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From Seismic Codes to Disaster Outcomes: Institutional Learning, Enforcement, and Casualty Patterns in Türkiye and Japan

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Abstract

Earthquakes of comparable magnitude can produce markedly different casualty outcomes, indicating that hazard intensity and the formal existence of seismic codes alone do not explain disaster losses. This study examines how seismic regulation, enforcement, retrofit policy, and post-disaster institutional learning shape life-safety outcomes in Türkiye and Japan. Using a structured, focused comparative case design, the analysis traces twelve earthquakes between 1923 and 2024 through legislation, official post-event reports, and peer-reviewed disaster-risk literature. A Code–Loss Institutional Learning Framework is developed to connect event-level damage lessons with subsequent code, inspection, retrofit, land-use, and policy responses, while distinguishing measures directed at new construction from those reaching the existing building stock. The comparison shows that the two countries differ less in the technical sophistication of current seismic provisions than in the consistency of enforcement and the extent to which post-disaster learning is translated into interventions for existing buildings. The 2023 Kahramanmaraş and 2024 Noto Peninsula earthquakes further demonstrate that substantial vulnerability can persist under advanced codes when older building stock remains outside effective assessment and retrofit mechanisms. The findings position seismic codes within a wider disaster-risk-governance system and identify institutional learning, enforcement capacity, and existing-stock coverage as critical conditions for converting regulatory provisions into life safety.

Keywords: Seismic building codes; disaster risk governance; institutional learning; building inspection; seismic retrofit; casualty outcomes

1. Introduction

Earthquakes are major natural hazards, but their consequences are not determined by ground-motion intensity alone. Disaster losses emerge from the interaction of hazard, exposure, and vulnerability, including the quality of the built environment and the institutional capacity to regulate, inspect, and improve it (Blaikie et al. 1994). Seismic safety should therefore be evaluated as the outcome of a wider socio-technical system rather than as a direct product of code provisions alone.

Türkiye and Japan provide a useful comparative setting because both experience recurrent destructive earthquakes but differ in tectonic context, building-stock characteristics, and institutional development. Japan is exposed to subduction, intraplate, and shallow crustal earthquakes as well as secondary hazards such as tsunamis and liquefaction; Türkiye is dominated by shallow continental earthquakes along major strike-slip fault systems. In both countries, however, repeated disasters have made seismic regulation, building inspection, and risk reduction persistent public-policy concerns (Bommer et al. 2002; Matsu'ura 2017).

The contrast became especially visible after the 6 February 2023 Kahramanmaraş earthquake sequence in Türkiye and the 1 January 2024 Noto Peninsula earthquake in Japan. The Kahramanmaraş earthquakes caused 53,537 fatalities in Türkiye and approximately USD 34.2 billion in direct physical damage, whereas the Noto earthquake produced a substantially lower number of direct deaths despite extensive housing damage and multiple cascading hazards (Republic of Türkiye Ministry of Interior 2024; World Bank and GFDRR 2023; Suppasri et al. 2024; Japan Cabinet Office 2026). These events do not constitute directly equivalent hazard tests, but they sharpen a broader question: under what institutional conditions do seismic codes translate into life-safety outcomes?

Recent research in Natural Hazards has documented the persistence of structural vulnerabilities in Türkiye despite successive code improvements. Post-event studies of the 2020–2023 earthquakes identify recurring deficiencies in reinforced-concrete construction and implementation (Tunç et al. 2024), while an interdisciplinary review of soft-storey vulnerability links technical deficiencies to regulatory, architectural, socioeconomic, and construction practices (Morales-Beltran 2025). Other work has moved toward adaptive disaster-risk-reduction frameworks that integrate exposure, sensitivity, and institutional capacity (Gursoy Haksevenler et al. 2025). What remains less developed is a longitudinal comparative account of how documented earthquake damage is converted into code, inspection, retrofit, land-use, or policy responses, and whether those responses reach the existing building stock before the next major event.

This study addresses that gap through a structured comparison of twelve earthquakes in Türkiye and Japan between 1923 and 2024. It makes three contributions. First, it reframes cross-country seismic-code comparison as a disaster-risk-governance problem by separating the technical content of codes from enforcement, inspection, and retrofit capacity. Second, it develops a Code–Loss Institutional Learning Framework that traces how event-level damage lessons are interpreted and translated into institutional responses, including cases in which no event-specific response can be established. Third, it distinguishes responses that affect new construction from those that reach existing buildings, allowing the analysis to identify where the post-disaster learning cycle remains incomplete. The central proposition is

not that codes are unimportant, but that their life-safety effect depends on the institutional mechanisms that carry their provisions into the built environment.

2. Theoretical Framework

A common analytical error in international seismic comparisons is to equate the enactment of a building code with its effect in practice. Vulnerability research shows that hazards become disasters through their interaction with fragile physical, social, and institutional conditions (Blaikie et al. 1994). From this perspective, casualty outcomes are produced by an interconnected system that includes code provisions, construction quality, inspection, retrofit, preparedness, and the capacity to learn from prior events. The relevant analytical question is therefore not simply whether a code exists, but how effectively its safety objectives are implemented across both new and existing building stock.

2.1 Code–Loss Institutional Learning Framework

The proposed Code–Loss Institutional Learning Framework treats post-earthquake learning as a conditional rather than automatic process. Each event produces a damage pattern that institutions interpret through technical investigations, policy debate, and administrative review. That interpretation may generate a code revision, inspection reform, retrofit programme, land-use measure, broader disaster policy, or no identifiable event-specific response. The field effect of any response depends on implementation capacity and, crucially, on whether it reaches vulnerable existing buildings rather than only future construction (Fig. 1). This logic is consistent with policy-learning research showing that disasters can open opportunities for institutional change, but that learning from failure varies with institutional conditions (May 1992; Birkland 2006; O'Donovan 2017).

Fig. 1 Code–Loss Institutional Learning Framework

2.2 Positioning the Framework in Disaster Risk Governance

The framework is aligned with the Sendai Framework for Disaster Risk Reduction 2015–2030, which places building regulation within a wider system of risk understanding, governance, investment in resilience, preparedness, and Build Back Better (UNDRR 2015). This perspective is important because technical requirements can reduce vulnerability only when they are supported by implementation, inspection, and investment mechanisms. Post-disaster reconstruction is therefore treated not merely as restoration, but as an opportunity to reduce inherited vulnerability in the existing building stock.

Analytically, the Sendai priorities map onto the stages of the proposed framework. Damage assessment contributes to understanding risk; code, inspection, and retrofit responses represent governance and resilience investment; and the feedback of event lessons into future practice represents institutional learning. The framework therefore evaluates code evolution together with enforcement, retrofit, and existing-stock coverage rather than treating code revision as the sole indicator of progress. This enables a comparison of why technically advanced regulatory systems can still produce different disaster outcomes when their implementation and learning mechanisms operate differently.

