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S.I. : NATECH RISK ASSESSMENT OF HAZARDOUS

Field reconnaissance on seismic performance and functionality of Turkish industrial facilities affected by the 2023 Kahramanmaras earthquake sequence

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Abstract

On February 6th, 2023, an earthquake sequence with moment magnitudes (Mw) of 7.8 and 7.5 rocked southern and eastern Turkiye, affecting 15 million-residents and a significant portion of Turkiye's industrial community. In the days following the earthquake sequence, a reconnaissance team was organized to visit the industrial districts in the five provinces of the earthquake region. While performance and functionality of 131 industrial facilities were inspected using the proposed data-collection protocols, 18 interviews with industrial representatives were conducted. The inspection and interview results show that the earthquake sequence had a significant impact on industrial facilities, resulting in enormous economic losses and business disruptions lasting three months to two years. While the sequence imposed severe demands on the facilities, their poor performance is mostly due to discrepancies between seismic design code requirements and building practice. The most affected facilities were found to be those built before 2000, as well as precast reinforced concrete structures with pin-supported roofs. As a result, these types of facilities in earthquake-prone areas are strongly advised to be re-evaluated. Furthermore, various nonstructural building components, such as claddings and equipment/machinery, were substantially damaged at the majority of the assessed sites, causing lengthy interruptions. To reduce future seismic losses and disruptions to industry, the proposed protocols and findings of this field study can be utilized to support further resilience studies on the development of business continuity plans and risk management approaches for industrial facilities.

Keywords Industrial facilities · Seismic performance · Kahramanmaras earthquakes · Field study · Seismic damage · Functionality

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1 Introduction

At 04:17 am and 01:34 pm TRT on February 6th, 2023, two devastating cascading earthquake events struck the southern and eastern Turkiye. The events took place on the East Anatolian Fault, one of Turkiye's most active fault zones with a left-lateral strike-slip mechanism, with the epicenters located nearby Pazarcik and Elbistan in the city of Kahramanmaras. The events were felt extremely intensely, and occurred at focal depths of first 8.6 km and then 7.0 km (AFAD 2023) with significant moment magnitudes (Mw) of 7.8 and 7.5, respectively (USGS 2023; the Mw magnitudes were reported as 7.7 and 7.6, respectively, based on AFAD 2023). The events had a massive geographical impact, hitting 11 cities in Turkiye, a territory of around 100,000 km^2 with a population of more than 15 million people, as well as certain regions of northern Syria. More than 107,000 buildings in Turkiye were reported to be collapsed or heavily damaged (primarily, in Hatay and Kahramanmaras), resulting in 50 thousand confirmed casualties and around 110 thousand injured people (Coskun 2023; AFAD 2023).

Widespread damage to buildings and infrastructure resulted in total economic losses expected to exceed $100 billion (considering both direct and indirect losses), equivalent to 9% of the expected 2023 national income of Turkiye (Buyuk 2023; CSBB 2023; Evans 2023; Goren 2023) and approximately six times the losses experienced in the 1999 Marmara Earthquake. A significant portion of the reported economic losses comes from damage to industrial facilities (Buyuk 2023). Several facilities collapsed, or lost production equipment, or had to halt operations for an extended period of time despite not being directly damaged. Understanding vulnerability of such facilities is critical, as they play an important role for the Turkish economy and the quick recovery of the community. As a result, gathering, reporting, and analyzing field data on seismic performance and functionality of Turkish industrial buildings are critical in efforts to support their earthquake resilience, particularly in developing business continuity plans and risk management strategies.

In the days following the earthquake sequence, a reconnaissance team was formed to visit industrial areas in the five provinces of the earthquake region: Adana, Osmaniye, Kahramanmaras, Gaziantep, and Hatay. In total, 131 industrial facilities were visited, located in various organized industrial sites (OIZ), small industrial sites (IS), and free sites (FS; not belonging to OIZ or IS). Their structural and nonstructural performance and post-event functionality levels were investigated using an inspection tool developed by the team. Furthermore, 18 semi-structured interviews were conducted with facility owners or industrial representatives in order to understand the general impacts on the industrial areas caused by the earthquake sequence.

In the following sections, this paper first provides a brief overview on the inspected industrial locations and their general characteristics. Then, in comparison to design spectra values provided by the modern building codes, the seismic demands imposed on the industrial facilities by the 2023 Kahramanmaras earthquake sequence are briefly described. Next, the inspection tool and the interview questionnaire used to collect data from the visited sites are presented. Following a summary of the details of the gathered data, the interview and inspection results for the visited facilities, as well as the reasons for their failure, are thoroughly discussed.

2 Surveying and data collection

The team arrived in the earthquake zone on February 17th, 2023, just 11 days after the occurrence of the earthquake sequence. The trip was limited to five days (February 17–21, 2023) due to the chaotic conditions in the earthquake region, which included significant aftershocks and a general cut on utility lines in some areas. The reconnaissance team's goal was to conduct their field studies in two stages: inspections of industrial facilities and interviews with industrial owners or representatives.

Fig. 1 depicts surveying and data collection methodology used for the field study. Prior to the field study, several internet sources (such as several aerial maps by Atlas (2023) and newspapers) were thoroughly searched to understand the distribution of damage to industrial facilities in the affected region. Due to time constraints and the sparseness of the affected region (100,000 km^2), only the following five but critical affected provinces were chosen for the field study: Adana, Osmaniye, Kahramanmaras, Gaziantep, and Hatay. While some selected provinces were severely damaged (i.e., Kahramanmaras and Hatay), others were only slightly damaged, providing opportunities for studying different damage aspects for inspections. A preliminary itinerary for the daily site visits was then planned based on the limited information obtained from the internet sources. Prior to the field study, the team also contacted some industrial representatives from the affected region, scheduled meetings for semi-structured interviews, and prepared questionnaires to gather information on the general status of industrial areas. Also, an inspection sheet was prepared to conduct seismic performance inspections on the facilities. In the following sections, more details are given on the protocols followed for interviews and inspections.

2.1 Investigated site locations

During the five-day field study, the reconnaissance team inspected 131 industrial facilities and interviewed 18 industry representatives. The locations of the facilities were marked on the map in Fig. 2 with building identification numbers (IDs). Table 1 also shows how the inspected industrial areas and facilities were divided into thirteen distinct zones. Some facilities are located in organized industrial sites (OIZ) or small industrial sites (IS), and

