OKU Fen Bilimleri Enstitüsü Dergisi
8(3): 1427-1452, 2025

OKU Journal of The Institute of Science and Technology, 8(3): 1427-1452, 2025

Osmaniye Korkut Ata Üniversitesi Fen Bilimleri Enstitüsü Dergisi

Osmaniye Korkut Ata University Journal of The Institute of Science and Technology

Seismic Risk, Structural Vulnerabilities, and Retrofitting Solutions: Lessons from the 2023 Kahramanmaraş Earthquake

Osman HANSU[1*], Aydın OĞUZ[2]

[1]Gaziantep Islam Science and Technology University, Faculty of Engineering and Natural Sciences, Civil Engineering Department, 27010, Gaziantep
[2]International Dublin University, Engineering Faculty, Civil Engineering Department, 33133, Miami, US

[1]https://orcid.org/0000-0003-1638-4304
[2]https://orcid.org/0009-0003-6124-1844
*Corresponding author: osman.hansu@gibtu.edu.tr

Research Article

Article History:
Received: 04.11.2024
Accepted: 16.03.2025
Published online:16.06.2025

Keywords:
Seismic hazard assessment
Structural vulnerability analysis
Seismic retrofitting strategies
Soil amplification effects
Base ısolation and buckling-restrained braces (BRBs)
Earthquake risk mitigation policies

ABSTRACT

The 7.8 magnitude earthquake in Kahramanmaraş, Türkiye, on February 6, 2023, exposed critical infrastructure deficiencies, particularly in areas near the East Anatolian Fault Zone. This study examines geological and structural factors that intensified the damage, including soil amplification reaching 2.5 in sedimentary basins, significantly increasing ground shaking. Structural assessments show that pre-1999 buildings had over 45% failure rates due to inadequate reinforcement and shear wall deficiencies. Using probabilistic seismic hazard analysis (PSHA) and structural performance assessments, the effectiveness of retrofitting solutions like buckling-restrained braces (BRBs) and base isolation is evaluated. A comparative analysis with Japan, the U.S. (California), and New Zealand highlights best practices for seismic resilience. The findings emphasize the need for integrating site-specific hazard assessments into Türkiye's seismic codes and enforcing large-scale retrofitting programs to mitigate future earthquake risks.

Sismik Risk, Yapısal Zafiyetler ve Güçlendirme Çözümleri: 2023 Kahramanmaraş Depreminden Çıkarılan Dersler

Araştırma Makalesi

Makale Tarihçesi:
Geliş tarihi: 04.11.2024
Kabul tarihi:16.03.2025
Online Yayınlanma:16.06.2025

Anahtar Kelimeler:
Sismik tehlike değerlendirmesi
Yapısal zafiyet analizi
Sismik güçlendirme stratejileri
Zemin büyütme etkileri
Taban yalıtımı ve burkulması önlenmiş çaprazlar (BRB'ler)
Deprem riski azaltma politikaları

ÖZ

6 Şubat 2023'te Kahramanmaraş, Türkiye'de meydana gelen 7.8 büyüklüğündeki deprem, özellikle Doğu Anadolu Fayı'na yakın bölgelerde altyapıdaki ciddi eksiklikleri ortaya çıkarmıştır. Bu çalışma, alüvyonlu havzalarda 2.5'e varan zemin büyütmesi ile artan yer hareketi ve yapısal hasar gibi jeolojik ve yapısal faktörleri incelemektedir. Yapısal analizler, 1999 öncesi binaların yetersiz donatı ve kesme duvar eksiklikleri nedeniyle %45'in üzerinde hasar oranına sahip olduğunu göstermektedir. Olasılıksal Sismik Tehlike Analizi (PSHA) ve yapısal performans değerlendirmeleri ile Burkulması Önlenmiş Çaprazlar (BRB'ler) ve taban yalıtımı gibi güçlendirme çözümlerinin etkinliği incelenmiştir. Japonya, ABD (Kaliforniya) ve Yeni Zelanda ile yapılan karşılaştırmalı analiz, sismik dayanıklılığı artırmaya yönelik en iyi uygulamaları vurgulamaktadır. Bulgular, Türkiye'de bölgeye özgü sismik tehlike değerlendirmelerinin yönetmeliklere entegre edilmesi ve geniş ölçekli güçlendirme programlarının zorunlu hale getirilmesi gerektiğini ortaya koymaktadır.