3. Literature Review: Seismic Codes, Vulnerability, and Institutional Capacity

3.1 The Historical and International Development of Earthquake Regulations

To evaluate the development of earthquake regulations in Türkiye and Japan, it is necessary to first look at the international history of the concept. The demand for systematic regulation of earthquake-resistant design increased after the 1906 San Francisco earthquake, which killed between 700 and 3,000 people and caused 9 billion USD in damages in current values. The first seismic code in the United States was the 1927 Uniform Building Code, which was prepared in the aftermath of the 1925 Santa Barbara earthquake. The 1933 Long Beach and 1971 San Fernando earthquakes were incorporated into this regulation by amendments in 1949 and 1973, respectively (Ghosh 2002; Rossberg and Leon 2013).

In the course of the development of regulation destructive events have also occurred in Japan. The first building code was introduced in 1920 as the Urban Building Law; earthquake-related provisions were added in 1924 following the Great Kantō earthquake in 1923, which killed 105,385 people (Ishiyama 2012). Similar processes have been seen in other countries too. Seismic codes were developed in Chile in 1935, in India in 1962, and in the People's Republic of China in 1974 (Fenwick and MacRae 2009; Wang 2008). New Zealand developed NZS 95:1935 in response to the 1931 Hawke's Bay earthquake. These examples illustrate that most of the time, earthquake regulations evolve or are created because of high-casualty events.

3.2 Vulnerability, Exposure, and Loss of Life

Another widely accepted approach in the literature is to explain earthquake-related fatalities not only in terms of the magnitude of the hazard, but also in terms of the vulnerability of the affected community and building stock. Türkiye, Iran and Pakistan as well as India and China are also rated by Crowley and Elliott (2011) as countries with a high exposure to seismic risk. The authors argue that poor planning and insufficient building standards make this risk worse by leading to more severe consequences. Countries that lack adequate or properly enforced building codes (unlike California or Japan) may experience higher casualties from earthquakes of similar size. This view supports the main argument of the

study: earthquake consequences depend not only on the existence of technical standards but also on the extent of their application and enforcement.

The comparative approach of this study is based on the distinction between hazard, exposure and vulnerability. The number of casualties is mainly related to the vulnerability level of the buildings stock. The number of affected populations and structures reflects the magnitude of the event impact. Construction quality, the implementation and enforcement of regulatory provisions and past retrofitting policies shape this vulnerability. Loss models developed for Türkiye also assess insured earthquake damages not only using ground motion parameters but also using the fragility of the building portfolio (Bommer et al. 2002). In this case, the normalized indicators discussed in Section 4.3 can provide a quantitative basis for comparison. But the differences in data definitions and reporting units across countries have prevented the development of a common set of indicators.

3.3 Seismic Source Characteristics and Hazard Profiles

It is not sufficient to account for the seismic differences between Türkiye and Japan as "shallow" or "deep" focused earthquakes alone. Türkiye has shallow continental earthquakes on the North Anatolian and East Anatolian fault systems, whereas Japan has a more complex tectonic setting with subduction zones, intraplate and shallow crustal earthquakes occurring simultaneously. Earthquakes in Japan can also cause secondary hazards such as tsunamis, landslides, fires and liquefaction. The 2024 Noto earthquake produced a tsunami and extensive liquefaction, demonstrating that the country is not characterized by deep-focus earthquakes. Therefore, despite the different source mechanisms for both countries, they have a high level of exposure to seismic hazard.

Different hazard profiles result in different outcomes depending on the nature of the exposed building stock. Shallow and near-fault earthquakes generate strong horizontal and vertical ground motions, which affect the dense mid-rise reinforced concrete building stock in Türkiye. The extent of damage is closely related to the construction quality, structural system characteristics, and detailing adequacy. In Japan, the coexistence of subduction and crustal earthquakes necessitates that building design and disaster management systems address long-duration tremors, short-duration strong impacts, and secondary hazards such as tsunamis and liquefaction together. Therefore, the earthquake results in the two countries should be examined not only based on magnitude and focal depth but also by evaluating the source characteristics and the vulnerability of the affected building stock together.

3.4 Institutional and Societal Preparedness Capacity

Türkiye and Japan differ significantly in terms of their institutional preparedness levels for disasters. Japan has developed long-term plans and preventive policies for the major earthquakes expected along the Nankai Trough; it has created different risk scenarios such as the Tōkai, Tōnankai/Nankai, and Tokyo Inner Region earthquakes. In the country, the design and implementation of seismic-isolated structures are carried out within an institutional framework, with more than half of these structures consisting of residential and office buildings (Pan et al. 2005). In Türkiye, however, the use of methods such as seismic isolation has been more limited due to various reasons, primarily cost. This difference illustrates not only the prevalence of technical solutions but also the extent to which disaster preparedness is integrated in planning and implementation processes.

Social preparedness is a complementary dimension to this institutional capacity. Japan has a nationwide early warning system and regularly conducts drills and disaster education programs. The limited loss of life from the tsunami in the Noto earthquake underscores the value of societal awareness and behavioral preparedness in risk reduction. In Türkiye efforts are being made through AFAD to provide disaster education and enhance first response capacity; the importance of preparing school-age children for disasters is particularly emphasized (Mermer et al. 2018). However, education, early warning, and drills cannot replace the physical improvement of the vulnerable building stock. Therefore, social preparedness is considered not as an independent event-level variable in the study but as a contextual element that shapes the impact of codes, controls, and reinforcement mechanisms.

4. Methodology

The study uses a structured, focused comparative case-study design that combines descriptive indicators, qualitative document analysis, and event-level process tracing. The evidence base consists of legislation, seismic regulations, official post-event reports, government damage assessments, and peer-reviewed field and disaster-risk studies. For each selected earthquake, the analysis reconstructs the pre-event regulatory and inspection regime, identifies documented damage lessons, traces subsequent code, inspection, retrofit, land-use, or policy responses, and assesses whether those responses reached the existing building stock. The two national trajectories are then compared using a common set of variables and coding rules.

OpenAI's ChatGPT was used during manuscript preparation to assist with language refinement and editorial restructuring of author-generated text. The tool was not used as an author or as a substitute for source evaluation, data extraction, event coding, or scientific judgement; responsibility for the manuscript and its claims remains with the authors.

4.1 Case Selection

Three criteria guided case selection. First, an operational threshold of approximately Mw 6.5 was used to retain seismically significant events with documented structural consequences while excluding smaller events; this is a research-design threshold rather than a universal damage threshold. Second, casualty and building-damage information had to be available from official or peer-reviewed sources. Third, each event had to be informative for assessing the performance of the prevailing regulatory regime and/or a subsequent code, inspection, retrofit, land-use, or policy response. Six events from Türkiye and six from Japan between 1923 and 2024 met these criteria. Pre-1980 events were retained in the historical and process-tracing analysis but excluded from denominator-based assessment because reliable exposure and building-stock denominators could not be harmonised.

The Türkiye sample comprises Erzincan (1939), Kocaeli/Gölcük (1999), Van (2011), Elazığ (2020), İzmir (2020), and Kahramanmaraş (2023). The Japan sample comprises Great Kantō (1923), Fukui (1948), Great Hanshin/Kobe (1995), Fukuoka (2005), Tōhoku (2011), and Noto (2024). The purposive sample combines high-impact disasters that reshaped or challenged regulatory regimes with benchmark events that produced relatively low direct losses or tested system resilience. The design is therefore intended for theory-guided comparison and process tracing, not statistical representation of the complete earthquake histories of the two countries.