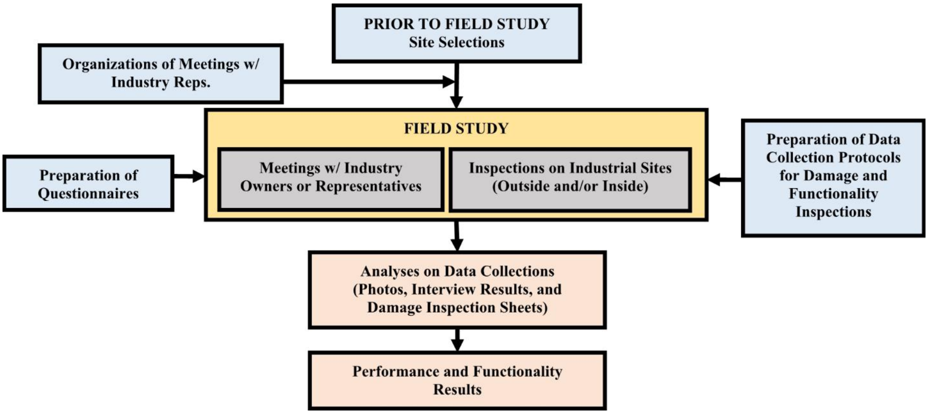


Fig. 1 Surveying and data collection protocols used in the field reconnaissance

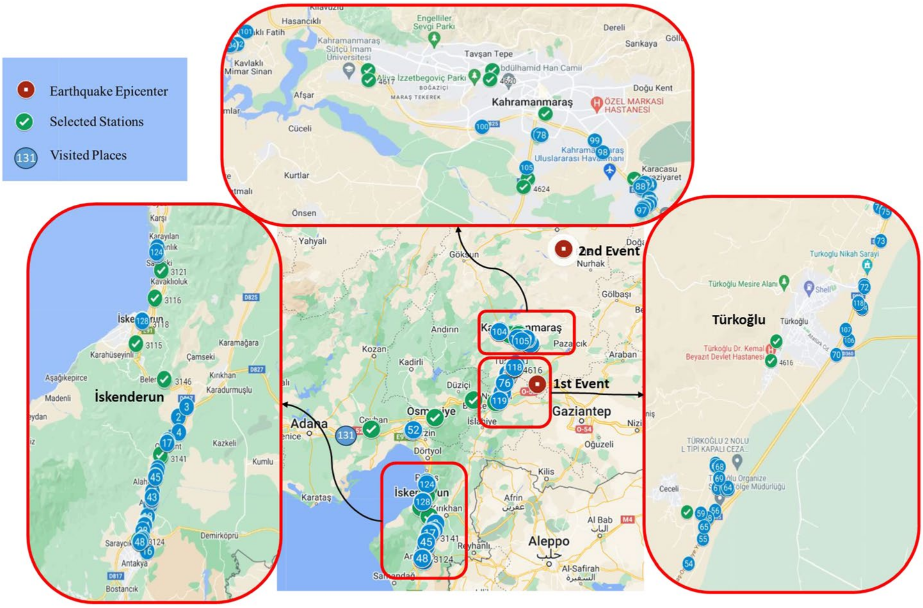


Fig. 2 Locations of the visited sites, together with epicenters of the earthquake sequence and the selected nearby stations

others are scattered throughout the affected provinces and are referred to as free site facilities (FS). The primary distinction between OIZ and others is that OIZ provides an organized utility service, convenience in all licensing procedures, and security services to its industrial residents. The Turkish Ministry of Industry and Technology regulates both OIZ and IS. While IS is reserved for smaller or more entrepreneurial industrial firms, OIZ is reserved for larger, more established firms. In the OIZ, IS, and FS zones, respectively, 26%, 18%, and 56% of the inspections and 67%, 0%, and 33% of the interviews were conducted.

Table 1 also depicts the distribution of inspected industrial facilities by province, industry sector, and structural type. The team prioritized inspections on the most affected provinces, Kahramanmaras and Hatay, corresponding to 82% of the building inspections, because the goal of the field study was to collect as much field data on damage as possible in the limited time available on site. While the facilities in OIZs and FSs work primarily in the chemical, textile, and food sectors, the ones in IS zones mostly work in the automotive sector. Furthermore, as is typical of Turkiye's industrial building stock, the majority of industrial facilities in the inspected OIZs are one-story structures with precast reinforced concrete structural systems. Facilities in ISs have much smaller workspace areas than the ones in OIZs and are typically built with simple one or two-story in-situ reinforced concrete structures or simple steel framed systems with lateral bracing. Lastly, steel structures such as silos are often used in the agri-food industry for forage storage in airtight systems. They were also included in the inventory and evaluated together as a part of the building facilities under investigation.

Table 1 Industrial locations visited during the field study (note: OIZ, IS, and FS stand for organized industrial site, small industrial site and free site (not in OIZ or IS) respectively)

Ind. Zone No.	Province	District	Ind. Zone Type	Visit Date	No. of interviews	No. of Inspected Facilities	No. of Facilities in Each Sector					No. of Facilities in Structural Systems		
							Textile	Food	Metal	Chem.	Other*	Precast Reinf. Conc.	Reinf. Conc.	Steel
1	Hatay	Antakya	OIZ	Feb.17, 2023	2	3	0	1	2	0	0	0	2	1
2			IS	Feb.17, 2023	0	16	0	0	2	0	14	0	11	5
3			F	Feb.17, 2023	2	27	0	11	1	5	10	3	17	7
4	Osmaniye	Toprakkale	OIZ	Feb.18, 2023	2	4	2	0	1	0	1	3	0	1
5	Kahramanmaras	Turkoglu	OIZ	Feb.18, 2023	3	13	4	2	0	4	3	10	2	1
6			FS	Feb.19, 2023	1	19	6	5	3	0	5	10	2	7
7		Onikisubat	OIZ	Feb.19, 2023	1	5	2	1	2	0	0	4	1	0
8		Dulkadiroglu	FS	Feb.19, 2023	2	25	12	3	4	0	6	22	2	1
9	Gaziantep	Nurdagı	IS	Feb.19, 2023	0	4	0	0	0	0	4	0	4	0
10			FS	Feb.19, 2023	1	2	0	0	0	0	2	1	0	1
11	Hatay	Iskenderun	OIZ	Feb.20, 2023	2	5	0	1	3	0	1	2	0	3
12			IS	Feb.20, 2023	0	4	0	0	0	0	4	0	4	0
13	Adana	Hacı Sabancı	OIZ	Feb.21, 2023	2	4	1	0	0	3	0	4	0	0
				Total #	**18**	**131**	**27**	**24**	**18**	**12**	**50**	**59**	**45**	**27**

*Other sectors include automobile sub-industries, retail industry…etc

2.2 Protocols followed for site interviews and inspections

During the field study, while semi-structured interviews with industrial owners or representatives were set up to gather general impact information on the visited and nearby industrial facilities, individual performance inspections were conducted to make specific damage and functionality assessments of the visited facilities. Table 2 shows the key parameters considered in the data collection protocols for both interview questionnaires and inspection sheets.

It should also be highlighted that just one-third (37%) of the facilities were evaluated both internally and outside. While an interior examination might yield more accurate results on damage assessments, most investigated facilities were inaccessible, necessitating an outside investigation. On the inspection sheets, those which were inspected 'outside' or 'both outside and inside' were noted.

Table 3 shows an example of summary of the data collected from the first five buildings inspected in the region, including damage and functionality assessments. Following a similar system used in the literature (Sezen and Whittaker 2005; Cevre Sehircilik Bakanligi 2019), five damage state (DS) levels were defined here, ranging from none to collapse. To better understand the earthquake's impact on the facility, separate damage assessments for structural and nonstructural states were conducted (see Table 4). Furthermore, to assess the current state of production or work capacity of the visited facilities, a functionality inspection system with three levels (almost full or partial functionality or none; see Table 4) was developed and implemented.

Table 2 Key parameters considered in the data collection protocols

Questionnaires for Site Interviews with Industrial Reps.*	Facility Inspection Sheets
Site location	Exact location of the facility (GPS coordinates)
Number of the facilities in the industrial site of interest	Structural type & built year
General distribution of the sectors	Story number & story height
General damage status of facilities	Bay length, number of bays
General damage status of the utility lines: • If there was any utility cut just after the event, duration of the cut • The most critical utility line to continue production for facilities	Current condition of utility lines
General functionality status of facilities: • Just after the event • At current time	Structural damage state and related details
Observation on any cascading or simultaneous hazard triggered by the earthquake	Nonstructural damage state and related details
General insurance profile of the facilities in the zone	Functionality state: • If not functional, duration of not being functional • If functional, current production level in %

*If the interviewee is an industrial owner, the same questions were separately asked considering both general status of the industrial zone and the status of owner's individual facility.

