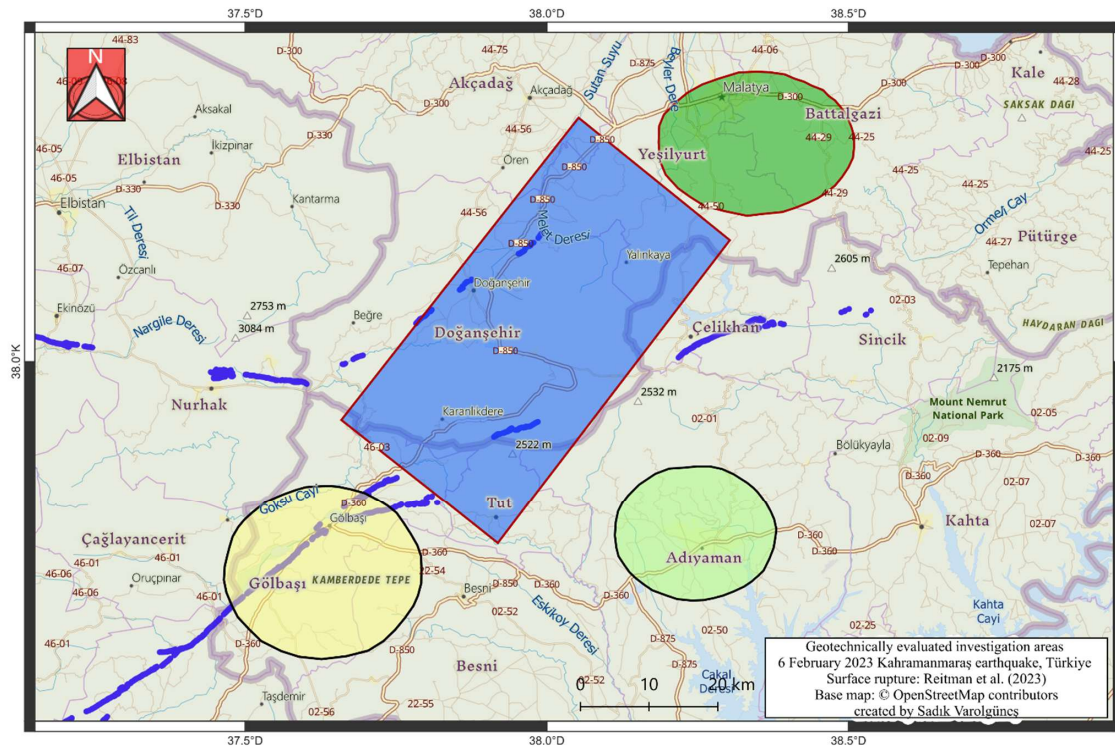
Figure 9. Damage mechanisms observed in newer RC buildings

270

4. Geotechnical Evaluation

271

272 Geotechnical conditions played a decisive role in the spatial distribution and severity of damage observed
273 during the earthquake sequence. In addition, within the scope of this study, the areas of Malatya, the
274 Malatya–Gölbaşı corridor, Gölbaşı/Adıyaman, and central Adıyaman were investigated following the
275 February 6, 2023 Kahramanmaraş earthquakes, with particular attention to their geotechnical
276 characteristics (Fig 10).



277

278

Figure 10. Geotechnically evaluated investigation areas (Reitman et al., 2023)

279

280 The field observations conducted in these areas revealed various geotechnical effects, including
281 liquefaction, lateral spreading, and ground settlements. The influence of these ground-related phenomena
282 on the performance of structures was also examined. In addition, damage to engineering structures such
283 as highways, railways, and retaining walls was evaluated, together with rockfalls and landslides observed
284 within the investigated region. These geotechnical effects produced damage patterns that differed
285 markedly from conventional superstructure failures, particularly where the foundation system lost support
286 or experienced differential settlement during strong shaking (Karasin, 2023; Onat et al., 2024).