4.2 Variables and Data Sources

The comparison incorporates event characteristics, casualty and damage outcomes, the seismic code in force, post-event institutional responses, inspection and retrofit capacity, response delay, access to the existing building stock, and evidence of institutional learning. These variables extend the analysis beyond magnitude and loss counts to the mechanisms through which technical provisions are implemented. Table 1 defines each variable and identifies its principal data sources.

Table 1 Variables, operational definitions, and principal data sources

Earthquake magnitudes are given in moment magnitude (Mw) when possible. In cases where there is an institution-specific scale, such as the Japan Meteorological Agency magnitude, the difference is clearly indicated. The JMA magnitude and Mw are not the same measurement system. Therefore, "similar magnitude" events have been considered not as exact equivalents but as indicators providing a general comparison.

4.3 Indicator Selection and Comparability Limitations

In the construction of the dataset three normalized indicators were assessed: deaths per 1,000 heavily damaged or destroyed buildings, deaths per million people directly affected and rate of severe damage. The use of different units and classifications to report damage by countries has meant that these indicators could not be applied to a common comparative dataset. Moreover, reliable denominator data could only be obtained for a limited number of events. Rather than calculate direct ratios in Section 7.2, an explorative and descriptive assessment was made to highlight differences in data, scope and units that limit comparability.

The denominators that can be used in the indicator calculations also contain significant uncertainties. "The examined building stock" can be considered an indicator representing the total exposed building stock; however, the number of buildings examined after the event depends on the scope of the damage assessment studies and the level of access. Therefore, it may under-represent or over-represent the actual building stock. Similarly, the value of the "directly affected population" also varies depending on how the official disaster area is defined. These variables were not used in this study to produce cross-country comparative results; instead, they were considered analytical indicators that could be evaluated if harmonised data are provided in the future.

4.4 Event-Level Process Tracing and Coding Protocol

The unit of process tracing is the individual earthquake event. Each case is examined according to the code and inspection regime in force before the event, documented damage lessons, subsequent code responses, inspection or retrofit responses, response delay, the extent to which measures reached existing buildings, and the strength of evidence for an institutional learning link. Code change, inspection reform, and retrofit policy are coded separately so that the absence of a technical code revision is not treated as evidence that no institutional response occurred.

Coding categories were defined before the comparative interpretation. Response delay is classified as short (0–3 years), medium (4–7 years), or long (8 years or more). When no regulatory or institutional response can be directly linked to an event, the case is coded as “no response”; when the policy process remained open at the study reference date, it is coded as “ongoing.”

Access to the existing building stock is coded as none, low, partial, or extensive. “Not applicable” is used when no event-specific institutional response is identified, and “not evaluated” when documentary evidence is insufficient or the response primarily addresses a non-structural hazard. Learning evidence is coded as clear, limited, undetermined, or ongoing. A clear link requires primary documentation or reliable historical and academic evidence connecting the event to a subsequent regulatory or policy response; limited evidence indicates an indirect or mainly chronological relationship.

Primary evidence consists of laws, regulations, government reports, and official post-event assessments. Peer-reviewed field studies and institutional reports are used as supporting evidence. Where original regulatory documents for historical events are unavailable, credible historical or academic sources are used to establish the chronology and documented relationship between an event and a response. The evidence supporting each coding decision is reported in Tables 8 and 9.

Where a direct relationship between an earthquake and a subsequent measure cannot be documented, the analysis reports chronological proximity without inferring causation. Conflicting casualty and damage figures are retained in the original classifications and reporting units of their sources, and cross-event ratios are not calculated from non-harmonised denominators. The coding was conducted by the first author; the second author reviewed the coding matrix and document matches for methodological consistency, with disputed interpretations checked against the underlying sources.

5. Case 1: Türkiye

5.1 Seismic Context

Türkiye is located on the Alp-Himalaya seismic belt, which is one of the major earthquake zones in the world. The Anatolian plate is surrounded by the Eurasian plate in the north, the African and Arabian plates in the south, the Eastern Anatolia block in the east and the Aegean block in the west. This tectonic structure brings a large part of the country's territory under the earthquake risk. The historically destructive events have occurred mainly on the North Anatolian and East Anatolian fault lines as well as the local faults in the Aegean Region (Bikçe 2015). This danger requires all planning areas including emergency medicine to take into consideration earthquake risk as a basic variable (Gündüz et al. 2013). The increasing detail in the earthquake regulations of Türkiye over time should also be evaluated considering this constant danger.

One of the most remarkable phenomena in the recent earthquake history of Türkiye is the series of significant earthquakes that started with the 1939 Erzincan earthquake along the North Anatolian Fault and propagated westward. The 1999 Kocaeli and Düzce earthquakes brought the process to the Marmara Region, once again bringing the issue of earthquake hazard in Istanbul and its surroundings to the forefront. The 2023 Kahramanmaraş earthquakes broke a large part of the East Anatolian Fault that had been relatively inactive before. The developments on both fault systems suggest that the densely populated areas and the built environment are continuously exposed to known earthquake sources. Therefore, in an effort to reduce future losses, it is necessary to not only monitor seismic hazards, but also to systematically evaluate, inspect and strengthen the existing building stock.

5.2 Major Earthquakes and Loss of Life

In the recent earthquake history of Türkiye, there were many devastating events in different regions, which caused great loss of life and property. One of the starting points of this process was the Mw 7.9 magnitude 1939 Erzincan earthquake, which resulted in the deaths of about 33,000 people, with 100,000 injured and more than 116,000 houses damaged or destroyed. The Varto and Lice earthquakes between 1966 and 1975 caused some 2,400 deaths. The Kocaeli/Gölcük earthquake of 1999 was among the country's most serious disasters, with 17,479 casualties and more than 244,000 damaged buildings. Even the 2003 Bingöl and 2011 Van earthquakes, which were limited to a relatively smaller area, indicated that the present building stock is not without vulnerabilities. When these events are considered together, it is observed that heavy losses were repeated particularly in the Eastern Anatolia and Marmara regions, and that the structural damage is related not only to the magnitude of the earthquake but also to the quality of the building stock and the conditions of supervision (Table 2).

Table 2 Major earthquakes in Türkiye: deaths, injuries, and building damage (Bikçe 2015; Ambraseys and Zátopek 1968; Mitchell 1976; Koç 2016; Kalafat et al. 2003; Nurlu 2012)

The number of structures damaged and destroyed in the events listed in Table 2 far exceeds the number of casualties. While this data cannot be used to produce a direct ratio, it shows that old and substandard building stock can increase losses in moderate to large magnitude earthquakes. A similar pattern was observed in the 2020 Elazığ and İzmir earthquakes, as well as the 2023 Kahramanmaraş earthquake.