Table 3 An example of summary of the data collected from the first five inspected facilities

Building ID	Date of Site Visit	Location	Sector	Structural System	Damage Inspection Method	Structural Damage State (SDS)	Non-structural Damage State (NDS)	Functionality State (FS)
1	Feb. 17, 2023	Antakya-OIZ	Metal	Reinforced Concrete	Inside and Outside	SDS1	NDS3	FS1
2	Feb. 17, 2023	Antakya-OIZ	Metal	Steel	Inside and Outside	SDS1	NDS2	FS2
3	Feb. 17, 2023	Antakya-OIZ	Food	Reinforced Concrete	Inside and Outside	SDS2	NDS5	FS3
4	Feb. 17, 2023	Antakya- FS	Food	Precast Reinf. Concrete	Outside	SDS1	NDS3	FS2
5	Feb. 17, 2023	Antakya-FS	Metal	Steel	Outside	SDS1	NDS2	FS2

Table 4 Assumed definitions for structural and nonstructural damage states and functionality states (following a similar system in the studies by Sezen and Whittaker (2005) and Cevre Sehircilik Bakanligi (2019))

	Level	Description	Definition
Str. Damage State (SDS)	SDS1	None	Negligible
	SDS2	Minor	Minor cracks in reinforced concrete members; bolt failures in steel frames
	SDS3	Moderate	Significant cracks in reinforced concrete members; yielding in steel moment frames
	SDS4	Major	Spalling and crushing of reinforced concrete members; rebar fracture in reinforced concrete members; fracture of steel components
	SDS5	Collapse	Multiple component failures; a significant part or full loss of floors or roofs; gross distortion of steel frames; large permanent drifts
Non-str. Damage State (NDS)	NDS1	None	Negligible
	NDS2	Minor	Small movement of unanchored equipment; overturning of cabinets and shelved products
	NDS3	Moderate	Modest damage to architectural, mechanical, and plumbing systems; failure of equipment anchorage; movement/overturning of equipment
	NDS4	Major	Significant damage/cracking to some non-structural building components but no collapse
	NDS5	Collapse	Partial or total collapse of several non-structural building components such as claddings/ infill walls
Func. State (FS)	FS1	Functional	Industrial facility is fully or almost fully operational
	FS2	Partially Functional	Industrial facility is partially operational
	FS3	Not Functional	Industrial facility is closed or cannot operate

3 Demands of the earthquake sequence on the investigated sites

The Disaster and Emergency Management Authority of Turkiye (AFAD) operates 244 strong-motion stations within 445 km of the earthquake zone. Fig. 2 shows the stations selected nearest to the visited industrial facilities. Using the earthquake motion recordings from these selected stations, Table 5 summarizes the seismic demands imposed on the visited sites in terms of peak ground acceleration (PGA) values. These demands are later considered in the following section to assess their relevance to the performance and functionality levels of the visited facilities. Table 5 does not display the PGA values for the second earthquake event, which were less than 0.1 g at the selected stations. This might be due to the positioning and directivity of its fault rupture (METU-EERC Report 2023), which was to the north of the visited zones, therefore the second event did not significantly affect the facilities inspected in this field study.

Table 5 shows the highest PGAs for the industrial zones in Antakya, Hatay, which are horizontally 1.23 g and vertically 1.05 g (Station No. 3126). Even though Antakya is more than 100 km from the epicenter of the initial event (see Table 5), due to its placement on the fault direction and alluvial site soils (Korkmaz 2006; METU-EERC Report 2023), it received larger PGA values, resulting in more substantial damage than the other places in Table 5.

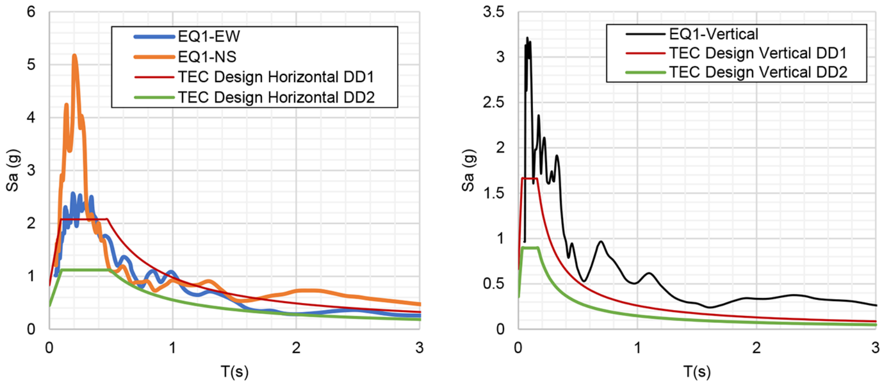
In Fig. 3, the elastic spectra acceleration values from Antakya (Station No. 3126) and Turkoglu (Station No. 4616) station recordings were compared to the 2019 Turkish Earth-

Table 5 Peak ground acceleration (PGA) values for the first earthquake (Pazarcık) at the selected stations nearest to the visited locations

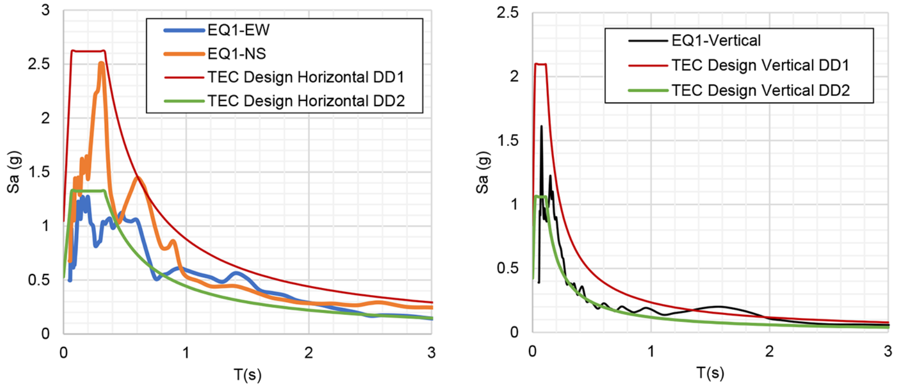
							First Earthquake Near Pazarcık #			
Industrial Zone No. (see Table 1)	Province	District	Ind. Zone Type	Rep. Station No. Selected within the Zone	Soil Type	Distance of Station to the Zone (km)	Dist. to the Epicenter (km)	PGA-NS (g)	PGA-EW (g)	PGA-Vert. (g)
1	Hatay	Antakya	OIZ	3146	ZD*	6.4	114.6	0.493	0.354	0.348
2			IS	3126	ZD	5.1	143.5	1.234	1.050	1.092
3			F	3124	ZD	0.5	140.1	0.584	0.651	0.589
4	Osmaniye	Toprakkale	OIZ	8003	ZD	17.5	72	0.144	0.189	0.204
5	Kahramanmaras	Turkoglu	OIZ	4616	ZC	5.2	20.5	0.665	0.513	0.405
6			F			3.1				
7		Onikisubat	OIZ	4624	ZD	6.9	29.7	0.365	0.326	0.165
8		Dulkadiroglu	F	4625	ZD	0.5	28.4	0.457	0.493	0.374
9	Gaziantep	Nurdagı	IS	4616	ZC	3.1	20.5	0.665	0.513	0.405
10			F	2712	ZC*	2.0	29.8	0.566	0.614	0.353
11	Hatay	Iskenderun	OIZ	3116	ZB	6.5	105.4	0.167	0.172	0.169
12			IS	3116	ZB	5.6	105.4	0.167	0.172	0.169
13	Adana	Hacı Sabancı	OIZ	125	ZD	18.3	114.6	0.131	0.085	0.036

*Assumed soil type

#The first event occurred with a highest horizontal PGA value of 2.2 g recorded at its epicenter Pazarcık, Kahramanmaras (AFAD Station No. 4614).