287 In the Gölbaşı/Adıyaman area, which was one of the investigated locations, severe liquefaction effects
288 were observed after the earthquakes. This was mainly attributed to the presence of loose to soft soil profiles
289 composed of sandy, silty, and low-plasticity clayey soils, together with shallow groundwater conditions.
290 Liquefaction is among the geotechnical phenomena that can have the most adverse effects on structural
291 performance during earthquakes.

292 Within the investigated areas, earthquake-induced liquefaction led to significant ground settlements and
293 the partial sinking of several structures into the soil. As a result, damage and collapses were observed in
294 many buildings, with settlements reaching 60 cm or more in some cases (Fig 11).

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Figure 11. Settlements of superstructure induced by bearing capacity loss and differential foundation settlement

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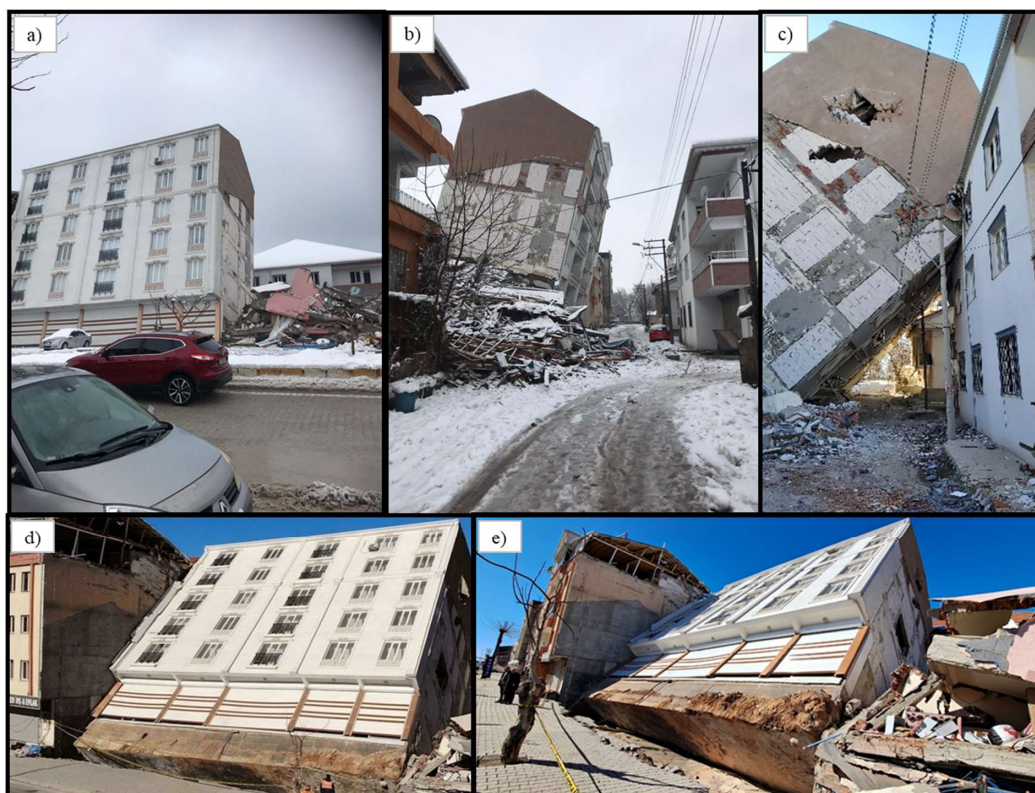
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As illustrated in Figure 12, the consequences of liquefaction on structural performance can be observed in a progressive manner. The affected building gradually penetrated into the softened ground due to the loss of soil bearing capacity and eventually experienced substantial overturning, coming to rest against the neighboring structures located behind it. Such field evidence demonstrates that earthquake-induced damage may be governed not only by the seismic resistance of the superstructure but also by the response of the supporting ground. Therefore, the observed damage patterns should be interpreted as the combined outcome of liquefaction susceptibility, foundation performance, and soil–foundation–structure interaction rather than as a consequence of superstructure behavior alone. (Erbaş et al., 2025).