5.3 The Evolution of Earthquake Regulations

Following the 1939 Erzincan earthquake, post-disaster relief and technical construction regulations in Türkiye began to develop as two distinct areas of legislation. Assistance, resettlement, land, and material support for earthquake-affected populations were regulated by Law No. 3773, while technical provisions for seismic design were developed through separate regulations and directives (Law No. 3773, 1940; Soyluk and Harmankaya 2012). This process was followed by technical regulations in 1947, 1953, 1961, 1968, 1975, 1998, 2007, and 2018 (Soyluk and Harmankaya 2012; Regulation on Buildings to be Constructed in Earthquake Zones 2007; TBDY 2018). Since post-disaster relief legislation and seismic design regulations serve different purposes and application areas, they are treated as two separate regulatory layers in the study. However, the growth of technical provisions over time does not mean that implementation and enforcement have improved as much. This relationship is examined through building inspection and retrofit policies in the following sections.

Fig. 2 The development of earthquake regulations in Türkiye between 1940 and 2018 and the earthquakes associated with them in the timeline

Table 3 Main provisions and historical context of earthquake regulations in Türkiye (compiled from Soyluk and Harmankaya 2012; Regulation on Buildings to be Constructed in Earthquake Zones 2007; TBDY 2018)

Regulatory development in Türkiye has not followed regular and uninterrupted progress. The first comprehensive revision was made eight years after the Erzincan earthquake, quantitative calculation provisions were developed in 1953, and seismic zoning and reinforced concrete rules were strengthened in the 1975 regulation. But between 1975 and 1998 there was no significant change. For more than two decades, from 1975 to 1998, no major revision was introduced. The 1998 revision came into effect only a year before the Kocaeli and Düzce earthquakes; no new technical code was prepared immediately after these events. The 2007 regulation introduced performance-based methods for the evaluation and strengthening of existing buildings. The 2018 regulation, which is still in effect, was published seven years after the Van earthquake. The Elazığ, İzmir, and especially Kahramanmaraş earthquakes have reopened the discussion on the implementation of current regulations in the field.

5.4 Major Earthquakes and Their Effects After 2020

In 2020, Türkiye was affected by two major earthquakes. The Mw 6.8 Elazığ-Sivrice earthquake affected Elazığ and Sivrice in eastern Türkiye as well as Kale, Pütürge and Doğanyol in the Malatya Province on 24 January. The earthquake caused 41 casualties and around 1,600 injuries. The main shock was followed by 23 aftershocks in the range of 4.0–5.1 (Mertol et al. 2020). On October 30 of the same year, in the Mw 6.9–7.0 magnitude İzmir earthquake, 117 people lost their lives, and 1,034 people were injured. Casualties were concentrated in a limited number of soft-story reinforced concrete buildings built before 2000 in Bayraklı and Bornova (Deniz et al. 2020). In the earthquake zoning map in effect before 2018, Elazığ and İzmir were classified under high earthquake hazard. In the current approach, seismic hazard is defined through site-specific spectral acceleration parameters instead of regional classifications. Therefore, the losses incurred in both earthquakes are more related to the vulnerabilities in the existing building stock and the deficiencies in implementation rather than the absence of an up-to-date regulation.

On February 6, 2023, two earthquakes with magnitudes Mw 7.8 and Mw 7.5 centered in the districts of Pazarcık and Elbistan in Kahramanmaraş occurred nine hours apart, and a state of emergency was declared in eleven provinces. According to the official update, 53,537 people lost their lives in Türkiye, the total death toll in Türkiye and Syria reached approximately 60,000, and the number of injured exceeded 107,000 (Republic of Türkiye Ministry of Interior 2024). This series of earthquakes has been the deadliest earthquake disaster in the history of the Republic and the world in 2023. The World Bank has estimated the direct physical damage to be approximately 34.2 billion USD. This figure equates to around 4% of Türkiye's GDP in 2021 and the costs of recovery and reconstruction are expected to be much higher (World Bank and GFDRR 2023).

Field surveys indicate that the losses incurred during the 2023 Kahramanmaraş earthquakes cannot be explained solely by the content of technical regulations; the main issue lies in the gap between code provisions and the characteristics and application conditions of the existing building stock. Among the most frequently observed collapse mechanisms are soft story irregularities in commercial ground floors, weak column-strong beam behavior, insufficient transverse reinforcement and confinement, low concrete quality, and the short column effect, as well as plan and vertical irregularities (AFAD 2023). Subsequent peer-reviewed field studies have also supported these findings and revealed that some post-2000 buildings collapsed with similar mechanisms (Avğın et al. 2024; Ulutaş 2024; Tan et al. 2025; Aras et al. 2025). Hazardous conditions such as liquefaction, near-fault effects, and high vertical acceleration observed in Gölbaşı have exacerbated the aforementioned structural defects. The extensive pre-2000 building stock that has not undergone systematic assessment and effective inspection, the legalization of unlicensed structures, and the zoning amnesties that have legitimized incompatible buildings have also deepened the vulnerabilities in the implementation and inspection chain. Therefore, the scale of loss in 2023 is more related to the insufficient transfer of existing provisions to building production and the retrofitting of the existing building stock than the absence of an up-to-date earthquake regulation. The main collapse mechanisms are schematically shown in Fig. 3.

Fig. 3 Main structural failure mechanisms repeated in the 2023 Kahramanmaraş earthquakes: (a) soft story, (b) weak column–strong beam behavior, (c) insufficient confinement and low concrete quality, (d) short column effect, (e) vertical irregularity, and (f) bending due to liquefaction (schematic representation based on failure mechanisms reported in AFAD 2023)

6. Case 2: Japan

6.1 Seismic Context

Situated in the northwestern Pacific Ocean, Japan is located on the Pacific Ring of Fire, an active boundary where four lithospheric plates converge (Ishibashi 2004). This makes the country prone to high seismic activity and keeps the threat of tsunamis on the agenda constantly along with earthquakes. The archipelago is also subject to other natural hazards such as volcanic eruptions, typhoons and floods, which also put it in danger. The risk of disaster is increased by active faults beneath large cities and dense settlements in coastal plains. Therefore, in a comparison of Japan and Türkiye, we

should consider the frequency of earthquakes, as well as the institutional capacity that has been developed to counteract various hazards.

The main sources of earthquakes in Japan are the Nankai Trough, the Japan Trench and many shallow crustal faults underlying the islands. The Nankai and Japan Trenches are subduction zones that produce large interplate earthquakes and tsunamis, while shallow crustal faults produce more localized but intense tremors. Examples of this variety are the 1923 Great Kantō 2011 Tōhoku and 2024 Noto earthquakes. These are associated with a plate-boundary earthquake along the Sagami Trough, a megathrust tsunami-generating earthquake and a tsunami-generating shallow crustal earthquake. This structure has forced Japan to see earthquakes as a structural design problem and to build tsunami planning and land use regulation into the system. The abundance of hazards and the intensity of exposure in coastal plains have kept disaster management on the national agenda.

6.2 Major Earthquakes and Loss of Life

Major earthquakes at different times in the modern earthquake history of Japan have resulted in heavy loss of life and property. The 1923 Great Kantō earthquake killed 105,385 people and damaged or destroyed about 700,000 buildings. The 1948 Fukui earthquake, which killed 3,895 people and damaged more than 51,000 buildings, was one of the most serious disasters of the post-war period. The 1968 Tokachi-Oki and 1978 Miyagi-ken earthquakes resulted in 52 and 28 casualties, respectively, but the structural damages observed in these events provided valuable lessons for subsequent regulatory adjustments. The loss of 6,434 lives in the 1995 Great Hanshin/Kobe earthquake demonstrated the continued impact of the pre-1981 building stock, fires and infrastructure vulnerabilities. It is shown that the magnitude of the earthquake does not fully account for its destructiveness, as exemplified by the 2005 Fukuoka earthquake of comparable size that was reported to have caused only one death. When these events are viewed collectively, the long-term fatality pattern in Japan is generally decreasing, but the old building stock and secondary hazards can break this trend.