(a) Horizontal and vertical spectral acceleration components at AFAD Station No. 3126



(b) Horizontal and vertical spectral acceleration components at AFAD Station No. 4616

Fig. 3 Horizontal and vertical elastic spectral acceleration (Sa) values from the recordings of the first earthquake at **(a)** AFAD Station No. 3126 in Antakya City Center and **(b)** AFAD Station No. 4616 in Turkoglu; and their comparisons with the design values from current Turkish Earthquake Code (TBEC 2019)

quake Code design spectra values for DD1 (2% probability of exceedance in 50 years) and DD2 (10% probability of exceedance in 50 years) design earthquakes. It should be mentioned that DD2 is often used for the seismic design of standard industrial buildings with periods ranging from 0.5 to 1.5 s. The horizontal and vertical seismic demands were observed generally above the DD1 design limits for Antakya and the DD2 design levels for Turkoglu, indicating how the magnitudes of the seismic demands were significant for the inspected facilities.

4 Results for interviews and inspections

The current Turkish earthquake code (TBEC 2019) focuses on preventing collapse for high-intensity earthquakes to keep life safety. However, similar to experiences in previous earthquakes (Sezen et al. 2000; Erdik 2001), while properly designed and built industrial buildings generally sustained minor or no damage, industrial buildings with insufficient seismic design or unaudited construction process performed very poorly during the 2023 Kahramanmaras earthquake sequence. Even some recently built industrial buildings have been observed to fail due to construction or design flaws (e.g., inadequate corbel sizes, insufficient reinforcement detailing, low material quality). The following section provides an overview of the collected results before delving into the reasons for the various forms of poor performance noticed at the facilities.

4.1 Overview of results

Based on collected inspection data, Table 6 shows the distributions of the damage and functionality assessments of the inspected industrial facilities. Results show that 33% of totally inspected 131 facilities have a partial or total structural collapse state (SDS5), while 55% has none or minor structural damage (SDS1 & SDS2). The ratio of collapsed facilities is very high, mostly observed in Kahramanmaras (Turkoglu, Dulkadiroglu) and Hatay (Iskenderun, Antakya). Furthermore, 54% of the facilities were assessed to be in a nonstructural collapse state (NDS5), and 77% were completely closed and out of service. It should also be emphasized that just one-third (37%) of the facilities were accessible for both external and internal inspections. This can explain the lower percentages found for SDS3 and SDS4, which could be more significant.

Fig. 4 categorizes the inspected facilities into three types of industrial zones, as mentioned before in Sect. 2.1 (see Table 1). The facilities in organized industrial zones (OIZ) tend to have less serious damage than those in free sites (FS) and small industrial sites (IS). Because the requirements and constraints for an OIZ are more stringent than those for IS and FS zones, buildings are more likely to be properly designed for earthquakes, and as a result, fewer significant damages were observed for both structural and nonstructural assessments, even for OIZs in Hatay and Kahramanmaras. Similarly, although factories in OIZs have mostly FS1 and FS2 functionality levels, the other two zones all have FS3, indicating no functionality.

To assess the relevance of the seismic demands imposed on the visited facilities to their performance and functionality levels, statistical analyses were performed on the collected

Table 6 Performance and functionality results of the inspected industrial facilities

State Level	Structural Damage State (SDS)	Nonstructural Damage State (NDS)	Functionality State (FS)
1	36%	8%	2%
2	19%	13%	21%
3	5%	11%	77%
4	6%	15	-
5	33%	54%	-

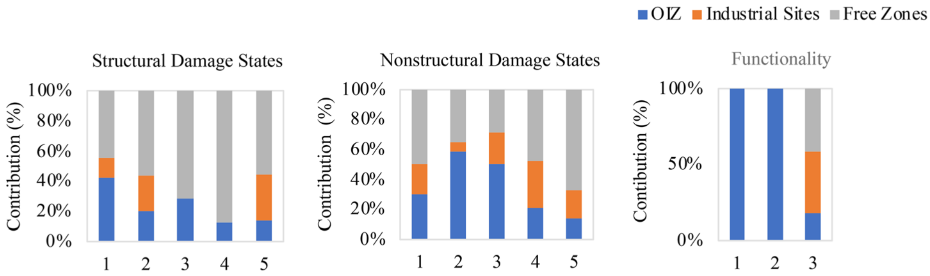


Fig. 4 Distributions of performance and functionality assessment results based on the industrial zone types (note: OIZ, IS and FS stand for organized industrial zone, industrial site, and free site)

assessment data (Table 3) and seismic demands (Table 5). Because all facilities have different structural systems that result in high variability in assessment results, the 59 inspected precast reinforced concrete buildings (precast RC types, including precast column buildings with steel roofs) were focused on here to assess the relationships for the exceedance of probabilities (i.e., fragilities) with respect to PGA values. It should be noted that the horizontal PGA values (maximum of north-south or east-west) of the first earthquake at the nearby stations (see Table 5) were used directly in the assessment of the fragility relations for the facilities, without considering high spatial variability of the ground motion recordings between the stations and the facility sites. The empirical performance and functionality fragility models for the investigated precast RC structures are depicted in Fig. 5. As predicted, all models exhibit a nearly increasing trend as the PGA gets larger.

Nonstructural fragilities have higher probability than structural ones, indicating that nonstructural components are sensitive to even minor seismic demands. At higher PGA values, structural fragilities for major and more severe states display closer curves. This might be due to brittle pin-failures, which were commonly observed as the failure type for this structural system and are addressed more in the next section. Also, even at smaller PGA values around 0.1 g, exceedance probability of partial functionality reaches to 67%. This is mostly due to nonstructural damage levels sustained on the facility. Lastly, it should be noted that these models are the preliminary results and further refinements are needed on the models, considering the effects of distances of the facilities to the selected stations on the seismic hazard demands.

4.2 Structural performance of industrial structures

The industrial facilities in Turkiye are mostly composed of precast or in-situ reinforced concrete structural systems. With focusing on these structural systems, the following sections discuss the performance of each structural system together with the observations made by the team.

