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Turkish earthquake death tolls: lessons from downward counterfactual analysis and informal construction

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Earthquake death tolls are a basic statistical measure of the capability of a country to manage seismic risk. The extremely high Turkish death toll of 50,000 from the Kahramanmaraş earthquake doublet of 6 February 2023 is the product of a cascade of detrimental factors. These need to be explained if lessons from this disaster are to be learned. This is the purpose and objective of this paper, which is a contribution to the interdisciplinary Frontiers research topic on integrated perspectives on the 2023 Turkey and Syria earthquakes: advancing understanding and preparedness across earth sciences, engineering and public health. This paper covers these three disciplines by focusing on casualties, and identifying crucial aspects of earth sciences and engineering which contributed to the high death toll. First, there was a surprising combination of multiple fault segment ruptures, and a high level of ground motion relative to the risk-based Turkish code, indicative of the under-representation of the M7.5+ earthquake doublet event in the national probabilistic seismic hazard model. This combination of fault segment ruptures was missing from all seismic source models. Furthermore, the capability of buildings to cope with strong ground motion was much reduced by informal construction methods, which eroded the margin of safety needed to avoid building collapse. The extent of building code non-compliance was widely underestimated in seismic risk models. Non-compliance is often hard to identify, but construction amnesties make non-compliance more transparent and trackable. The disastrous outcome of the Kahramanmaraş earthquake doublet of 6 February 2023 has drawn global attention to systemic building code non-compliance, and the open official acceptance of informal housing. To demonstrate that this key systemic risk is far from being just a Turkish problem, notably in Istanbul, the challenge of Italian informal housing is highlighted within the context of international building code non-compliance.

KEYWORDS

Turkey, earthquake, death tolls, counterfactual analysis, informal construction

1 Introduction: the Kahramanmaraş earthquake doublet of 6 February 2023

Insight into a runaway multi-fault rupture scenario can be gained from counterfactual analysis: exploring alternative realizations of past events. Prior to 2023, the preceding major Turkish earthquake disaster was the Kocaeli earthquake of 17 August 1999, which caused the deaths of 17,000. This earthquake ruptured a large section of the North Anatolian Fault. But the fault rupture might have runaway westwards, and propagated past Istanbul. The aggregate death toll from this downward counterfactual is estimated to have been three times that of the 17 August 1999 Kocaeli earthquake, similar to that of 6 February 2023.

Such downward counterfactual analysis exposing the seismic vulnerability of Istanbul is insightful for decision-makers. The mayor of Istanbul reported on 15 February 2023, that around 317,000 buildings in Istanbul took advantage of a construction amnesty, and there was a serious risk of collapse of around 90,000 buildings in a major earthquake in Istanbul. He further stressed that Istanbul is not yet ready for a large earthquake; but neither was it in 1999. Counterfactual thinking about this earlier disaster would have concentrated the minds of public officials on building code enforcement.

Whenever an earthquake occurs that claims the lives of tens of thousands, any in-depth earthquake study should extend beyond geohazard analysis and incorporate a georisk forensic investigation to identify the principal underlying causes of the earthquake catastrophe. These interlinked causes are partly in the realm of seismology; partly in the broader realm of earthquake engineering; and also partly in the realm of urban planning and disaster economics. A universal disaster metric is the population death toll, the reduction of which is a key driver of earthquake risk management and decision-making. The history of the development of seismic design codes in Turkey is punctuated with improvements in the wake of large earthquake death tolls (Soyluk and Harmankaya, 2012).

An interdisciplinary approach to comprehending the scale of the death toll on 6 February 2023 is essential, beginning with the assessment of seismic hazard. As in most seismically active countries, it is not economically prudent or viable in Turkey to design in a deterministic manner for the maximum credible earthquake; a risk-based approach is needed. A standard design ground motion level for ordinary buildings has a 10% exceedance probability in 50 years, corresponding to a return period of 475 years. The ground motion criteria for tall buildings above 70 m are more rigorous, and involve a collapse prevention performance criterion under ground motion which has a 2% exceedance probability in 50 years, corresponding to a return period of 2,475 years (Sucuoğlu, 2018). Calculation of design ground motion levels for these return periods requires probabilistic seismic hazard analysis (PSHA).

PSHA began half a century ago with seismic sources being represented as polygonal area zones (Cornell, 1968), which was a convenient pragmatic simplification when computing resources were very limited. Progressively, seismic source modeling has evolved to capturing the ensemble of potential fault rupture sequences (Danciu et al., 2021), with the residual lesser seismicity of lower magnitude being represented via kernel statistical smoothing methods (Woo, 1996). In terms of modeling fault ruptures, the task of seismic hazard analysts is greatly facilitated by the seismicity of Turkey and adjacent areas being thoroughly researched, e.g., Ambraseys and Finkel (1995). The availability of the outcome of the latest seismotectonics studies, linking mapped faults with historical earthquakes, is also a substantial benefit.

A year before the Kahramanmaraş earthquake doublet of February 2023, Güvercin et al. (2022) reviewed the active seismotectonics of the East Anatolian Fault (EAF) in Turkey. The main fault, from east to west, comprises of the Karlıova, Ilıca, Palu, Pütürge, Erkenek, Pazarcık and Amanos segments. These are shown in Figure 1, along with the principal historical earthquakes, which include the 1795 (M7.0, Pazarcık), 1872 (M7.2, Amanos), 1893 (M7.1, Erkenek), 1971 (M6.6, Karlıova) and 2020 (M6.8, Pütürge) earthquakes. Each of these events ruptured a segment of the EAF; but none extended over multiple segments as happened with the February 2023 event, which caused the third largest economic earthquake loss after the great Japanese earthquakes of January 1995 and March 2011.

Güvercin et al. (2022) inferred that the seismicity patterns and strain-rate field along the EAF were shaped by several factors such as strong geometrical irregularities, heterogeneous coupling and complex plate motion. They estimated the maximum magnitude (Mmax) for the Palu and Pütürge segments as being similar at M6.9 with a return period of about 150 years. To the west, their extrapolation of the Gutenberg–Richter magnitude-frequency curve for the Pazarcık segment yielded Mmax of 7.3, with a return period of about 772 years. For the Amanos segment, Mmax was estimated at 7.4 with a return period of about 915 years.