309



310

311 **Figure 12.** *Overturning of a superstructure step by step due to low bearing capacity of soil with high*
312 *ground water table*

313

314 Lateral spreading was also observed in the investigated area as a result of earthquake-induced liquefaction (Figure
315 13 a and c). The combined effects of liquefaction and lateral spreading caused severe damage and, in some cases,
316 collapse in buildings, highways, and railway infrastructure (Figures 13 b, d, e and f).

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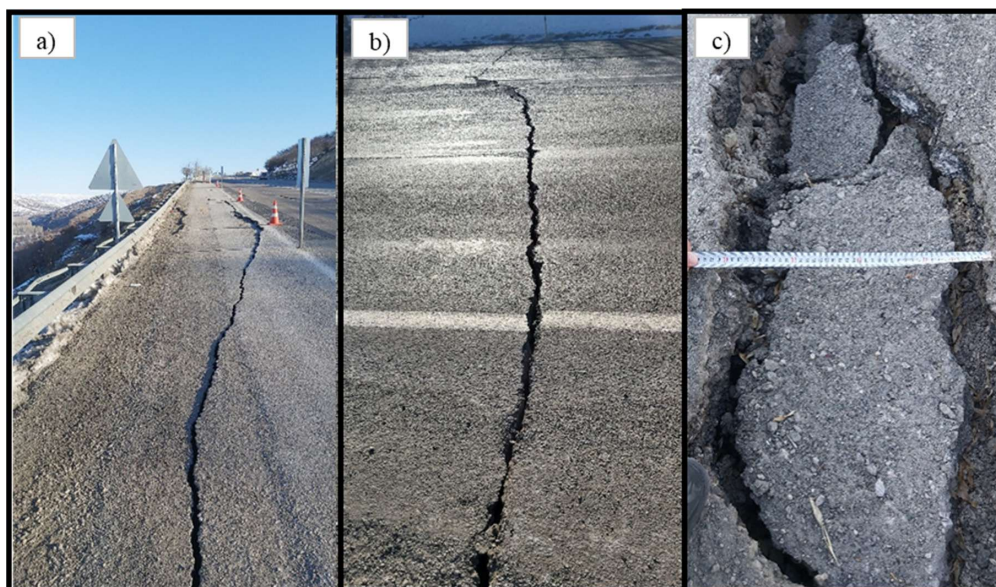
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322

Figure 13. Lateral spreading observed in the ground



323 During the field observations conducted along the Malatya–Gölbaşı route, earthquake-induced damage
324 was identified on several roadway sections. The inspections revealed cracks in the road pavement reaching
325 widths of up to 40 cm in some locations (Fig 14).



326

327

Figure 14. Damage observed on roadways

328 In the investigated areas, damage was particularly observed in gravity-type stone retaining walls located
329 along roadways. In sloping terrain, landslides together with the failure of these retaining walls led to the
330 closure of road transportation in certain sections of the affected region (Fig 15).

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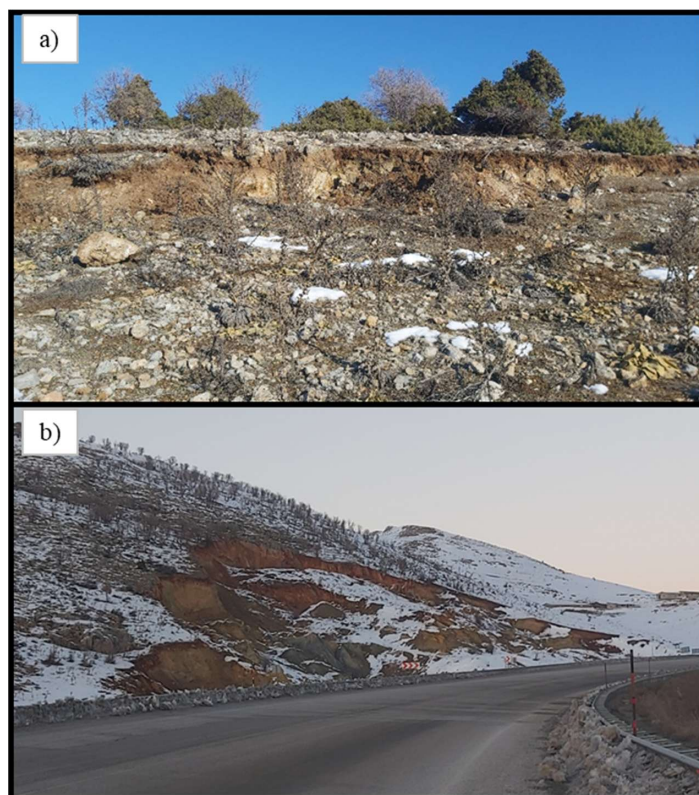
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Figure 15. Damage observed in gravity-type stone retaining walls