Table 4 Historical earthquake examples and data on death, injury, and building damage in Japan that contextualize the development of regulations (compiled from Ellingwood and Brady 1980; Otani 2000; Ishiyama 2011; Yoshimi 1970; Chung 1996)

6.3 The Evolution of Earthquake Regulations

Fig. 4 The evolution of earthquake regulations in Japan from 1920–2013 and the associated earthquakes in the timeline

Table 5 Main provisions of earthquake regulations in Japan and their historical context (compiled from Otani 2000; Ranghieri and Ishiwatari 2014)

Two aspects of Japan's regulatory development are noteworthy First, the relatively short time span for a large number of high-impact events has resulted in documented regulatory or institutional responses. Three years after the Tokachi-Oki earthquake, provisions regarding shear reinforcement and reinforced concrete foundations were changed; immediately after Kobe, strengthening legislation targeting pre-1981 stock was enacted. However, this pattern does not hold for every event. No code change related to the earthquake was identified after Fukuoka, and the institutional response regarding Noto has not been completed as of the reference date. Secondly, the long-term mortality pattern in the selected comparable events is generally downward. The difference between the thousands of deaths in Fukui and the single casualty in Fukuoka is consistent with the cumulative development of code, control, reinforcement, and preparedness capacity.

6.4 Tohoku (2011) and Noto (2024): Limits of Institutional Capacity

The 2011 Tohoku earthquake (Mw 9.0–9.1) was the largest earthquake recorded in Japan and one of the largest worldwide since 1900. The resulting tsunami reached approximately 40 m in some areas and caused severe damage at the Fukushima Daiichi Nuclear Power Plant. Official police data recorded 15,899 deaths and 2,526 missing persons as of March 10, 2021, with the overwhelming majority of identified deaths attributable to drowning caused by the tsunami (National Police Agency of Japan 2021). This illustrates that, despite extensive preparedness and relatively good seismic performance of many structures, the prevailing hazard surpassed existing risk assumptions and protective measures. The Tohoku earthquake therefore shows that modeling, design, and preparedness can reduce risk but cannot eliminate uncertainty.

The Noto Peninsula earthquake (Mw 7.5–7.6) on 1 January 2024 triggered a cascade of interconnected hazards such as crustal uplift, liquefaction, landslides, fires and tsunamis. Official data as of 31 March 2026 recorded 720 deaths, comprising 228 direct deaths and 492 indirect deaths associated with the disaster. Approximately 165,813 houses were damaged (6,536 were totally destroyed and 23,707 were partially destroyed). The maximum number of evacuees reached around 34,000 (Suppasri et al. 2024; Japan Cabinet Office 2026). The relatively low number of direct tsunami deaths, only two, demonstrates the role of societal tsunami awareness and evacuation practices. Conversely, building collapses and post-disaster problems such as the severe winter, lack of shelter, and hypothermia accounted for a large share of the losses. The number of disaster-related deaths is still increasing as per the assessment processes and the figures provided are not the final total but the situation as at the date of reference specified.

The Noto earthquake demonstrates that major vulnerabilities can remain in a system with advanced disaster management, inspection, and institutional learning mechanisms, if these mechanisms are not sufficiently extended to the existing

building stock. There was a sophisticated regime of regulation, but the loss of life was due to, among other things, pre-1981 rural housing, an aging population, the geographic isolation of settlements and harsh winter conditions. The finding suggests that the comparison between Türkiye and Japan is not a simple story of success versus failure. When both events are taken into account, the outcome of disasters is determined not only by regulatory provisions but also by the cumulative effects of the inspection capacity, the strengthening of the existing building stock, the preparedness of the society and the post-disaster response conditions.

7. Comparative Analysis

7.1 Institutional Learning and Casualty Patterns After Disaster

Table 6 and Fig. 5, together, show two major patterns. Firstly, countries vary in how and how fast lessons learned from disasters are converted into institutional responses. Japan has had a large share of high impact earthquakes that have resulted in regulatory responses in the form of regulations, inspections, reinforcement or disaster policy in a relatively short period. A good example of this process is the Law on Promoting Seismic Retrofitting of Buildings, enacted after the Kobe earthquake. However, not all earthquakes have resulted in a regulatory change. Since the earthquake, there has been no code response that can be clearly linked to the Fukuoka earthquake, and the institutional evaluation and regulatory process regarding the Noto earthquake has not yet been completed. In Türkiye, earthquake regulations have been developed over time; however, the transfer of lessons learned from events to inspection, implementation and the strengthening of the existing building stock has been limited and inconsistent.

Secondly, when casualties are evaluated in conjunction with earthquake magnitude, predominant hazard type, and the characteristics of the exposed building stock, it is observed that the long-term trend in the selected events for Japan is generally decreasing. However, this trend is not linear. The Tohoku earthquake's tsunami becoming the dominant cause of death, and in Kobe, the pre-1981 building stock, fires, and infrastructure damage increasing casualties, constitute the main deviations from this general pattern. The Turkish examples do not show a similarly consistent reduction in casualties. However, since the events were not randomly selected, these findings should be considered as exploratory patterns determined through the selected cases rather than as a statistical trend.

Fig. 5 Fatalities in selected major earthquakes (logarithmic scale)

In Fig. 5, the magnitudes of the events are labeled, and different symbols are used to represent the dominant types of hazards. The lack of connecting the points indicates that the figure presents a comparison between selected events rather than a time series. In Table 6, earthquakes are compared based on magnitude, dominant hazard, loss of life, structural damage, prevailing regulations, and post-event institutional responses. Due to the reporting of damage data in different units such as buildings, residences, and independent sections, the evaluation has been kept at a descriptive level, and direct ratios between events have not been calculated. Unless otherwise specified, magnitudes are in Mw; Noto data reflect the situation as of March 31, 2026.