Typically, in seismic hazard source modeling, combinations of fault segments rupturing together are considered if there is some empirical observation of a historical or geological precedent. For EAF, there was no such precedent, but fault ruptures may be complex and span multiple connected fault segments, even if the segments are separated by distinct geological and geomorphological features. Accordingly, Gülerce et al. (2017) developed a simplified seismic hazard rupture model by combining some of the neighboring segments: the Ilıca–Karlıova segments; the Palu and Pütürge segments; as well as the Erkenek and Pazarcık segments. There is a wide variety of multiple segments that might potentially rupture together.

Inevitably, the possibility exists of some particular combination of faults rupturing which has no observed precedent and is beyond anticipation based on experience, and thus constitutes a seismological surprise. This was the situation with the destructive doublet earthquakes of 6 February 2023 (Jia et al., 2023). A number of M7 earthquakes occurred on the East Anatolian Fault (EAF) historically, but these had ruptured specific segments. The estimated dimensions of the historic events suggest that geometric complexities such as fault bends and step-overs may have controlled the event. Indeed, the M7.8 main earthquake propagated across at least four possible geometric barriers, including fault bends and stepovers (Jia et al., 2023).

The dynamic rupture models of Gabriel et al. (2023) illustrate the predisposition of complex fault geometries, prevalent in tectonically complex immature fault systems, for cascading multi-fault and multi-event earthquake sequences.

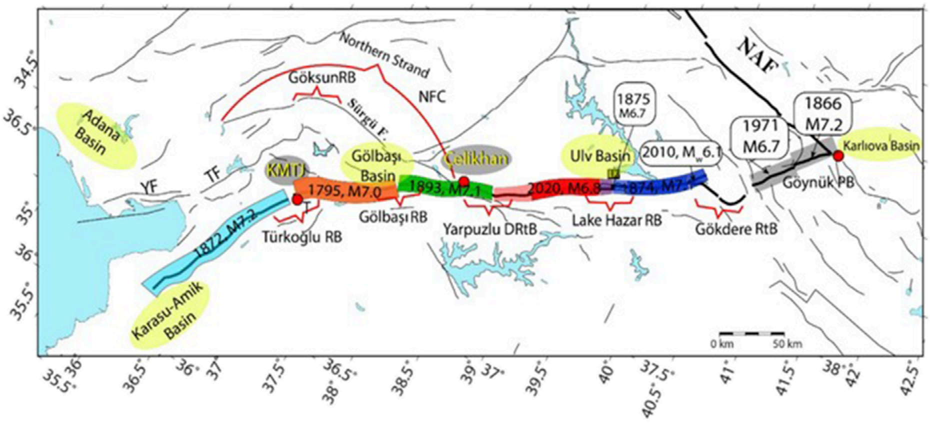

FIGURE 1
Fault segmentation based on the historical earthquakes and geology along the East Anatolian Fault (EAF). The major structural features are also shown. The colored bands indicate the segments of the EAF: Palu (blue), Pütürge (red), Erkenek (green), Pazarcık (orange), Amanos (cyan) and Karliova (grey); the basins are shaded in yellow (from Güvercin et al., 2022, Figure 2).

The 2023 Kahramanmaraş doublet and other recent large earthquakes involving multi-fault rupture sequences highlight how understanding their underlying mechanics is crucial to improving earthquake hazard assessment and mitigation.

The Kahramanmaraş doublet originated as a moderate event on the Nurdağı-Pazarcık fault (NPF) branch fault with a magnitude of only 6.8, yet the rupture was able to successfully cross the junction of the NPF and EAF, which would usually be considered a geometric barrier that conditionally limits the rupture propagation (see Figure 2). As a result, the earthquake intensified with the northeastward propagation along the EAF then dynamically triggered backward rupture toward the southwest by continuously unclamping and stressing from the forward branch, eventually culminating in a M7.8 event, with total seismic moment increased by a factor of 30 compared with the initial rupture on the NPF.

In addition, the M7.8 earthquake increased the Coulomb stress on the central part of the Çardak Fault, which is a part of the predominantly strike-slip Sürgü–Çardak–Savrun fault (SCSF) system. This may have aided the nucleation of the M7.7 earthquake just 9 h later (Liu et al., 2023). The entire process highlights the additional hazard brought by rupture triggering across a network of faults. The stochastic process of rupture triggering constitutes a major challenge for earthquake hazard assessments that typically do not consider such multi-fault triggering scenarios.

The high degree of complexity of possible multi-fault ruptures, illustrated by the Kahramanmaraş earthquake doublet of 6 February 2023, shows the limitations of developing ensembles of fault ruptures based narrowly on historical or geological precedent. This can be a constraining factor in imagining an ensemble of possible multi-fault sequences for PSHA. As with the 14 November 2016 M7.8 Kaikoura, New Zealand earthquake (Cesca et al., 2017), there are numerous alternative ways in which the complex rupture process might have evolved on 6 February 2023. Indeed, the rupture process involved backward fault branching, which is highly unfavorable from a dynamic perspective, thus commonly neglected in hazard studies (Jia et al., 2023). A lesson for seismic hazard analysts is that backward fault branching should not be neglected.

To expand the considered spectrum of multi-fault rupture scenarios, alternative realizations of historical or geological precedents can be explored. Traditional seismic hazard studies for the East Anatolian Fault Zone (e.g., Bayrak et al., 2015) are limited in their rigid data interpretation. However, the underlying dynamics of fault rupture are intrinsically stochastic rather than deterministic. This approach of reimagining earthquake history has been developed by Woo and Mignan (2018) for the Kocaeli earthquake of 17 August 1999, which is discussed next.

The structure of this study is as follows. The first introductory section discusses the earthquake doublet of 6 February 2023, and the unforeseen sequence of fault ruptures. The second section reviews the 1999 Kocaeli earthquake, and the downward counterfactual that the rupture might have extended past Istanbul. The third section addresses the very high seismic ground motions recorded on 6 February 2023, relative to the design spectra. The fourth section provides a social economics explanation for the Turkish construction amnesties. The fifth section considers the prospect of a great Istanbul earthquake. The sixth section discusses international earthquake building code compliance issues. The final concluding section stresses the high death toll as being compounded by underestimation of both the fault rupture hazard, as well as the prevalence of informal housing.