339 As a result of the earthquakes, the loss of soil strength in sloping areas triggered landslides and rockfalls
340 at various locations within the affected region (Figs 16 and 17).



341

342

Figure 16. Landslides observed in the investigated areas

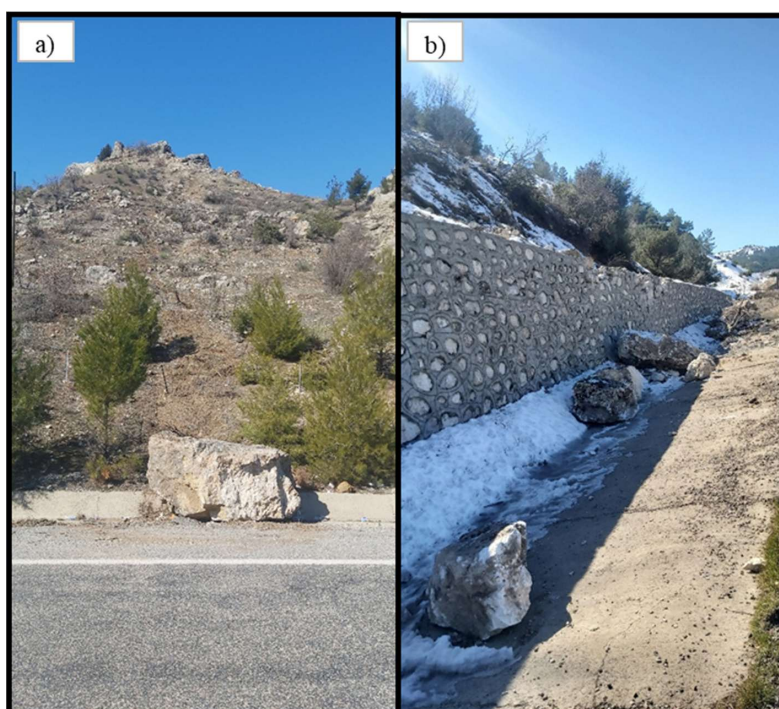


Figure 17. Rockfalls observed in the investigated areas

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345

346 **5. Discussion**

347

348 **5.1. Seismic demand and field-observed building performance**

349 The field observations presented in this study provide clear evidence on the seismic performance of RC
350 buildings subjected to extreme near-fault ground motions during the February 6, 2023, Kahramanmaraş
351 earthquake sequence. The observed damage patterns indicate that earthquake-induced building
352 performance cannot be explained solely by seismic demand intensity or by structure-specific defects.
353 Instead, damage resulted from the interaction of multiple factors, including extreme ground motion
354 characteristics, structural system properties, construction practice, and site conditions (Sezgin et al., 2024;
355 Atmaca et al., 2025; Erbaş et al., 2025; Yön et al., 2025). Recorded ground motions at several near-fault
356 stations exceeded code-based design spectra, particularly in the short- and intermediate-period ranges that
357 govern the seismic response of low- and mid-rise RC buildings (Karasin, 2023; Sezgin et al., 2024). These
358 demand levels exposed vulnerabilities in both older and newer buildings, highlighting the importance of
359 evaluating building performance under seismic loading conditions that go beyond routine design
360 assumptions.