4.2.1 Precast reinforced concrete industrial structures

One-story precast reinforced concrete (precast RC) structural systems with cast-in socketed spread footings are widely used in Turkish industrial facilities because they are quick to build and manufactured locally, making them extremely cost-effective. These structural

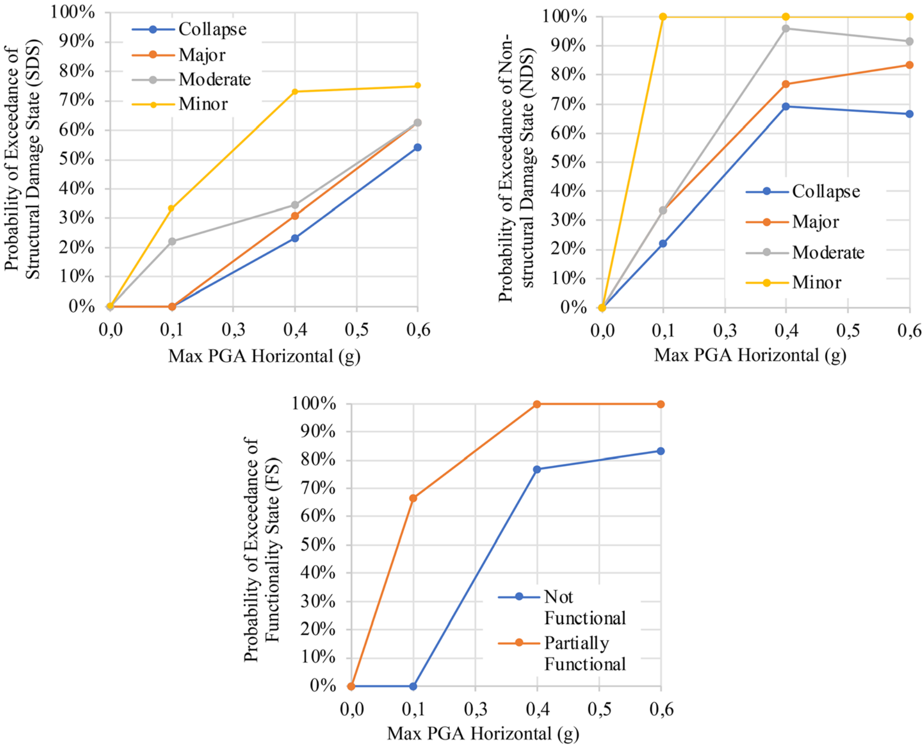


Fig. 5 Empirical performance and functionality models for precast RC buildings (note that spatial distances of the facility sites to the recording stations were not considered yet in these preliminary models)

systems usually have an average story height of 7-8 m with a typical bay length of around 20 m (Eren et al. 2015; Olmez and Deniz 2023). After the cantilever columns are installed inside the footings, they are usually pin-connected to roof beams at the top to form the frame systems. Dowels are commonly used to make the pin-connections, resulting in negligible beam-to-column joint stiffness in comparison to the flexural stiffness of the connected elements. Consequently, only columns can provide lateral stiffness against seismic demands, and they are typically designed to dissipate seismic energy by forming plastic hinges at their bases (Labo et al. 2022; Palanci et al. 2017).

During the inspections, certain precast RC columns were found to have flexural cracks at the base (see Fig. 6-top; where a lateral deflection of 4.7 cm was measured at one-fourth height of the column with respect to ground) or at lateral supports (see Fig. 6- middle), indicating the energy dissipation against the earthquake demands, but the number of these columns was low. In contrast, multiple incidents of partial or total roof collapses were detected in the inspected facilities in Hatay and Kahramanmaras, including the recently constructed post-2015 facilities in Turkoglu OIZ, without showing any hinging at the column base (see Fig. 6-bottom). The main reason was due to loss of connection support at the column-roof beam, which resulted in rotation or collapse of the main roof beams in these systems (see Fig. 7-top). This is a very common damage pattern that has been seen in several recent earthquakes, such as the 1999 Kocaeli earthquake (Erdik 2001) and the 2012 Emilia earthquake

Fig. 6 Plastic hinges and flexural cracks observed at the column bases (top) and lateral support (middle); and complete collapses of roof systems together with main and supporting beams (bottom)

sequence (Liberatore et al. 2013; Belleri et al. 2014). It shows that these connections were insufficient to support the seismic displacement demands associated with the structure's high flexibility, which comes from the tall cantilever columns. Insufficient anchorage in the dowels and improper grouting around them (see Fig. 7) can all contribute to beam-column connection failures, which can lead to roof beams falling from support systems and eventually leading to roof collapses for precast concrete structures. These factors, as well as smaller corbel dimensions that support the roof beams, poor detailing or preexisting deterioration or corrosion at the column corbel-beam connection, may also play a role.

The latest Turkish earthquake code TBEC 2019 provides limitations on the precast reinforced concrete frame structures with pinned joint systems at the roof by reducing their

Fig. 7 Examples of pin failures on precast reinforced concrete industrial facilities located in Turkoglu (top); shear cracks and/or spalled concrete at corbels or roof beam ends observed in Adana, Nurdagi, Iskenderun, Turkoglu respectively (middle part from left to right and bottom-left); and severe corrosions observed on the elements (bottom-middle and right)

force reduction factors R to the lower values of 3 (without any shear walls), which was the same in TBEC 2007, but 5 in TBEC 1998. The design concepts for precast reinforced concrete structures were not even taken into consideration by the codes before 1998 (TEC 1975). This is because precast systems were initially utilized in Turkiye around 1965, and their application in industrial buildings increased after the 1980s (Bekiroglu 2006). These facts all may explain why some pre-2000 or even older buildings performed poorly and didn’t dissipate enough seismic energy and failed in brittle mode.

Moreover, the severity of the first earthquake was very high and felt strongly in Antakya, Hatay and Turkoglu, Kahramanmaras (see Sect. 3). Seismic demands exceeded the design earthquake values at some locations, especially between the period ranges of 1.0 to 1.5 s, where represent the typical period range for precast RC industrial structures (Eren et al.

2015). Furthermore, strong vertical accelerations may contribute to the collapses of heavy roof systems by causing shear cracks and concrete spalls at roof beam ends or corbels, as a result of continuous poundings between them during the earthquake sequence (see Fig. 7-middle).

Lastly, as observed during the inspections, the adjacent industrial facility structures were often not constructed with a proper spacing (i.e., seismic construction joint), even these spacings are required in current or prior Turkish seismic design codes (TEC 1975; TBEC 2019). This spacing is very significant as it allows both structures to deform freely without damaging each other under seismic excitations. The effect of one building hitting the adjacent one during seismic excitation is called pounding effect. This effect was observed in a factory in Kahramanmaras, where pounding of one building caused the other one to completely collapse (see Fig. 8).

4.2.2 Cast-in-situ reinforced concrete industrial structures

Cast-in-situ reinforced concrete (RC) moment framed buildings are frequently used in industrial facilities, particularly in small industrial sites serving the retail and automotive sub-industries. During the Kahramanmaras earthquake sequence, while some RC facilities showed significant drifts under plastic hinging (see Fig. 9), many failed in a pancake or soft-story collapse mode (see Fig. 10). As experienced in past earthquakes, similar problems were identified contributing to their brittle failures (see Figs. 11 and 12), including inadequate concrete and reinforcement quality, corrosive environments, poor reinforcement detailing, ignorance of strong column-weak beam principles, and short column effects.