2 The Kocaeli earthquake of 17 August 1999

Damaging earthquakes are common in Turkey. In the 1990s, Erzincan (M6.8) was struck in 1992; Dinar (M6.0) in 1995; and Adana (M6.3) in 1998. But the most destructive in this decade was the Kocaeli (M7.4) earthquake of 17 August 1999 which caused severe damage or collapse of buildings over a 250 km distance. The epicenter was close to the city of Izmit, at the eastern end of Izmit Bay, which is an east–west elongated structural basin situated

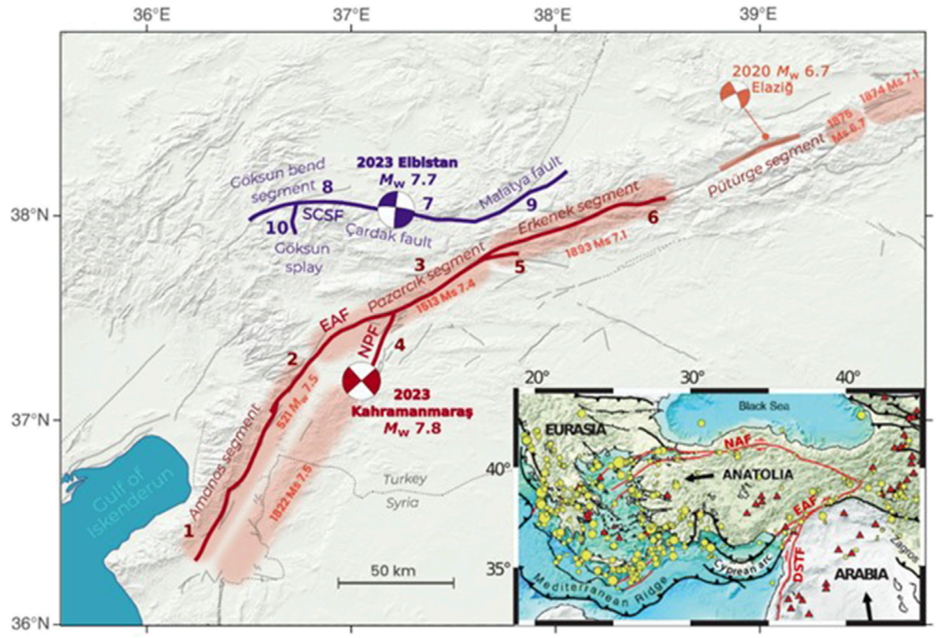

FIGURE 2
Fault map with surface ruptures of the 2023 Kahramanmaraş earthquake sequence (from Gabriel et al., 2023). Red and blue numbers correspond to fault segments modeled by Gabriel et al., and named following Duman and Emre (2013). The first earthquake ruptured six segments of the EAF: 1 and 2, Amanos segment; 3, Pazarcık segment; 4, Nurdağı-Pazarcık fault (NPF); 5, unnamed Erkenek splay; 6, Erkenek segment. The second earthquake ruptured four segments of the SCSF: 7, Çardak fault; 8, Göksun bend segment; 9, Malatya fault; and 10, unnamed Göksun splay.

along the North Anatolian Fault at the eastern margin of the Sea of Marmara. The rupture propagated bilaterally to the west and east, rupturing a total of four fault segments, with a total length of 126 km. The eastward rupture of the 17 August 1999 earthquake might well have continued to include the section that ruptured only several months later on 12 November 1999 (M7.1), which killed a further 894 people (Bakir and Boduroglu, 2002).

The Kocaeli province was the worst affected. 70% of the buildings in parts of the main cities were severely damaged or collapsed. Almost 20,000 buildings collapsed and another 14,000 were irreparably damaged. Nearly all the approximately 17,000 deaths and 43,000 injuries of the Kocaeli earthquake were due to building collapse. A crucial factor in the construction loss was building code non-compliance. If the latest Turkish earthquake building code been properly implemented, many modern buildings would have been far less vulnerable. Communities living on loose silt, sand layers, and saturated alluvial material were vulnerable to seismic ground motion and settlement. The international earthquake engineering consultancy, EQE International (1999), concluded that buildings were knowingly allowed to be built on active faults and in areas of high liquefaction potential. The socio-economic pressures on urban planners in allowing code violations need to be better comprehended by risk stakeholders.

The western termination of the Kocaeli earthquake fault rupture has been an intriguing research issue, of practical importance for those residing around the Sea of Marmara. Woo and Mignan (2018) considered a downward counterfactual of the Kocaeli earthquake, in which there was a runaway rupture of the North Anatolian Fault, as shown in Figure 3. A runaway earthquake starts with a historical sequence, and continues to rupture additional segments, through jumping over to neighboring faults. In this case, the runaway earthquake extends past Istanbul, and includes the Marmara Fault, which has not been activated by a major earthquake since 1766. In respect of the M7.4 1944 Bolu-Gerede earthquake on the North Anatolian Fault, Kondo et al. (2010) found that multisegment earthquakes exhibit various spatial patterns, regardless of recurrence with quasiperiodicity and characteristic slip.

The modeled runaway rupture is compatible with previous geometrical constraints observed in Turkey, and with static stress loading computations in the Marmara region. Results are also consistent with the dynamic stress results of Harris et al. (2002), who hypothesized the westward termination of the 1999 Izmit earthquake to be due to a remnant stress shadow from the 10 July 1894 Gulf of Izmit event. Had no event occurred in 1894, the 1999 earthquake might have been far more disastrous.

For the additional rupture segments, Erdik et al. (2003) have estimated that about 70,000 buildings would have been severely damaged, of which 35,000 to 40,000 buildings would have been damaged beyond repair. The corresponding death toll is estimated between 30,000 and 40,000. For the runaway North Anatolian earthquake scenario, the cumulative death toll would thus have been around 50,000, which is similar to estimates of the Turkish earthquake deaths for the multi-fault segment rupture on 6 February 2023. (The additional death toll in Syria was around 8,000).