361

362 **5.2. Conventional damage mechanisms in older RC buildings**

363 In older RC buildings, damage mechanisms were predominantly associated with structural deficiencies
364 that have long been recognized in earthquake engineering literature. These included inadequate transverse



365 reinforcement, weak concrete, insufficient confinement, soft-storey formation, torsional irregularities,
366 and pounding between adjacent buildings (Sevim et al., 2024; Sezgin et al., 2024; Erbaş et al., 2025).
367 Such mechanisms reflect limited ductility and insufficient capacity design, and their repeated occurrence
368 during the Kahramanmaraş earthquake sequence confirms the persistent seismic vulnerability of a large
369 portion of the existing building stock in Türkiye (Avcil et al., 2024; Atmaca et al., 2025; Varolgüneş,
370 2025; Aras et al., 2026). From an engineering standpoint, these observations reinforce the need for
371 systematic assessment and retrofit programs for older buildings. In particular, structures characterized by
372 open ground storeys, poor confinement regions, irregular plan geometry, and close adjacency conditions
373 remain highly sensitive to strong shaking and displacement concentration (Calayir et al., 2012; Hancılar
374 et al., 2013; Erbaş et al., 2025).

375

376 **5.3.Damage patterns in newer code-era RC buildings**

377 Damage observed in newer code-era RC buildings points to a different but equally critical challenge.
378 Although these buildings generally exhibited improved material quality and more modern detailing than
379 older structures, some still sustained severe damage. Field evidence indicates that such damage was more
380 closely related to structural system adequacy and implementation-related deficiencies than to material
381 weakness alone (Erbaş et al., 2025; Yön et al., 2025). In particular, low shear-wall ratios and unfavorable
382 distribution of shear walls within the structural plan reduced the effectiveness of lateral load-resisting
383 systems in several damaged buildings (Onat et al., 2024; Sezgin et al., 2024). When combined with
384 construction quality problems, inadequate site supervision, and deviations between design intent and
385 as-built conditions, these factors contributed to unsatisfactory seismic performance even in buildings
386 designed in compliance with modern seismic regulations. These findings suggest that, in newer buildings,
387 the primary engineering challenge has shifted from traditional material- and detailing-related deficiencies
388 toward system-level adequacy and implementation quality. Formal compliance with code provisions may
389 therefore be insufficient to ensure intended seismic performance when lateral force-resisting systems are
390 inadequately proportioned or when construction practice does not fully reflect design assumptions (Onat
391 et al., 2018; Onat, 2019; Erbaş et al., 2025).

392

393 **5.4.Influence of geotechnical conditions on damage distribution**

394 Geotechnical conditions were identified as critical modifiers of building performance during the
395 earthquake sequence. Liquefaction, high groundwater tables, differential settlement, and
396 excavation-related instabilities were observed in several affected areas and significantly influenced the
397 territorial distribution and severity of damage (Karasin, 2023; Onat et al., 2024; Öztürk Karadoğan, 2026).
398 In many cases, these ground-related effects interacted with existing structural weaknesses, amplifying
399 damage that could not be attributed to superstructure deficiencies alone. These observations confirm that
400 seismic performance should be treated as an integrated structural–geotechnical problem, particularly in
401 regions characterized by weak or saturated soils subjected to strong and repeated shaking (Erbaş et al.,
402 2025; Moss et al., 2025; Öztürk Karadoğan, 2026) .

403

404 **5.5.Implications for seismic design practice and implementation**

405 The combined field evidence demonstrates that improving earthquake resilience in Türkiye requires more
406 than periodic updates of seismic code text. While advances in code provisions have clearly improved
407 baseline design requirements, the results emphasize the importance of system-level design adequacy,



408 construction quality assurance, and site-sensitive decision-making in achieving satisfactory seismic
409 performance (Sezgin et al., 2024; Varolgüneş, 2025). From a design perspective, greater emphasis should
410 be placed on the adequacy and distribution of lateral load-resisting systems and on ensuring consistency
411 between design intent and as-built structural systems. From a policy perspective, the findings support the
412 need for stronger design review procedures, enhanced construction supervision, and closer integration of
413 geotechnical hazard considerations into zoning, permitting, and inspection processes (Sevim et al., 2024;
414 Erbaş et al., 2025; Yön et al., 2025).