Table 6 Comparison of major earthquakes in Türkiye and Japan based on common variables (Suppasri et al. 2024; Japan Cabinet Office 2026; National Police Agency of Japan 2021; World Bank and GFDRR 2023; Republic of Türkiye Ministry of Interior 2024)

This comparison shows that how regulations are implemented is more decisive than the date they come into effect. Although some regulations in Türkiye came into effect shortly before major earthquakes, the inadequacy of inspection and reinforcement mechanisms limited the expected safety level of the technical provisions in the building stock. In Japan, however, many regulations were developed after examining the causes of earthquakes and damage patterns; they were supported by inspection, certification, and reinforcement tools. According to Teshigawara (2012), this approach is based on a two-stage seismic design: The first stage focuses on ensuring safety and reparability during moderate ground motions, while the second stage seeks to prevent collapse during severe shaking. However, the impact of technical regulations is also influenced by the extent to which communities are involved in disaster management processes. Özerdem and Jacoby (2006) point out that considering the population as a passive victim instead of an active component in decision-making processes can increase disaster loss

7.2 Structural Damage, Collapse Mechanisms, and Casualty Patterns

There are immediate comparisons that can be made with normalized indicators relating deaths to the stock of damaged buildings. However, two fundamental issues prevent the establishment of a definitive international ratio. First, national systems do not use the same damage unit. In Türkiye, ministry assessments count independent units, in Japan, housing statistics count houses, and some structural surveys count buildings. Therefore, the death rate per building will be based on unequal denominators (Table 7). The second issue is the difference in the predominant type of hazard. The majority of the casualties in Tohoku were caused by the tsunami, not by building collapses. For these reasons, the comparison has been kept at a qualitative and exploratory level, and an inter-country fatality rate has not been calculated

Table 7 Fatalities and reported structural damage values in recent events

Table 7 presents the fatalities in recent events along with the reported structural damage data. Damage values have been preserved in their original units from the sources. Since the numbers of buildings, residences, and independent units are

not equivalent, the comparison has been kept at a descriptive level, and the death rate per building has not been calculated. The study acknowledges that the tsunami caused a significant portion of the casualties in the Tohoku earthquake. In the Noto earthquake, however, only direct deaths were used in the comparison associated with structural damage, and deaths related to post-disaster shelter and health conditions were evaluated separately.

As damage units cannot be standardized, the study does not calculate relative lethality per unit of damage. The comparison is rather based on documented differences in collapse mode, construction quality, ductility and post-collapse survival probability. In Kahramanmaraş, the almost simultaneous collapse of substandard mid-rise reinforced concrete buildings, which were brittle, reduced the chances of escape and rescue. However, the Japanese examples showed that the patterns of damage and collapse varied with the predominant hazard of the event and the building stock affected. The findings suggest that the results of casualties depend not only on the presence of regulations but also on the institutional interpretation, implementation, construction quality, ductility and access to the existing stock.

7.3 The Reflection of Regulatory Provisions in Practice and Institutional Responses at the Event Level

The comparison shows that the key difference lies not in the technical content of the current rules but in the ability to enforce and reinforce them so as to bring about the provisions. Regulations establish the necessary safety level. The extent to which this safety is achieved in the built environment is determined by licensing, independent control, design and supervision of construction, and the assessment and retrofitting of existing structures. Zoning amnesties and implementation gaps might blunt this transfer. Therefore, in the study the development of regulations and the capacity for supervision were considered as separate variables. The casualty values in Table 6 were not considered as criteria indicating the independent effect of the regulations, but were evaluated together with the current regulations, supervision conditions, predominant hazard type and the characteristics of the building stock.

This difference can be more clearly observed through the institutional mechanisms in the countries. In Japan, mandatory certification, oversight during the construction process, and legal regulations aimed at strengthening the pre-1981 building stock support the implementation of technical provisions. In Türkiye, however, zoning amnesties, deficiencies in independent control and design supervision, and the extensive pre-2000 building stock that has not been evaluated according to current requirements have limited this transfer. The post-2023 damage assessment, reconstruction and inspection efforts are important institutional initiatives but do not yet constitute a completed national strengthening system that includes the entire existing building stock.

To examine this assessment at the event level, the process tracing protocol defined in Section 4.4 has been applied separately to each of the twelve earthquakes (Tables 8 and 9). The separate columns for code response, control, and reinforcement response prevent the regulations in effect before the event from being interpreted as a result of post-event organizational learning. The analysis was conducted qualitatively, and instead of numerical scores in each cell, process evaluations based on documentary evidence were included.

The event-level findings reveal three fundamental patterns. Some earthquakes have led to regulatory responses that are clearly documented and developed relatively quickly. In some cases, instead of a direct regulatory change, regulations in the areas of inspection, reinforcement, land use, or disaster policy have come to the forefront. In some other incidents, however, a clear and event-specific learning relationship between the earthquake and the subsequent institutional response could not be identified. These differences indicate that institutional learning after a disaster does not occur automatically; it depends on how the event is interpreted, the existing institutional capacity, and the level of implementation of the decisions made. Therefore, in terms of reducing losses, it seems more decisive to effectively implement existing provisions, strengthen building inspections, and systematically improve the current building stock, rather than revising new regulations.

Table 8 Event-level institutional learning analysis of selected earthquakes in Türkiye

Table 9 Event-level institutional learning analysis of selected earthquakes in Japan

In Tables 8 and 9, the pre-event regime and the post-event response are displayed in separate columns. Thus, measures have been taken to prevent the previously existing regulations from being interpreted in the same way as the response produced by the examined earthquake. The matrix also shows that the lesson learned from damage does not always translate into a technical code change. Depending on the institutional interpretation, the response can develop in the form of an audit, reinforcement, land use, policy review, or non-response.

Table 10 Key governance, inspection, and retrofit milestones beyond design codes

When the design code chronologies in Tables 3 and 5 are considered together with the governance and control steps in Table 10, the fundamental difference between the two countries becomes clearer. The difference lies not so much in the date the codes were published, but in when and to what extent the inspection and retrofit mechanisms that implement these codes in the existing building stock were established.

8. Discussion

The comparison indicates that seismic codes are necessary but insufficient conditions for life safety. In Türkiye, successive improvements in technical provisions have coexisted with uneven enforcement, incomplete inspection coverage, recurrent construction-quality problems, and a large pre-2000 building stock that has not been systematically assessed or retrofitted. In Japan, technical provisions are more consistently embedded in certification, inspection, and construction practice for newer buildings, but the Noto earthquake demonstrates that significant vulnerability can persist when retrofit policies do not fully reach older rural housing. The central difference is therefore not simply the sophistication or date of a code, but the institutional capacity to translate safety requirements into both current building production and the existing stock.

This interpretation is consistent with recent Natural Hazards research on Türkiye. Post-event observations from the 2020–2023 earthquakes document repeated reinforced-concrete deficiencies and the continuing importance of implementation and construction quality (Tunç et al. 2024). The persistence of soft-storey vulnerability has likewise been linked to regulatory, architectural, economic, and social conditions rather than to a purely technical design problem (Morales-Beltran 2025). The present study extends these findings longitudinally and comparatively: rather than examining a single vulnerability or earthquake sequence, it traces whether damage lessons are converted into institutional responses and whether those responses reach the stock exposed to subsequent events.

The Code–Loss Institutional Learning Framework also extends vulnerability analysis by specifying mechanisms through which vulnerability can be reproduced or reduced. Established disaster research shows that casualties are shaped by social and structural vulnerability as well as hazard intensity (Blaikie et al. 1994; Crowley and Elliott 2011). Here, those vulnerabilities are connected to licensing, inspection, construction control, retrofit policy, and the speed with which post-disaster lessons are transferred into practice. This mechanism-based view complements adaptive risk-reduction approaches that integrate exposure, sensitivity, and adaptive capacity (Gursoy Haksevenler et al. 2025), while placing particular emphasis on the institutional treatment of existing buildings.