The 1999 Kocaeli earthquake death toll of 17,000 was about half the 33,000 who died in the 27 December 1939 Erzincan earthquake, in Eastern Turkey. At M7.8, this Erzincan earthquake was of similar size to the larger event that occurred on 6 February 2023, and

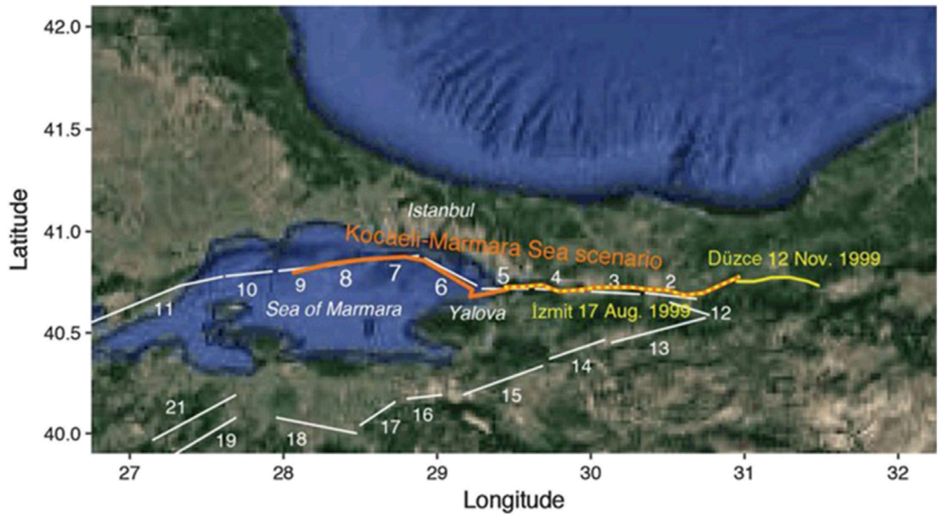

FIGURE 3
Westward extension of the 17 August 1999 Kocaeli earthquake past Istanbul, covering segments 5 to 9 of the North Anatolian Fault (Woo and Mignan, 2018). The subsequent Düzce fault rupture of 12 November 1999 is also indicated.

was a watershed moment in that it resulted in the development of a comprehensive national disaster management program, a Turkish seismic zone map and earthquake building codes (Tunc and Tunc, 2022). A downward counterfactual realization of the 1999 Kocaeli earthquake, with a runaway fault rupturing past Istanbul, would have been a similar watershed moment in Turkish disaster management.

If the 1999 North Anatolian Fault earthquake death toll had reached the alarming threshold of 50,000, it should have jolted public earthquake risk perception of the downside of construction amnesties. Understandably highly popular amongst the Turkish electorate, a construction amnesty is not an astute financial provision of disaster management, but rather a wager against a disaster materializing. This example illustrates the psychological value of downward counterfactual thinking in influencing public risk perception. The downward counterfactual terminology originated in social psychology (Roese, 1994), and provides an essential public communication bridge linking the social and geosciences.

3 Earthquake seismic ground motions

Whenever a major earthquake occurs, comparison of the ground motions recorded with the requirements of the regional seismic code is highly instructive. For the M7.8 earthquake on 6 February 2023, Papazafeiropoulos and Plevris (2023) have analyzed the strong motions of a set of earthquake records for the primary Turkish seismic zone 1. Response spectra plots are shown and compared with the provisions of the Turkish seismic code for two site classes, stiff and soft soils, in Figure 4. Of special note is that there are higher spectral acceleration values for a broad range of periods for many of the recordings. Based on the envelope spectrum, a maximum spectral acceleration of 5.35 g is observed, which substantially exceeds the design spectra.

Further code comparisons have been made by Alpyüryür and Ulutas (2024). According to the measurements obtained from Station 3126 and Station 4614 in Antakya (Hatay) and Pazarcık (Kahramanmaraş), the geometric mean of the two horizontal response spectra surpasses the Turkish Earthquake Building Code TBEC-2018 design spectrum for a return period of 475 years across most periods. This was particularly the case in areas with high levels of destruction. According to the data presented in Figure 5, the geometric averages of both stations surpass the design spectrum for a return period of 2,475 years when considering short periods of less than 0.5 s.

The downward counterfactual analysis of the 1999 Kocaeli earthquake has identified the possibility of large runaway Turkish earthquakes. These may arise from multi-fault segment ruptures, not just on the North Anatolian Fault, but also on the East Anatolian Fault. A key motivation for counterfactual analysis is the search for surprising unknown events that are under-represented in seismic source models. The completeness of a stochastic event set of a seismic source model can be queried by exploring counterfactual realizations of historical earthquakes. Potentially surprising multi-fault segment earthquakes are not addressed well in PSHA. Given the high multiplicity of fault rupture combinations, this is a complex high-dimensional challenge. This is despite the diligent compilation of large databases of active faults and fault segments in Turkey, with parameterizations of slip rate and maximum magnitude (Demircioğlu et al., 2018).

The observations of very high seismic ground motions from the 6 February 2023 M7.8 Kahramanmaraş earthquake significantly exceeding the risk-based Turkish code, provide evidence that the strong shaking from this earthquake doublet may be significantly more common than hitherto had been calculated. This may be partly explained by the deficiency in the frequency associated with multi-fault segment scenarios for M7.5+ earthquakes on the East Anatolian Fault. Indeed, such scenarios have been absent in the

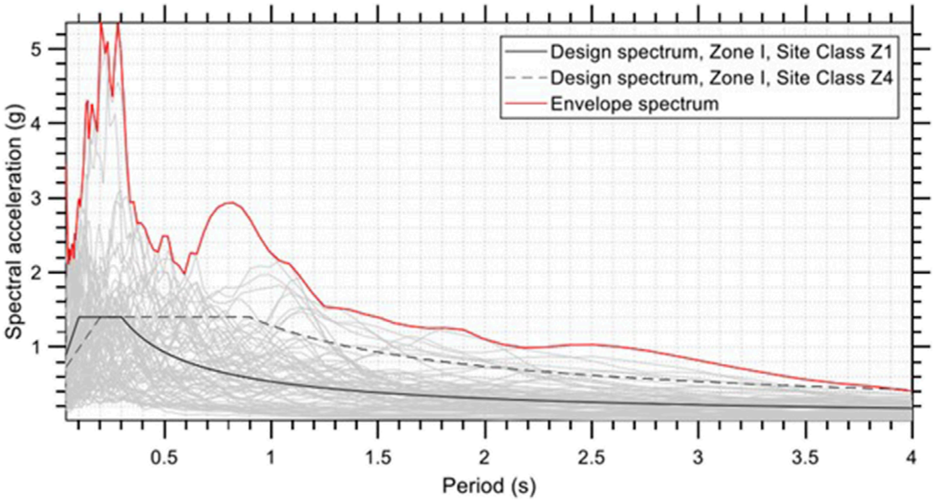

FIGURE 4
475 years return period design spectra of the Turkish seismic building code versus actual acceleration response spectra of an ensemble of records of the M7.8 Kahramanmaraş earthquake of 6 February 2023. Spectral comparisons are for the primary seismic zone 1, and two contrasting site classes Z1 and Z4 (from Papazafeiropoulos and Plevris, 2023).