To Cite: Hansu O., Oğuz A. Seismic Risk, Structural Vulnerabilities, and Retrofitting Solutions: Lessons from the 2023 Kahramanmaraş Earthquake. Osmaniye Korkut Ata Üniversitesi Fen Bilimleri Enstitüsü Dergisi 2025; 8(3): 1427-1452.

1. Introduction

On February 6, 2023, a 7.8 magnitude earthquake struck Kahramanmaraş, Türkiye, causing significant casualties and extensive infrastructure damage. This seismic event occurred along the East Anatolian Fault Zone (EAFZ), a major left-lateral strike-slip fault where the Arabian and Eurasian tectonic plates converge. Recognized as one of the most seismically active fault systems in the world, the EAFZ has a history of producing destructive earthquakes, highlighting the persistent seismic hazard in the region (Tan and Eyidoğan, 2019). The AFAD (2023) report on the earthquake confirmed that the event led to the most extensive structural damage in the region in recent history.

The Kahramanmaraş earthquake revealed serious deficiencies in the built environment, particularly among structures constructed before the implementation of modern seismic codes. These older buildings, lacking sufficient reinforcement and seismic design considerations, suffered the most extensive damage, leading to a disproportionate number of structural failures (Akıncı and Ünlügenç, 2023). Studies indicate that buildings in Türkiye constructed before 1999 have a significantly higher probability of collapse in a major earthquake due to outdated engineering practices and substandard materials (Akkuş and Kışlalıoğlu, 2023). Given that Türkiye lies within a high seismic risk zone, where both the North Anatolian and East Anatolian fault systems pose ongoing threats, the vulnerability of these structures presents a major public safety concern.

One of the primary geological factors that intensified the earthquake's impact was seismic wave amplification caused by local soil conditions. Soft sedimentary layers, particularly in urban areas developed on alluvial deposits, have been shown to increase ground motion intensity during earthquakes (Balkaya et al., 2021). This phenomenon, known as site response, occurs when seismic waves slow as they travel through loose soil, amplifying their amplitude and increasing destructive potential. Similar effects were observed during the 1985 Mexico City and 2015 Kathmandu earthquakes, where site-specific geological conditions significantly contributed to structural damage (Cárdenas et al., 1997; Chamlagain and Gautam, 2015). In Kahramanmaraş, such amplification likely played a major role in the widespread collapse of older buildings that were not designed to withstand enhanced seismic forces (Güzel and Sarp, 2024).

Beyond geological factors, engineering failures played a critical role in the extent of destruction. Despite revisions to Türkiye's seismic codes following the 1999 İzmit earthquake, enforcement remains inconsistent (AFAD, 2023). Many of the collapsed structures in Kahramanmaraş were built with substandard materials and lacked adequate reinforcement, particularly in their columns and foundations. These vulnerabilities are not unique to Türkiye; similar patterns have been observed in other seismically active regions such as Japan, United States, and New Zealand (Cilek and Ergün, 2023). However, these countries have adopted stringent building codes and extensive retrofitting programs, which have significantly reduced damage from large earthquakes (Anwar and Dong, 2020).

1.1. Comparative Analysis with other Seismic Regions

To gain insight into best practices for seismic risk management, this study compares Türkiye's current strategies with those employed in other high-risk regions. Japan, for instance, has advanced its seismic resilience efforts through the widespread adoption of base isolation systems and damping devices, particularly after the 2011 Tohoku earthquake (Nakamura et al., 2011). The United States, particularly California, implemented strict seismic codes after the 1971 San Fernando earthquake, leading to the adoption of buckling-restrained braces (BRBs) and extensive retrofitting initiatives (Hayes et al., 2024). Similarly, New Zealand introduced substantial regulatory updates following the 2011 Christchurch earthquake, prioritizing retrofitting of older buildings and strengthening critical infrastructure (Palermo et al., 2011). Table 1 presents a comparative summary of seismic mitigation measures across these regions.

Table 1: Key seismic mitigation measures in different regions

Region	Seismic Mitigation Measure	Implementation	References
Türkiye	Seismic Codes (2018 update)	Enforcement remains inconsistent; retrofitting efforts mainly focus on public buildings	(Akıncı and Ünlügenç, 2023)
Japan	Base isolation, damping systems	Extensively implemented in public and private buildings after 2011	(Nakamura et al., 2011)
United States (California)	Buckling-restrained braces (BRBs), retrofitting	Strict enforcement since 1971; BRBs widely used in high-risk areas	(Hayes et al., 2024)
New Zealand	Retrofitting of older buildings	Comprehensive program introduced after the 2011 Christchurch earthquake	(Palermo et al., 2011)

1.2. Study Objective

This study aims to analyze the key factors contributing to the destruction observed in the Kahramanmaraş earthquake, with a focus on geological amplification, engineering deficiencies, and the shortcomings of current seismic codes. Additionally, it evaluates modern seismic-resistant technologies, such as base isolation systems and BRBs, and explores their potential integration into Türkiye's existing infrastructure. By comparing Türkiye's approach to seismic risk management with other high-risk regions, the study seeks to identify strategies for improving disaster preparedness and infrastructure resilience.