The event-level matrices further show that institutional learning is neither automatic nor synonymous with code revision. Some events were followed by clearly documented and relatively rapid responses, as in Erzincan, Fukui, and Kobe. In other cases, institutional change occurred through inspection, retrofit, land-use, or disaster-policy measures rather than a new seismic code. For Fukuoka, Elazığ, and İzmir, the analysis could not establish a direct event-specific learning relationship from the available evidence. This variation is consistent with policy-learning research, which treats learning after failure as contingent on institutional interpretation, capacity, and implementation rather than as an inevitable consequence of disaster (May 1992; Birkland 2006; O'Donovan 2017).

The existing building stock emerges as the principal bottleneck in both national trajectories. Japan's post-Kobe retrofit legislation illustrates a direct attempt to extend learning to pre-1981 buildings, whereas Türkiye's post-1999 and post-2023 measures have combined inspection reform, urban transformation, reconstruction, and damage assessment without yet producing a fully comprehensive national retrofit system for vulnerable existing buildings. Noto is an important counter-case because it prevents the comparison from becoming a simple success–failure narrative: even a high-capacity system remains exposed where aging housing, demographic vulnerability, geographic isolation, and post-disaster conditions exceed the reach of existing measures.

The study also demonstrates why simple normalized fatality indicators must be used cautiously in international comparison. Damage classifications differ across buildings, dwellings, and independent units, while the dominant casualty mechanism varies substantially between events. Tōhoku, for example, was dominated by tsunami mortality rather than structural collapse. Without harmonised denominators and hazard-specific attribution, ratios such as deaths per destroyed building can create a false impression of precision. The present analysis therefore treats the available quantitative indicators as descriptive context rather than as causal estimates.

Several limitations follow from the research design. The twelve earthquakes were purposively selected to examine regulatory regimes and institutional responses; they do not constitute a random or statistically representative sample. Reliable exposure and building-stock denominators were unavailable for several historical events, and inspection and retrofit capacity could not be measured through a single quantitative indicator. The study therefore identifies documented mechanisms and comparative patterns but does not estimate the independent causal effect of enforcement, retrofit, or institutional learning on mortality.

Future research should pursue two extensions. First, harmonised event-level datasets are needed for exposure, building stock, damage categories, direct and disaster-related deaths, inspection coverage, and retrofit penetration. Second, the framework should be tested in additional seismic countries to determine whether the observed relationships between post-disaster learning, enforcement, existing-stock coverage, and casualty outcomes are transferable beyond the Türkiye–Japan comparison.

9. Conclusions and Policy Implications

The study shows that seismic safety depends on more than the technical sophistication of building codes. Across the selected events, the life-safety contribution of regulation is mediated by enforcement, inspection, construction quality, retrofit policy, and the institutional capacity to convert post-disaster evidence into action. Japan and Türkiye have both progressively strengthened their seismic provisions, but they differ in the consistency with which those provisions have been connected to inspection and existing-stock interventions.

The comparative evidence also rejects a simple narrative in which Japan represents success and Türkiye failure. Japan's post-Kobe experience demonstrates the value of linking damage lessons to retrofit legislation and inspection, yet the 2024 Noto earthquake shows that older rural housing, population aging, geographic isolation, and post-disaster shelter conditions can preserve substantial vulnerability. In Türkiye, the 2023 Kahramanmaraş earthquakes demonstrate that technically current regulations cannot compensate for persistent implementation gaps, vulnerable pre-2000 construction, insufficient retrofit coverage, and policies that weaken regulatory enforcement.

Three policy implications follow. First, code revision should be accompanied by transparent licensing, independent design and construction inspection, and mechanisms that verify compliance in practice. Second, seismic-risk policy should place the existing building stock at the centre of risk reduction through prioritized assessment and financially feasible retrofit programmes, with mandatory intervention where risk thresholds justify it. Third, post-disaster reviews should explicitly document how observed damage mechanisms are translated into code, inspection, retrofit, land-use, or preparedness measures and should track whether these measures are implemented before the next major event.

Comparative learning also requires better data governance. National damage classifications, reporting units (buildings, dwellings, and independent units), exposure denominators, and categories of direct and disaster-related deaths should be harmonised sufficiently to support international monitoring. Until such harmonisation exists, normalized casualty indicators should be interpreted cautiously and alongside the dominant hazard and characteristics of the exposed building stock.

The proposed Code–Loss Institutional Learning Framework provides a way to evaluate this wider chain. Its principal implication is that a regulatory response is incomplete if it remains on paper or applies only to future construction while known vulnerabilities persist in existing buildings. Closing the learning loop therefore requires institutions to move from damage evidence to implementation, inspection, retrofit, and follow-up evaluation.

In summary, seismic codes establish safety objectives, but institutions determine how far those objectives reach the buildings in which people live. The combined lesson of Kahramanmaraş and Noto is not that another code revision is necessarily the first priority; it is that enforcement capacity, systematic assessment, and retrofit of vulnerable existing stock are indispensable for translating regulatory knowledge into reduced disaster loss.

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Statements and Declarations

Data availability

All data analysed in this study were obtained from publicly available legislation, official reports, and published sources cited in the manuscript; no new primary dataset was generated.

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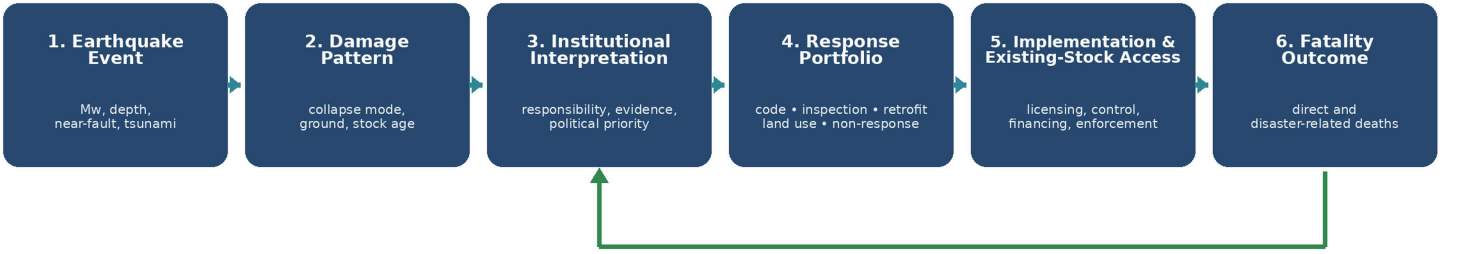
[AUTHOR CONFIRMATION REQUIRED] If no funding was received, use: “The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.”