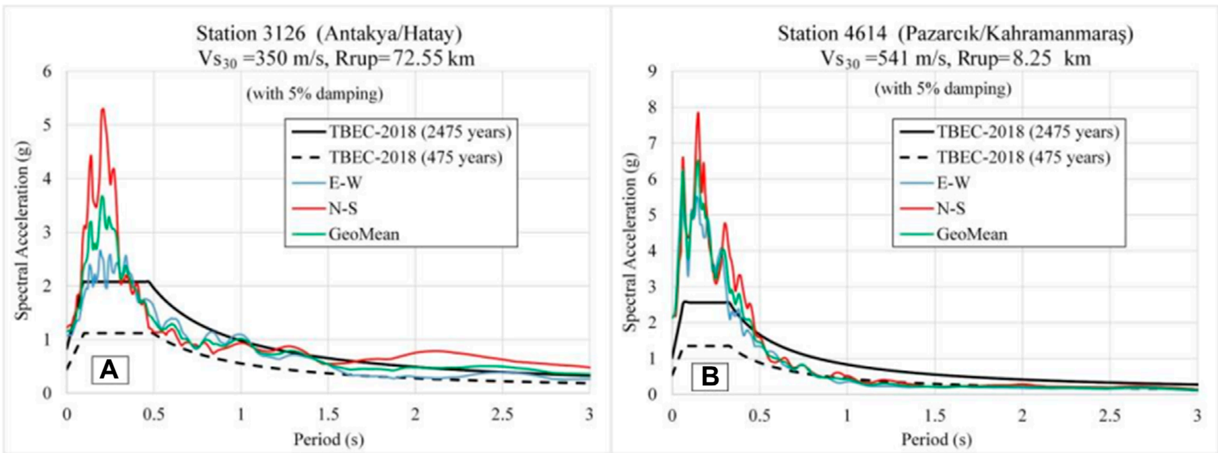

FIGURE 5
Response spectra compared with TBEC-2018 at stations **(A)** 3126 and **(B)** 4614, in relation to the Pazarcık earthquake (Mw = 7.7). (from Alpyürür and Ulutas, 2024).

seismic hazard assessment for the East Anatolian Fault (Bayrak et al., 2015).

Buildings are liable to suffer serious damage if shaken by high levels of ground motion that exceed the design basis. Pulse-like ground motions such as were observed due to directivity (Baltzopoulos et al., 2023; Wu et al., 2023) are characterized by narrowband amplification for both elastic and inelastic spectra and are known for imposing more severe inelastic demand on certain structures. These pulse-like ground motions would have been particularly threatening for buildings where sound construction procedures were not followed or maintained. Lack of structural reinforcement, soft stories, architectural irregularities, use of inferior construction materials, and other negligent modes of building code non-compliance, erode crucial safety margins, and make collapse more likely. More than 60,000 buildings had to be demolished.

According to the report by the Union of Chambers of Turkish Engineers and Architects in 2023, observations and evaluations regarding damaged and collapsed buildings in urban centers indicate that the following practices and decisions, all of which erode safety margins, have had an impact on the causes of structural damage and collapses (Gözlükaya, 2023):

- Urban planning and zoning revisions carried out without consideration of disaster data;
- Encouragement of illegal construction through zoning amnesties, noncompliant project and implementation practices, and unauthorized structures;

- Conversion of agricultural lands and low-bearing capacity soils into construction areas;
- Exclusion of qualified architectural, engineering, and planning services from the building production and inspection process;
- Inadequacy of technical personnel and lack of oversight in professional expertise areas.

4 Turkish construction amnesties

Irregular administrative practices and the bartering of political favors for planning permission are not unusual in countries where there is difficulty for local authorities in recruiting experienced trained engineers to ensure inspection competence. However, in most countries, these practices remain covert. But since 1948, construction amnesties in Turkey have allowed previous building code violations to be pardoned and current construction projects to be absolved from compliance (Jacoby and Őzerdem, 2008). The construction amnesty has given the freedom to contractors and owner-occupiers to build and extend dwellings without due regard for building design or regulations. Clearly, the anticipation that building code violations would be pardoned diminishes the obligation for compliance among developers, builders and contractors.

The idea of construction amnesties is hard for professional earthquake engineers to comprehend. As explained by Jacoby and Őzerdem (2008), these construction amnesty practices were a consequence of economic liberalization. The concept of construction amnesty began in 1948, but was officially introduced in 1984 under the government of General Kenan Evren, who came to power in a military coup on 11 September 1980. Ironically, the military coup happened during the seventh world conference in earthquake engineering, hosted in Istanbul from 8 to 13 September 1980. The Turkish seismic building codes are exemplary, and the Turkish earthquake engineering profession has a high international standing. However, economics is a fundamental driver of the seismic vulnerability of the built environment, and economists are rarely present at earthquake engineering conferences.

The tension between earthquake engineers and householders over post-earthquake reconstruction was identified by Ulabaş (1980) in his timely contribution to the Istanbul world conference on earthquake engineering. In the aftermath of the M7.1 Gediz earthquake, western Turkey, of 28 March 1970, which claimed the lives of more than a thousand, and left 80,000 homeless in Gediz, extended families wanted to add rooms and storage spaces to their dwelling units, notwithstanding building code violations.