415

416 **5.6.Synthesis of field observations**

417 Taken together, the results indicate that seismic vulnerability in Türkiye has evolved but has not been
418 eliminated. While older buildings remain highly susceptible due to well-known legacy deficiencies, newer
419 code-era buildings can also experience severe damage when system-level adequacy and implementation
420 quality are insufficient. Earthquake resilience should therefore be addressed through a multi-layered
421 framework that combines seismic design regulation, construction control, geotechnical assessment,
422 targeted retrofit strategies, and systematic post-earthquake learning (Varolgüneş, 2025; Onat et al.,
423 2026a).

424

425 **6. Conclusion**

426 This study presents a field-based evaluation of RC building performance during the February 6, 2023,
427 Kahramanmaraş earthquake sequence and highlights the evolving nature of seismic vulnerability in
428 Türkiye. The findings indicate that damage cannot be attributed to a single cause but results from the
429 interaction of seismic demand, structural configuration, construction quality, and geotechnical conditions.

430

- 431 • Earthquake damage was governed by the combined effects of near-fault ground motions,
432 structural irregularities, construction deficiencies, and adverse soil conditions, indicating a
433 system-level vulnerability rather than isolated failures.
- 434 • In older building stock, conventional deficiencies remain dominant, including inadequate
435 confinement, poor material quality, soft-storey formation, torsional irregularity, pounding effects,
436 and insufficient detailing. These repeating damages continue to represent a major source of
437 seismic risk.
- 438 • In newer code-era buildings, vulnerability has shifted toward system-level problems such as
439 discontinuous shear-wall layouts, insufficient wall ratios, interrupted load paths, and
440 inconsistencies between design and construction.
- 441 • Geotechnical effects, including liquefaction, groundwater-related distress, differential settlement,
442 and excavation-induced instabilities, significantly influenced damage patterns, confirming that
443 seismic performance must be addressed within a coupled soil-structure framework.
- 444 • Observed exceedances of design spectra at several stations emphasize the need to explicitly
445 consider near-fault pulse effects, local amplification, and basin response in seismic hazard
446 assessments.
- 447 • From an engineering standpoint, improving seismic performance requires stronger design control,
448 better construction supervision, and ensuring continuity and adequacy of lateral-load-resisting



449 systems.

- 450 • From a policy perspective, effective risk reduction depends on moving beyond code-based
451 approaches toward integrated frameworks that include building inventory assessment, targeted
452 retrofit strategies, and improved local-level screening and enforcement.
- 453 • Overall, enhancing earthquake resilience in Türkiye requires coordinated progress in design
454 practice, construction quality, regulatory enforcement, and geotechnical awareness, together with
455 proactive intervention in vulnerable existing building stock.

456

457 **Data availability**

458 The field observation data and photographic documentation used in this study are available from the
459 corresponding author upon reasonable request. Strong-motion records and seismic event information were
460 obtained from publicly accessible national databases, including AFAD and KOERI strong-motion
461 networks. Additional processed data supporting the findings of this study are available from the authors
462 upon request.

463

464 **Author contributions**

465 All authors contributed to the conception and design of this study. For detailed contributions, **Mehmet**
466 **Emin Öncü**: Conceptualization, Data curation, Formal analysis, Validation, Visualization, Writing –
467 original draft, Writing – review and editing. **Sadık Varolgüneş**: Data curation, Formal analysis,
468 Visualization, Writing – original draft, Writing – review and editing. **Onur Onat**: Data curation, Funding
469 acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing –
470 original draft, Writing – review and editing. **Burak Yön**: Conceptualization, Investigation, Methodology,
471 Resources, Software, Writing – original draft, Writing – review and editing. **Ali Uslu, İbrahim Baran**
472 **Karaşin and Mesut Gör**: Data curation, Writing – original draft, Writing – review and editing.

473

474 **Competing interests**

475 The authors declare no competing interests.

476

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