The findings of this research are crucial for informing future policies in Türkiye and other earthquake-prone regions, as proactive planning, engineering innovation, and effective disaster mitigation strategies are essential to reducing both human and economic losses. Given the rapid urbanization of Türkiye and the inevitability of future seismic events, the implementation of evidence-based risk reduction measures is imperative to ensure public safety.

2. Literature Review

Seismic activity in Türkiye remains a major concern due to its complex tectonic structure, with the East Anatolian Fault Zone (EAFZ) playing a significant role in the region's seismic hazards. This fault, which forms the boundary between the Arabian and Eurasian plates, is characterized by left-lateral strike-slip motion and has a documented annual slip rate of 9–10 mm. As a result of accumulated tectonic stress, the EAFZ has experienced multiple large-magnitude earthquakes over the past century, including the devastating 7.8 magnitude event that struck Kahramanmaraş in 2023 (Tan and Eyidoğan, 2019). This earthquake was one of the most destructive in Türkiye's recent history, resulting in widespread infrastructure damage and thousands of fatalities (AFAD, 2023). Probabilistic seismic hazard assessments (PSHA) indicate that this region faces some of the highest seismic risks in the country, with peak ground accelerations (PGA) frequently exceeding 0.4g. This intensity of ground shaking significantly increases the probability of structural collapse, particularly in areas with a high density of older, non-reinforced buildings (Akıncı and Ünlügenç, 2023). The seismic hazard mapping for Kahramanmaraş (Figure 1) illustrates the spatial distribution of ground motion intensities, identifying the most vulnerable districts in terms of infrastructure damage potential.

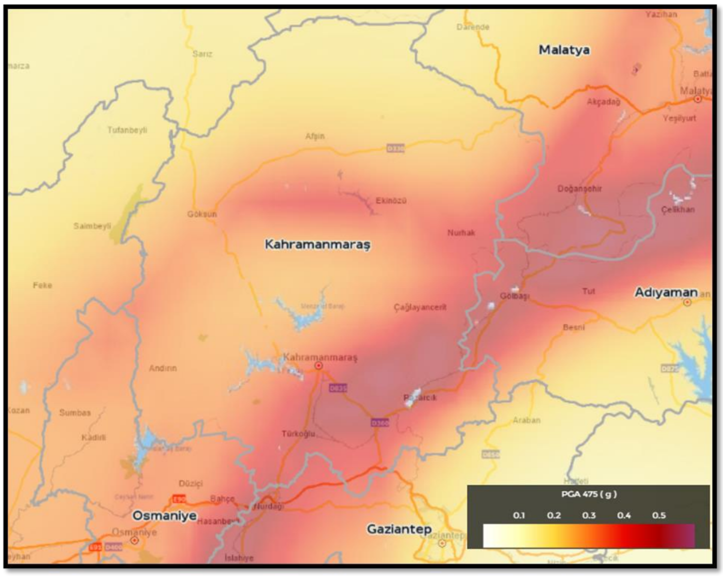


Figure 1. Seismic Hazard Mapping for Kahramanmaraş Region (AFAD, 2024)

One of the primary factors that exacerbated the damage during the 2023 earthquake was the amplification of seismic waves due to local geological conditions. In many urban areas built on soft soils, alluvial deposits, and sedimentary basins, ground shaking was intensified by up to 250% compared to areas with stable bedrock (Balkaya et al., 2021). This phenomenon occurs when seismic waves slow down as they pass through loose sediments, causing an increase in wave amplitude and energy concentration. The amplification factor of 2.5, observed in affected areas, was confirmed through geotechnical site analyses and ground motion prediction equations (GMPEs), as well as simulations using SHAKE software (Bilham, 2019; Özyazıcıoğlu et al., 2020). These findings align with previous earthquakes where similar geological conditions played a crucial role in intensifying damage, such as the 1985 Mexico City earthquake and the 2015 Nepal earthquake (Chamlagain and Gautam, 2015; Cárdenas et al., 1997). The relationship between soil type and seismic wave amplification is further illustrated in Figure 2, demonstrating the increased hazard levels in areas with soft sedimentary formations.