Like many governments around the world in the 1980s, the Turkish authorities under Evren aimed to minimize the role of the state in the economy. The World Bank and the International Monetary Fund supported such liberalization, which included the lifting of restrictions on the sale of public land to housing entrepreneurs. Encouraged to develop large-scale housing projects as cheaply as possible, the prospect of future construction amnesties incentivized entrepreneurs to focus on the reward of maximizing construction output, whilst minimizing concerns over seismic risk. From an entrepreneur's individual perspective, the benefit is immediate, whereas the risk horizon is distant; a damaging earthquake might well not occur within years, or even decades. This is a clear manifestation of optimism cognitive bias (Kahneman, 2011).

In order to appreciate the Turkish political seismic risk calculus, balancing the risk of earthquake occurrence against the benefit of informal construction, an understanding of modern Turkish history is needed. The years of the Second World War witnessed great population losses, as elsewhere, and policies were introduced until 1965 to increase the population. At the end of the Second World War, Turkey was still predominately a rural society with less than a quarter of its population living in cities and small towns. As the urban population quadrupled in four decades, the urbanization rate reached 50% by the early 1980s. According to a World Bank, (2015) celebrating the rise of the Anatolian tigers, Turkish policy makers recognized the importance of urbanization to the country's ambitions of becoming a modern, industrialized economy, and encouraged rural-to-urban migration flows that fueled agglomeration economies. Provided they are not unduly hazard-prone, megacities can power economic growth (McKinsey Global Institute, 2011).

The annual population growth rate in Turkey between 1955 and 1985 was 2.8% (Doğan, 2013). By 2008, more than 75% of the population were living in urban settings, 12 million of whom were in the Istanbul metropolis. By 2023, this rose to around 16 million, including half a million Syrian refugees. As a measure of the huge expansion in Istanbul seismic exposure over seven decades, Istanbul was just a medium-sized city of 1.1 million in 1945.

The exponential growth of the urban population put pressure on public services. When the rural migrants arrived in cities such as Istanbul to power the post-war Turkish growth and industrialization, they were not provided with adequate housing. In the absence of formal public housing provision, the practical answer was the *gecekondu*, a makeshift low-quality dwelling often built on public land without proper documentation. Progressively, properly licensed housing became overshadowed by the informally built structures in major Turkish cities like İzmir, Ankara as well as Istanbul. As informal houses grew into informal neighborhoods and districts, they have been tolerated by local and central governments alike during the second half of the twentieth century, as an imperfect remedy for the shortage of good quality housing. The pragmatic Turkish authorities' overall position towards informal housing has been one of formalization, rather than their prevention (Erensu, 2023).

This tolerant attitude towards informal housing is reflected in building amnesties that have been routinely passed by the Turkish Parliament. Since 1948, there have been 15 to 20 legislations. The first amnesty legislation was passed long before informal housing became a widespread urban matter. Rather than formally committing to the provision of public housing, priority is given to the absorption of informal settlements into the formal urban development structure.

The Ministry of Public Works and Settlement in Turkey (Eke, 1989) recognized that the domestic industry in the building sector is not equipped to perform the tasks on a scale commensurate with the needs. Along with the state's deficiencies in public housing provision has been a commonly shared tacit understanding that land use and building controls will sooner or later be relaxed. According to studies for the Ministry of Reconstruction and Settlement, in the first half of the 1960s, the percentages of the populations of Ankara, Istanbul and İzmir living in irregular settlements were 59%, 45%, and 33%

respectively. In the 1980s, these percentages were 55%, 70%, and 50% respectively. Buğra (1998) has noted that such development could only take place with the consent of the political authorities.

Relaxation of controls often is dictated by the electoral cycle. The Building Peace was introduced in April 2018 by the Justice and Development Party (AKP), 3 months before the 24 June Presidential and General Elections. It was AKP's first comprehensive building amnesty and the most ambitious of its kind since 1984. The legislation was designed to address and legalize all possible irregularities a building could have, from zoning to licensing. Its scope included all buildings completed until 2018 except for those built on any kind of privately owned land.

In 2018–2019, 7.4 million applications were registered with the program, earning about $4 billion for the national treasury. On 15 May 2018, an article was added to the construction amnesty law introduced in the 1980s that stated that over 50% of buildings in Turkey were not up to code. Therefore, the government would, until the end of that year, accept amnesty payments from builders totaling 3% of a property's value for residences and 5% for commercial buildings (Harrington, 2023). This led to a surge in the official registration of illegal structures.

President Erdoğan himself was keen to claim that an amnesty allowing builders to violate codes had solved the housing problems for 144,556 citizens of Kahramanmaraş. This solution would only last a few years longer; the 2023 M7.8 earthquake occurred with an epicenter only about 24 km away. The President's speech was actually delivered in Kahramanmaraş before local elections in 2018 (Harrington, 2023). The President made similar speeches in the cities of Hatay and Malatya, both of which were badly shaken by strong ground motion in 2023.

But one of every four applications, roughly 1.8 million cases, was from Istanbul. Like many metropolises, informal (*kaçak*) construction is not an exception in Istanbul, but rather the norm. Istanbul has been described as the *kaçak* city; 5.5 million Istanbulites reside in *kaçak* neighborhoods. The Turkish word *kaçak* has become a shorthand for the problems of urbanization in the country, particularly in Istanbul. In July 2018, construction amnesties came under strong public focus when an Istanbul building constructed without planning permission in 1994 collapsed as a result of subsidence (Ahval, 2018). The ambivalent public attitude towards construction amnesties is reflected in the warning headline: *Turkey's amnesty on illegal construction not all good*.

Despite its success in receiving a record number of applications, the amnesty legislation was highly controversial. The Chamber of Urban Planners called it a betrayal of Istanbul. Recalling the long history of building amnesties in the last seven decades and the accompanying expansion of informal housing, the opponents stressed the futility of pardoning building/zoning irregularities which perpetuates urban problems. In seismic risk assessment, consideration is given to human risk factors that elevate risk. These human risk factors include human error, negligence and malicious action in the design, construction, and regulation of buildings. An overriding human risk factor is the granting of construction amnesties for political electoral advantage.

But there is a contrary political perspective. The societal acceptance of informal housing may be viewed by social economists (Buğra, 1998) as just and legitimate when formal market and public redistribution mechanisms of housing fail to deliver fair outcomes for all. But whatever the level of societal acceptance of informal housing, the occupants themselves will pay a daily price in exposure to the risk of dangerous, potentially life-threatening, levels of earthquake shaking.