Findings from the recent earthquakes in Turkiye including this Kahramanmaras sequence event show that use of low strength concrete (usually 6–12 MPa, which is much lower than the accepted values by TBEC 2019) is one of the main deficiencies contributing to poor seismic performance of the failed RC structures (Erdik 2001; Yurdakul et al. 2021; RMS 2000). Most of existing RC structures, especially pre-2000, were constructed with on-site prepared concrete mixes without any official control, which resulted in use of improper aggregates (such as smooth and big sizes in Fig. 11d), high water/cement ratios, insufficient curing, and etc. In addition to use of improper aggregates, use of plain bars in pre-2000 RC structures (Fig. 11c) reduces more the interlocking mechanisms between concrete and reinforcement details, resulting in significant bond issues. Moreover, severe corrosion was observed at most industrial buildings, causing cracking and spalling of the concrete cover

Fig. 8 Complete collapse of a precast RC industrial building in Turkoglu, as result of pounding effect

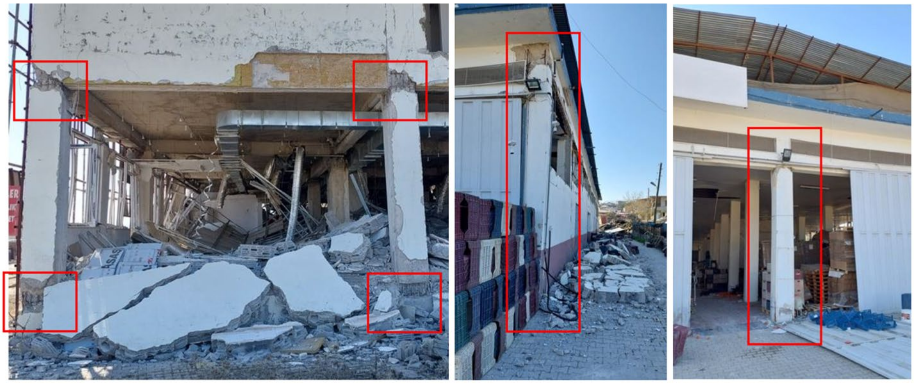


Fig. 9 Severally damaged reinforced concrete facilities with significant lateral drifts and plastic hinges at column ends: in Turkoglu (left) and Antakya (middle and right)

Fig. 10 Several collapsed reinforced concrete facilities at small industrial sites due to weak column-strong beam failures: in Antakya (left) and Iskenderun (right)

and exposing reinforcement (see Fig. 11e). The corrosion in reinforcement causes the bars to lose its layers, usually resulting in loss of reinforcement area and significant reductions in bonding between reinforcement and concrete (Broomfield 2002).

Poor reinforcement detailing was another significant issue observed for RC industrial buildings on the site, including insufficient reinforcement ratio, poor anchorages of reinforcement, and improper confinement of column and beam elements. Figure 11b shows an example of improper column confinement, where spacing of stirrups is up to 25 to 30 cm, significantly reducing the shear capacity of the columns. Another example in Fig. 11a shows lack of confinement or poor confinement at the beam-column joints, resulting in weak connections, therefore preventing to follow strong column-weak beam principles.

In addition, the short column effect was often observed at many inspected facilities. Fig. 12 shows one instance in which the columns near the windows suffered extensive shear fractures. The infill walls under the windows most likely restricted the columns' lateral

Fig. 11 Several failure reasons identified for the inspected RC facilities, such as (a) weak connections due to poor reinforcement detailing, (b) shear failures at the column ends due to large stirrup spacing (20-30 cm), (c) use of plain reinforcement, (d) use of improper aggregates in concrete structural elements, and (e) spalled concrete covers of columns due to severe corrosion

Fig. 12 Short column effects caused by the infill walls for a RC facility in Antakya (built in the 1970s)

displacements, limiting the effective length of the column to window height and increasing its lateral stiffness and therefore shear demands, which resulted in the column shear failures in Fig. 12.

4.2.3 Other structures

A minor percentage (20%) of the inspected industrial building facilities had a steel structural system. Based on this limited field data, the steel facilities visited in the earthquake region do not appear to be severely affected by seismic occurrences, as expected, because steel buildings are typically lighter and have less seismic demands than the ones for RC facilities. Several collapsed steel silos, however, were noticed in the visited industrial zones, where silos are widely used in the agri-food sector and are often constructed with thin-walled steel sections linked together with screws and zinc-plated. Fig. 13 depicts some of the silos inspected in Turkoglu, Kahramanmaras that were demolished by the earthquake. Their failures were most likely due to insufficient anchorage details at the base, which generally resulted in silos toppling and their thin walls bursting.

4.3 Nonstructural performance of industrial structures

The majority of the evaluated buildings had considerable damage to various nonstructural components, such as collapsed or cracked claddings (facades), damaged HVAC and piping systems, fallen ceiling panels, bowed storage racks, and overturned or buckled manufacturing equipment/machinery (see Figs. 14 and 15). Even though there was no substantial structural damage to certain facilities, nonstructural damage decreased their operability capacity, resulting in significant losses.

Most of the visited facilities' claddings (typically autoclaved aerated concrete masonry or hollow clay brick walls) were severely damaged due to failures in-plane and out-of-plane directions, including diagonal cracking within the infill walls, crushing at the corners, and partial or complete collapses. There was little or no connection found between the cladding systems and the structural components, increasing the possibility of partial or entire cladding panel failures.

At the interiorly inspected facilities, production items such as tanks and racks were found to be generally unanchored or laterally unbraced, making them more vulnerable to significant movements under the earthquake accelerations and even colliding with other items or factory walls, therefore increasing the losses. For example, at a recently visited textile company, a thread reel system comprised of multiple reels, each weighing one ton, entirely collapsed, resulting in enormous losses and lengthy business delays.

Fig. 13 Severely damaged or collapsed silos in Turkoglu, Kahramanmaras

Fig. 14 Cladding/facade damages observed at the facilities in Antakya, Turkoglu, and Iskenderun (top, from left to right); and other observed nonstructural building damages such as overturned chimneys in Turkoglu, broken pipelines in Dulkadiroglu, and fallen ceiling panels in Antakya (bottom, from left to right)

Furthermore, overloaded storage racks were detected in a chemical industry in Adana, where several racks badly bowed even at lower magnitudes of seismic accelerations (see Table 5). In addition, pipelines were seen often missing seismic connection details in several of the sites surveyed, causing them to break away from their connections or to slide entirely off the wall attachment. All of these findings indicate that losses may have been greatly minimized if modest but appropriate retrofit procedures (such as anchoring and bracing) had been implemented to decrease the risk of nonstructural seismic damage.

4.4 Functionality of industrial structures

Fig. 16 demonstrates that, while most facilities in Kahramanmaras and Hatay were either partially or completely functional, the sole places with nearly full functionality (FS1) were found to be in Adana, where low PGA values were reported in Table 5.

When the state distributions in Table 6 are compared, the ones for nonstructural damage states and functionality states show a similar increasing trend from none to severe case, indicating a closer relation. Even if some industrial firms had negligible structural damage (SDS1), the relocation of some production equipment as a result of earthquake shaking (NDS2) may necessitate some repair time before they can restart operations. This can also be seen from Fig. 16, where SDS1 and NDS2 contribute the most to partial functionality (FS2) state, with 74% and 37% respectively. This is especially true for textile manufacturers, as seen in Fig. 16, where the textile industry is one of the most affected industry sectors among the visited locations assessed with partial (FS2) or no (FS3) functionality. This is