Competing interests

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Code–Loss Institutional Learning Framework

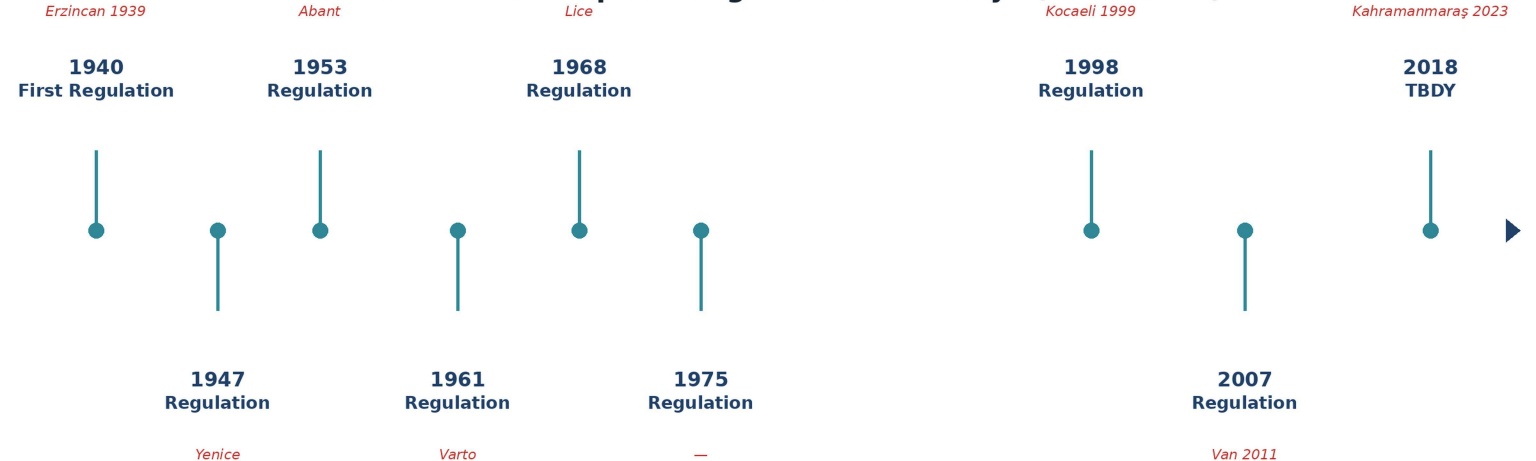
Damage lessons do not automatically become code; institutional interpretation produces different response pathways.



Post-disaster learning cycle: outcomes feed institutional interpretation and the next response.

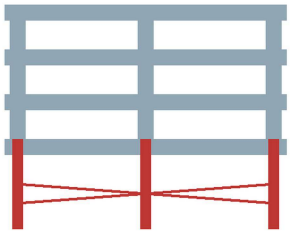
Sendai Framework • Build Back Better • access to existing building stock

Evolution of Earthquake Regulations in Türkiye (1940–2018)



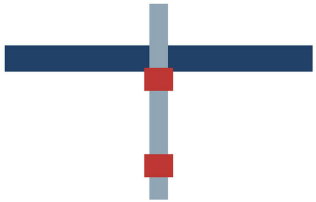
Recurrent Structural Failure Mechanisms in the 2023 Kahramanmaraş Earthquakes

(a) Soft story



Open commercial ground floor → soft-story collapse

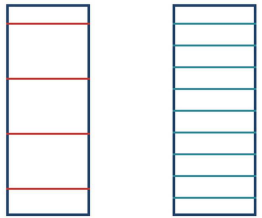
(b) Weak column / strong beam



Strong beam promotes plastic hinging in the column

(c) Insufficient confinement

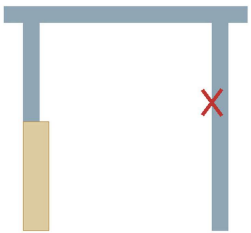
low concrete quality + wide tie spacing → brittle collapse



wide tie spacing

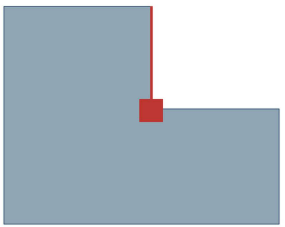
proper confinement

(d) Short-column effect



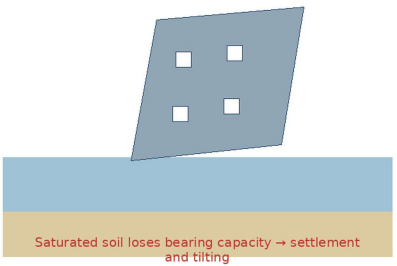
Partial infill shortens the column → brittle shear failure

(e) Vertical irregularity



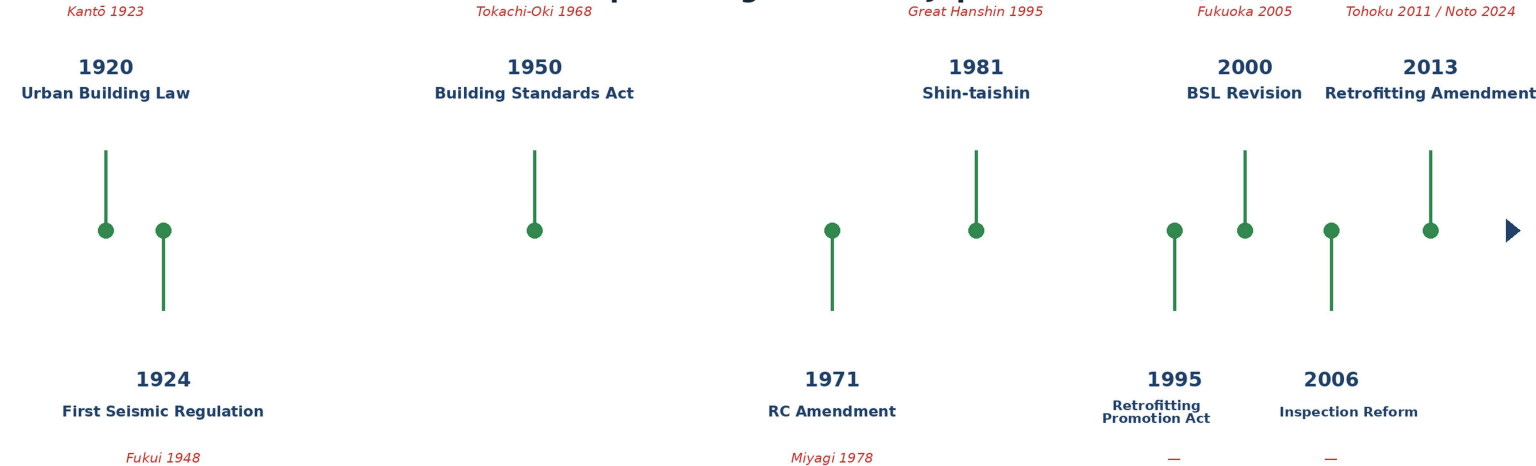
Setback / mass discontinuity → stress concentration

(f) Liquefaction and tilting



Saturated soil loses bearing capacity → settlement and tilting

Evolution of Earthquake Regulations in Japan (1920–2013)




Fatalities in Selected Major Earthquakes (Türkiye and Japan)
Fatalities (log scale)
10^5
10^4
10^3
10^2
10^1
10^0
1920
1940
1960
1980
2000
2020
Kantō M7.9
Erzincan M7.9
Fukui M7.1
Kobe M7.3
Kocaeli M7.5
Tohoku M9.0
K.maraş M7.8
Van M7.1
Noto M7.5
İzmir M7.0
Elazığ M6.8
Fukuoka M7.0
Note: all twelve events selected in the methodology are shown; points are not connected. The sample is non-random; fatalities should be interpreted together with hazard type and building-stock/implementation conditions.
Türkiye – shaking
Japan – shaking
tsunami-dominant
fire-dominant

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Tables.docx