The general sense of community seismic hazard derives from public awareness of past earthquake death tolls. In this regard, periods of relatively low or moderate death counts from recent historical earthquakes can be misleading, inducing a false sense of seismic security. Contributing to this misperception was the M7.0 Aegean Sea earthquake of 30 October 2020, in which 718 buildings collapsed or were severely damaged, and 117 people died in Izmir Province, Turkey. This is a comparatively light death toll given that the number of unlicensed buildings was around 800,000 (Karaca and Dilsiz, 2023). Most of the buildings that collapsed were built in the 1990s, and were vulnerable because of poor construction practices and the absence of code compliance.

The 30 October 2020 earthquake occurred at 1.51 p.m. in the afternoon, when there would have been far fewer people in the collapsed buildings than if the earthquake had occurred at night. An alarming downward counterfactual would have been a night-time earthquake, that might have claimed the lives of several thousand people in the code-noncompliant collapsed buildings. Cognitive outcome bias tends to diminish the psychological impact of near-miss disasters. For the correction of public risk misperception on the dangers of informal construction, consideration should be given to a downward counterfactual perspective on earthquake fatalities—how the death toll might have been worse.

5 The great Istanbul earthquake

Death tolls from earthquakes are subject to substantial sources of stochastic variability, which cloud the estimation of casualty risk. In the 60 years from 1960 to 2020, there were only about two hundred deaths in California from earthquakes; a tribute to the high standard of earthquake-resistant construction, and the professionalism of the building industry. However, this figure could have been massively inflated following the 1967 San Fernando earthquake, when the Lower San Fernando Dam was damaged and came close to failure. The type of flood catastrophe that might have unfolded is illustrated by the Libyan Derna dam disaster of September 2023. The volatility of earthquake death tolls applies also to Turkey.

When the East Anatolian earthquake doublet struck southern and central Turkey on 6 February 2023, thoughts turned northwards to the prospect of a great Istanbul earthquake, and the extent to which Turkey is prepared for this earthquake. Civic preparedness would be enhanced by a quantitative seismic risk assessment in which extreme hazard scenarios, such as a rupture on the North Anatolian Fault as posited by Erdik et al. (2003), were combined with a current perspective on Istanbul building inventory and earthquake vulnerability. A short return period for extreme casualties in Istanbul, or any other large metropolis, should trigger urban risk mitigation measures.

A housing exposure downward counterfactual for Istanbul is that the prevalence of informal construction might be notably worse than presumed in the Istanbul risk assessment of Erdik et al. (2003). A 24 February 2021 report by the Urban Transformation Foundation (Kentsev) reported there are 1.1 million buildings, and 4.5 million apartments in the Istanbul metropolis. Some 22.6% of these 1.1 million buildings were constructed before 1980. Two years later, on 15 February 2023, the mayor of Istanbul, Ekrem Imamoğlu, reported that around 317,000 buildings in Istanbul took advantage of the zoning amnesty and around 90,000 buildings were under the serious risk of collapse in case of a possible major earthquake in Istanbul. He further stressed that Istanbul is not yet ready for an earthquake, and pointed out an urgent need to take precautions and not leave it to destiny (Türkösü, 2023). Seismic hazard analysts use the scientific term "aleatory uncertainty" to express the good fortune that Istanbul has experienced for decades. The last significant earthquake shaking in Istanbul was from the Marmara Sea earthquake (M7.0) on 10 July 1894 (Finkel and Ambraseys, 1997). The population of Istanbul, together with Galata, was then 200,000, less than 2% of the current population.

Istanbul was not ready for a great earthquake a century later on 17 August 1999, when Izmit, to the east of Istanbul, was struck. As in Hatay, Kahramanmaraş, and Gaziantep in February 2023, buildings pancaked on 17 August 1999, tumbling in on themselves and killing over 17,000 people. Particularly critical of the government's response back in 1999 was the former mayor of Istanbul, Recep Tayyip Erdoğan. The earthquake crisis was his opportunity to advance his party, the AKP, in 2001, and to become prime minister in 2003.

The Turkish government did introduce strict building codes following the 1999 earthquake. These should have had a major impact on building standards in the 21st century. However, because of a building boom and the continuing practice of construction amnesty, many buildings did not meet the standards. A tax levy was mainly used to fund transport and other infrastructure development, where there is a rapid community payoff.

Earthquake death tolls are a basic statistic indicative of the capability of a country to manage seismic risk. The grim Turkish death toll of 50,000 from the Kahramanmaraş earthquake doublet of 6 February 2023 is a tragic indicator of the need for substantial national improvement in Turkish seismic risk management. On 12 April 2023, this need was addressed when Turkish President Erdoğan announced on CNN Türk a U-turn on construction amnesties. The construction and registration of buildings that do not meet license and zoning regulations will be considered a violation of Article 50 in Turkey's Constitution, and such offences will offer no possibility of pardon.

6 International earthquake building code compliance issues

As with all public protection measures, the importance of earthquake building codes is most appreciated when a dangerous event occurs. Deficiencies in public protection may not be noticed until they are exposed by danger itself. The diverse factors compromising compliance with an earthquake building code are manifest when an earthquake strikes the built environment.

The issue of building code compliance may not come up for practical remedial action until after the occurrence of an earthquake. In the context of the highly earthquake-prone country of Nepal, Ahmed et al. (2018) reported that enforcement and compliance with the building code gained attention in Nepal after the catastrophic destruction of the 25 April 2015 Gorkha earthquake. Attention should have been focused earlier on the seismic safety of school buildings. Counterfactually, the earthquake death toll of 9,000 would have been far worse if the earthquake had not occurred on a Saturday, when there were no children in the 26,000 wrecked classrooms. The date and time of an earthquake may be a lottery; but seismic safety need not be.

As with Nepal in 2015, the most significant earthquake in 2023 was in Turkey, and Turkish building code compliance has come to the fore as a priority issue for discussion. The seismic safety issues of informal construction in Turkey merit consideration within a broader international context. In many countries, building code regulation is dysfunctional regarding compliance. In some countries, compliance with the code regulations may be unrealistic due to the cost of construction materials and unavailability of the materials within reach of people. A World Bank report by Moullier (2014) noted that compliance issues in implementation, enforcement, verification and inspection played a major role in the 1999 Kocaeli earthquake.