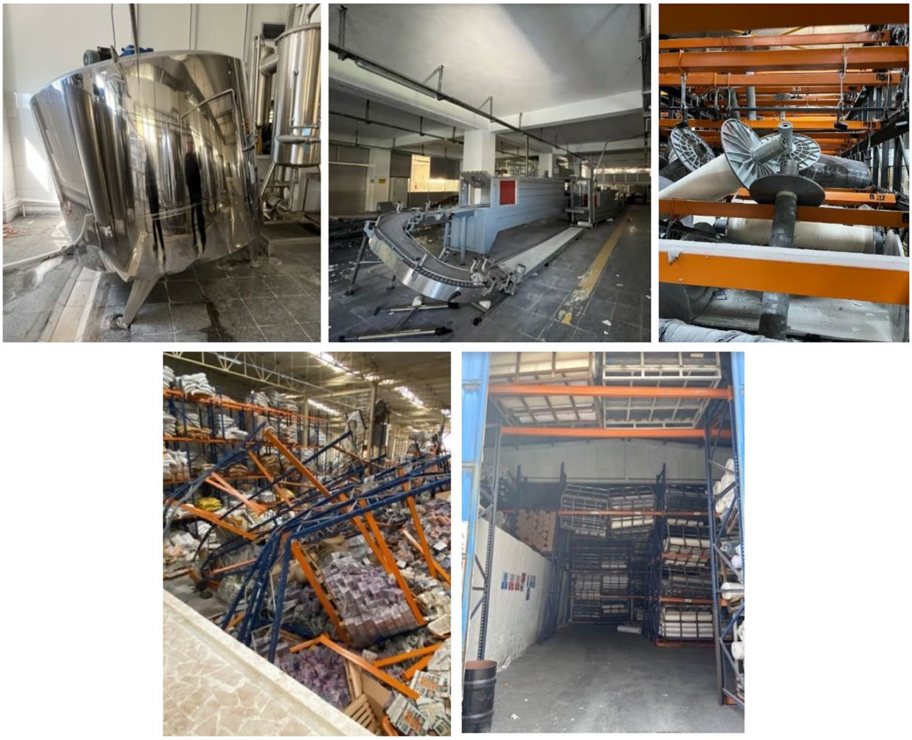


Fig. 15 Tipped over production equipment in a food processing plant in Antakya (top-left and middle); damage on a thread reel system in a textile factory in Dulkadiroglu (top-right); and buckled storage racks in a food depot in Antakya (bottom-left) and in a textile depot in Dulkadiroglu (bottom-right)

explained by the fact that thread machines in the textile industry are more sensitive to shaking and require a time-consuming balancing process to continue production, according to interview notes.

Based on the interview notes, other investigated facilities, such as some of those in Adana and Osmaniye, had to partially stop the work (FS2), although they suffered almost no physical structural or nonstructural damage (SDS1 and NDS1). This was primarily due to staff being unable to come to work on the site. Seismic damage to utility infrastructure was also noted as other reason for business interruptions in the days following the earthquake sequence. During the interviews, Hatay and Kahramanmaras’ utilities systems were reported to be the most severely damaged ones. The power, natural gas, water, and wastewater services were all out of service for 7 to 10 days after the earthquake sequence. Similarly, Osmaniye OIZ had water and power outages owing to major damage in the town of Osmaniye. However, Adana OIZ was not affected by any outages in the lifeline systems and Iskenderun OIZ was not significantly affected in terms of power because their electricity generation was within the OIZ.

Lastly, according to conversations with representatives and inspections, it is expected to take a substantial amount of time for the facilities to recover, ranging from 3 months to 2 years depending on the severity of damage incurred at the sites.

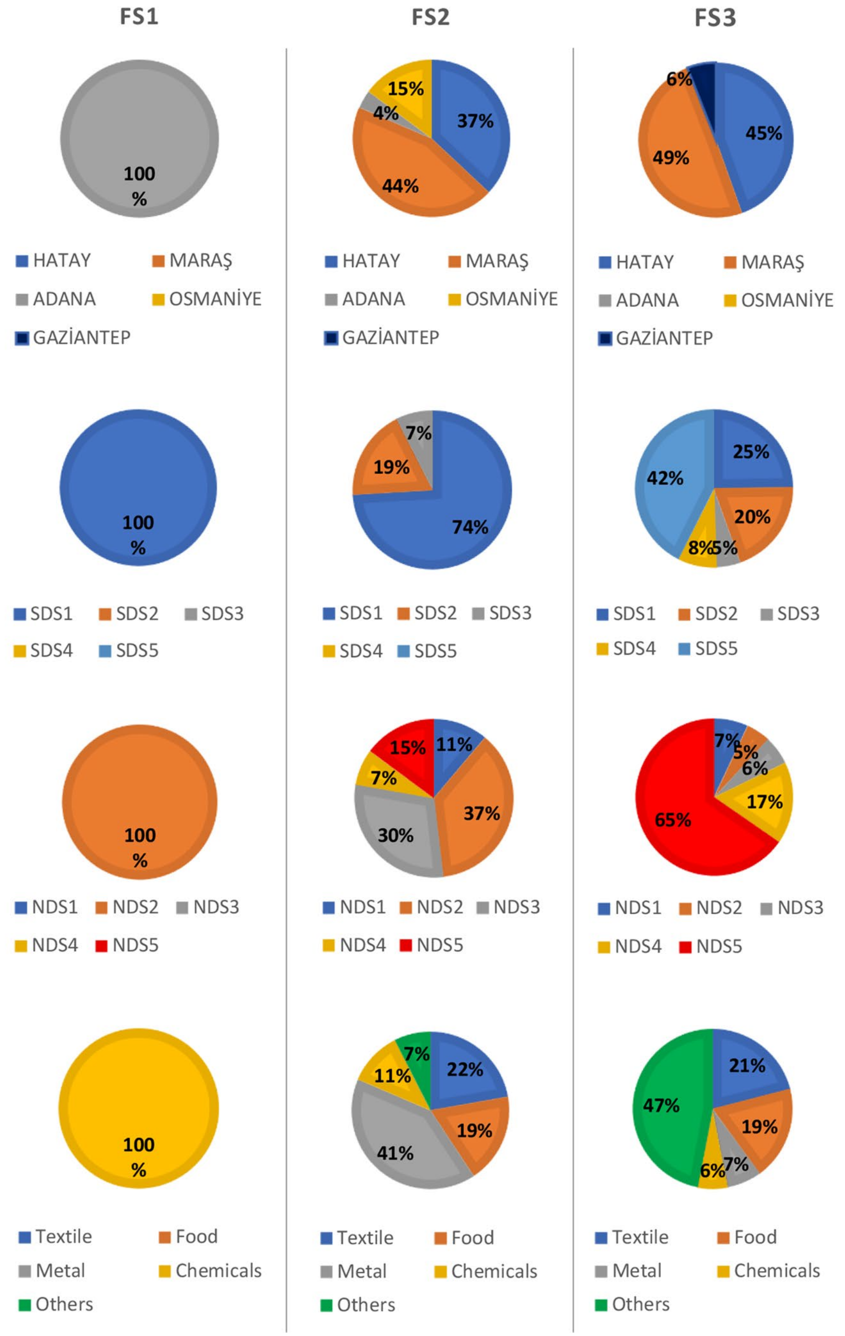


Fig. 16 Distributions of the functionality state levels FS1, FS2 and FS3 for the inspected industrial facilities based on their locations (note that Maras corresponds to Kahramanmaras), structural and nonstructural damage levels (SDS and NDS, respectively), and industrial sectors

4.5 Fires following the earthquakes on industrial structures

The 2023 Kahramanmaras earthquake sequence was also a multi-hazard event, including fires following earthquakes (FFE). The reconnaissance team observed three obvious FFE cases in industrial facilities. The first one is a textile precast-RC framed factory, with an interior steel truss system to carry nonstructural equipment, near Kahramanmaras International Airport. The factory following the FFE incident is seen in Fig. 17 (top), with the majority of the structure destroyed. According to the representative, the source of the incident was a probable spark of an electric arc during the first earthquake, which ignited the paint-based substances inside the facility. The fire lasted for hours and could not be extinguished immediately since water was ineffective in extinguishing the paint-based fire. While all steel components in Fig. 17 (top) seemed to be considerably bowed, precast RC roof components appeared to collapse mostly owing to pin failures at the ends, with some column failures also noted, most likely due to high bending demands at the base. Concrete elements are generally more resistant to fires, until the concrete cover spalls and heat spreads into the reinforcement inside (KCFD 1995; Chen et al. 2004). As a result, this fact shows how the heat was so extreme that it caused the facility to collapse completely under the FFE.