In a number of cities other than in Turkey, substantial levels of illegality in land-use and building development may be interpreted as a consequence of improper and unsatisfactory planning and zoning rules, rather than any intrinsically criminal intent. The possibility to access legal housing is profoundly influenced by the costs of conforming with official rules and standards. If these economic and social costs are too burdensome for individuals, they seek different, alternative routes. Non-compliance is therefore a survival strategy that gives access to assets that would otherwise remain outside reach.

Social scientists, rather than earthquake engineers, recognize that extra nuance in the choice of vocabulary is helpful if not essential in comprehending the prevalent human factors underlying building code non-compliance. The Italian philosopher, Amedeo Conte (2000), defines *nomotropism* as acting in light of rules (i.e., on the basis of rules, in view of rules, or with reference to rules). Acting in light of rules does not necessarily entail acting in conformity with rules. Indeed, acting in conformity with rules merely denotes a limiting case of *nomotropism*. Buildings that do not conform with rules may be categorized generically as informal, rather than illegal, which has a pejorative criminal connotation.

6.1 Urban construction informality in Italy and seismic risk

Like urban informality, building amnesties are far from unique to Turkey. One country that also resorts to building amnesties is Italy, where illegal construction accounted for a large slice of the Italian building sector for several decades during the second half of the 20th century (Zanfi, 2013), and building amnesties have been regularized since the early 1980s (Chiodelli, 2021). The issue of informal construction can be understood within the broad context of post-war building policy in Italy as an implicit social contract between the middle classes and the authorities (Chiodelli et al., 2021). However, with increased risk awareness, risk perception and communication, fewer citizens should prioritize immediate economic benefits (cheaper and laxer standards of construction) rather than more expensive mitigation strategies that might be beneficial in the longer term.

There are two main types of building violation in Italy. The first type of violation is represented by entire residential buildings erected without authorization on areas that are not zoned for residential use. In this case, it is mainly land-use laws at the national and regional level, and planning regulations at the local level, that are broken. This is the type of violation that is most commonly associated with unauthorized building in Italy. The second type of violation involves the illegal extension of authorized buildings, such as the addition of one room to an apartment through the enclosure of a balcony or the addition of an entire floor at the top of a building. In this case the land use rules are not violated, but local building regulations are. This second type of violation is generally less visible.

Unauthorized housing construction in Italy, *abusivismo edilizio*, in most cases is not dilapidated construction, but houses that, from a physical point of view, are very similar to, and sometimes indistinguishable from those built legally. The illegal extension of authorized buildings offers benefits for the occupants, but can produce negative safety externalities, such as a reduction in the integrity of buildings to earthquake shaking.

These negative externalities have been tragically exposed by the 2023 Kahramanmaraş earthquake doublet, which is of international importance in highlighting an insidious systemic risk which may only be appreciated fully when a major earthquake eventually strikes. Construction informality is not a matter just for individual households. There is an intrinsic socio-political dimension which spreads the principle of informality across entire cities and regions across a nation. Construction informality is an outcome of the acceptance by authorities that building code compliance may not be a realistically achievable societal objective in some active seismic regions.

7 Conclusion

The Kahramanmaraş doublet earthquakes of 6 February 2023 were generated by a surprising combination of multiple fault segment ruptures. The degree of surprise, combined with high levels of ground motion relative to the risk-based Turkish building code, indicate that the seismic hazard contribution from M7.5+ earthquakes involving runaway multiple fault ruptures on the East Anatolian Fault had been under-represented. Where ground motion levels exceed a building's design level, it is crucial that the construction process has been rigorous so that safety margins may be maintained. However, the large Turkish death toll of around 50,000 reflects the erosion of safety margins for Turkish homes, many of which received a construction amnesty for economic reasons. Afterwards, the mayor of Istanbul drew attention to the large number of buildings in the Istanbul metropolis that have received the construction amnesty, and lamented that Istanbul is not ready for a large earthquake. Two decades earlier, Bakir and Boduroğlu (2002) from Istanbul Technical University highlighted the pressure of economic migration to the Marmara region to increase informal housing and the offer of amnesties.

Counterfactually, a large fault rupture impacting Istanbul might have happened almost a quarter of a century earlier with the occurrence of the 17 August 1999 Kocaeli earthquake. There might have been a multiple segment runaway rupture of the North Anatolian Fault propagating westwards past Istanbul. As a further downward counterfactual, the degree of informal housing in Istanbul might have been significantly higher than generally estimated. Consideration of this downward counterfactual combination in the years prior to the 2023 Kahramanmaraş doublet earthquake would have contributed to raising seismic awareness and preparedness, particularly in the Istanbul metropolis. Furthermore, consideration of an analogous multiple segment runaway rupture on the East Anatolian Fault would have raised prior risk awareness of such a hazardous scenario.

In seismic risk assessment, consideration is given to standard human risk factors such as error, negligence and malice that contribute to aggravating the seismic risk. An additional human risk factor, publicized internationally as never before, by the high death toll from the 2023 Kahramanmaraş doublet earthquakes is the granting of construction amnesties for electoral advantage. Such amnesties are understandably popular, and serve a clear socio-economic purpose, but they hold a dangerous attraction for those who may have little option but to live in informal accommodation for lack of adequate provision of public housing.

In deference to the victims of any major disaster with a high death toll, lessons need to be learned for the future. In particular, previous shortcomings need to be identified clearly. There were deficiencies in both the assessment of seismic hazard and in the vulnerability of buildings. The specific sequence of fault segments which ruptured was missing from all seismic hazard models, both those developed within Turkey as well as internationally, and the extent of code-noncompliance had been widely underestimated. These are independent risk factors, which compounded to amplify significantly the scale of the earthquake disaster.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

GW: Writing–original draft, Writing–review and editing. MG: Writing–original draft, Writing–review and editing. FN: Writing–original draft, Writing–review and editing. OA: Writing–original draft, Writing–review and editing. RR: Writing–original draft, Writing–review and editing. PC: Project administration, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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