The second FFE example spotted by the reconnaissance team was a textile plant in Turkoglu OIZ, which experienced a similar roof collapse due to the fire that followed the earthquake. Figure 17 (bottom-left) shows the plant with dark-colored burnt building components and panels, which were most likely previously damaged by the earthquake, making them more vulnerable to FFE.

Fig. 17 Incidents of fires following earthquakes observed in Dulkadiroglu (top) and Turkoglu (bottom)

Roof-mounted solar panels have begun to be widely employed as a supplementary source of energy in industrial sites in Turkiye. While the increased mass provided by the panels must be addressed in earthquake design, the possible fire danger of their power storages must also be assessed. The reconnaissance team discovered their third FFE instance in the form of a charred solar panel at an industrial plant in Turkoglu (see Fig. 17-right). The panels were damaged when the roof fell immediately after the earthquake, according to the facility representative, and an ignition started, most likely owing to the battery housed inside the panels. It was stated that the winter storm conditions during that earthquake night kept the fire from spreading further.

5 Conclusions

The 2023 Kahramanmaras earthquake sequence is one of the deadliest and costliest disasters in Turkish history over the previous century, affecting a significant portion of the Turkish industrial economy (Buyuk 2023). Following the earthquake sequence, a reconnaissance team was formed to visit the impacted industrial areas in Adana, Osmaniye, Kahramanmaras (Onikisubat, Dulkadiroglu, Turkoglu), Gaziantep (Nurdagi), and Hatay (Iskenderun, Antakya). During the field study, while 18 semi-structured interviews with industrial owners or representatives were set up to gather general impact information on the visited and nearby industrial facilities, totally 131 performance inspections were conducted to assess both structural and nonstructural damage and functionality of the facilities visited in various industrial sites (OIZ, IS, FS). The proposed data-collection protocols were tested during this field investigation and would support other field studies on assessment of seismic impacts for industrial facilities.

According to data obtained, the ratio of collapsed facilities is particularly significant, accounting for 33% of the total examined 131 facilities, with the majority of them located in Turkoglu, Dulkadiroglu, and Antakya. Inconsistencies between seismic design code standards and building practice are mostly the reason for the poor performance of the assessed facilities. The majority of these facilities were constructed before 2000, but even recently constructed precast RC facilities in organized industrial zones sustained serious damage at the column corbels and roof beam ends due to inadequate pin-supports, and some even collapsed partially or completely due to roof beam rotations from the supports. As a result, facilities built before 2000 and pin-supported frame facilities in earthquake-prone areas are highly advised to be re-evaluated to avoid future earthquake losses and business interruptions.

Nonstructural seismic performance of industrial structures is crucial for assuring these buildings' safety and operation during and after seismic occurrences. Many nonstructural building components (e.g., cladding and pipelines) and equipment/machinery were severely damaged in the majority of the assessed sites. More than half of the facilities (54%) were found to be in a nonstructural collapse state, which indicates partial or entire failures in façade walls, resulting in lengthy downtimes and costly repairs. To secure their equipment, industrial owners should be encouraged to take simple retrofitting steps like anchoring and bracing. Furthermore, while several recent efforts in the literature have been made (Safecladding Project 2015; FEMA P-58-3 2016; Belleri et al. 2017; Perrone et al. 2019; Durukal et al. 2008), additional research on novel yet low-cost and practical solutions for lighter cladding elements with improved fastening mechanisms is required for existing facilities to reduce their seismic damage risk.

The earthquakes had a significant impact on facility’s functionality. According to the inspections, 77% of the facilities were entirely closed and out of operation. According to conversations with representatives and inspections, it will take a substantial amount of time for them to recover, ranging from 3 months to 2 years depending on the damage level sustained at the facilities. As the recovery process takes longer, it will inevitably result in more economic losses and a loss of reputation for the companies. Furthermore, throughout the interviews, some facility owners stated that they had little or no insurance to cover their direct and indirect losses. These findings highlight how vital it is for Turkish facilities to implement adequate mitigation measures in advance, such as a business continuity strategy and sufficient insurance packages.

The data gathered was used to develop empirical fragility models that connect seismic demands to the performance and functionality levels of the inspected facilities. While more research is needed to refine these preliminary models in light of the associated uncertainties (including spatial variability in ground motion recordings), the models and data collected would aid in the main efforts to improve earthquake resilience for Turkish industrial facilities, particularly in developing disaster resilience plans and risk management strategies.

However, there are several limitations to the data that should be addressed before using it in future investigations. First, the gathered data are not evenly dispersed across each visited province. Because the purpose of the field research was to collect as much field data on damage as possible in the short time available on site, the team emphasized inspections on the most devastated provinces, Kahramanmaras and Hatay, accounting for 82% of the building inspections. Second, just one-third of the facilities (37%) were evaluated both internally and externally. While an inside check may produce more precise damage evaluations, the majority of the inspected facilities were inaccessible, necessitating an outside investigation. These limitations may introduce some bias into the models derived from the acquired data, but they are nevertheless relevant and important in enlightening work on seismic risk assessment for industrial facilities. Further research is indeed required to examine the acquired data while keeping these inherent limitations in consideration.

Earthquakes can cause secondary hazards, such as fires, which can result in more deaths and property damage in seismic areas (Meacham 2016; Sekizawa et al. 2003; Scawthorn 1986). These hazard risks should also be examined and taken into account when designing seismic mitigation measures for industrial sites. Also, the findings from the fire incidents that occurred after the earthquake sequence show that nonstructural roof and cladding panels with greater fire insulation qualities are necessary, particularly in combustible sectors. Moreover, commonly utilized roof-mounted solar panels have been shown to be a fire hazard and should be used with caution in industrial establishments. While the added mass given by solar panels must be handled in earthquake design, the potential fire threat of their power storages must also be taken into account.

In conclusion, findings and lessons learned from the 2023 Kahramanmaras earthquakes and recent earthquakes, including 2012 Emilia earthquakes (Liberatore et al. 2013; Belleri et al. 2014) and 1999 Kocaeli earthquake (Erdik 2001), clearly show that improperly designed or constructed industrial facilities, especially precast ones, are significantly more vulnerable. It is very crucial to reliably assess seismic vulnerability of these industrial facilities, as the business continuity of industry plays a vital role in developing or maintaining national economies. This is essential in efforts to support seismic resilience of industrial sectors, especially in the development of relevant business continuity plans, insurance policies, risk management approaches and national building regulations. While findings of this field study can be utilized to support further resilience studies on vulnerabilty assessments, more efforts are indeed needed on collecting, reporting, and analyzing field data as well as developing robust models on seismic impacts for industrial buildings, considering their structural and nonstructural performance and functionality aspects.

Authors' contributions All authors contributed to the study conception, design, methodology and field data collection. Under the supervision of their graduate thesis advisor Dr. Derya Deniz, the three authors Gulsah Sagbas, Ramin Sheikhi Garjan and Kerem Sarikaya organized and processed the collected field data, performed analyses on the data, and prepared materials for the manuscript. All authors supported writing the first draft of the manuscript. The first draft was majorly revised several times by the supervisor Dr. Derya Deniz until the final version was created. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author Dr. Derya Deniz on reasonable request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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