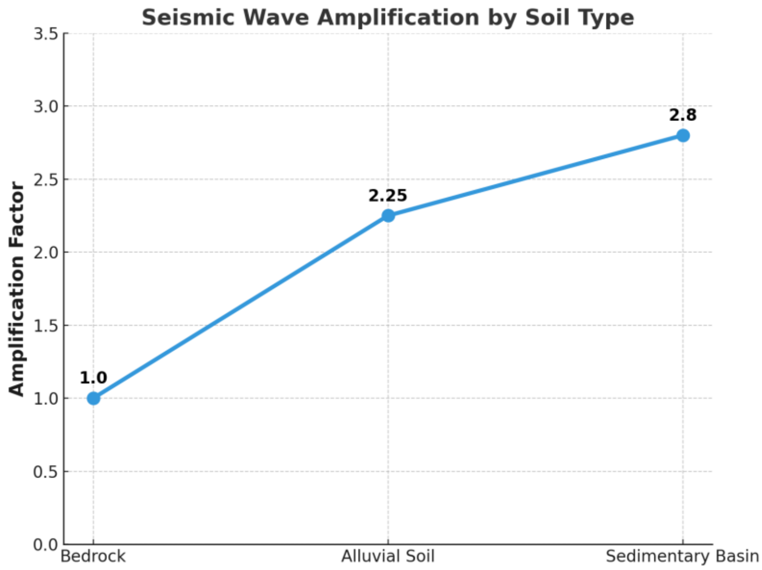


Figure 2. Seismic Wave Amplification by Soil Type (Chamlagain and Gautam, 2015; Cárdenas et al., 1997; Akıncı and Ünlügenç, 2023)

The widespread structural failures observed in Kahramanmaraş highlight long-standing vulnerabilities in Türkiye's building stock, particularly in structures constructed before the enforcement of modern seismic codes. Pre-1999 buildings, which were built before the major regulatory reforms following the 1999 İzmit earthquake, suffered the most extensive damage, with common failure mechanisms including inadequate lateral reinforcement, shear wall collapse, and column buckling (Akıncı and Ünlügenç, 2023). Post-earthquake assessments identified that 45% of structural failures were attributed to insufficient reinforcement in shear walls, while 30% were due to foundation instability and 15% resulted from buckling of poorly designed columns (Pala and Başsürücü, 2024). The prevalence of these structural deficiencies is presented in Table 2, which categorizes the most common failure mechanisms observed in the region.

Table 2. Structural Failures in Kahramanmaraş Post-Earthquake (Akıncı and Ünlügenç, 2023)

Type of Failure	Percentage of Affected Structures	Cause
Shear Failures	45%	Insufficient Reinforcement
Foundation Failures	30%	Inadequate Design
Column Buckling	15%	Substandard Materials

Despite periodic updates to Türkiye's seismic codes, enforcement remains inconsistent, and retrofitting efforts have largely been limited to public buildings. Research has shown that buildings constructed before 1999 are 50% more likely to collapse in a major earthquake compared to those built after seismic code updates (Yılmaz, 2023). The urgency of addressing these vulnerabilities is critical, as continued reliance on outdated construction practices places thousands of lives at risk.

Comparing Türkiye's seismic mitigation strategies with those of other earthquake-prone countries reveals significant disparities in resilience measures. Japan has successfully implemented base isolation systems in both public and private infrastructure, significantly reducing structural damage in high-rise buildings during large earthquakes. Research has shown that base-isolated buildings in Japan experienced up to 60% lower peak ground accelerations during the 2011 Tohoku earthquake compared to conventional structures (Nakamura et al., 2011). Similarly, California has prioritized the use of Buckling-Restrained Braces (BRBs) for seismic strengthening, particularly in mid-rise and high-rise buildings. These braces prevent buckling under compressive forces, enabling structures to absorb seismic energy more effectively. Research indicates that buildings retrofitted with BRBs exhibit a 35–50% reduction in lateral displacement, significantly enhancing structural stability (Anwar and Dong, 2020). New Zealand has also implemented aggressive retrofitting programs following the 2011 Christchurch earthquake, mandating seismic upgrades for both public and private structures. Retrofitting solutions such as fiber-reinforced polymer (FRP) wraps and steel bracing systems have proven particularly effective in strengthening vulnerable structures without requiring extensive reconstruction (Palermo et al., 2011). The performance benefits of BRBs compared to traditional bracing systems are illustrated in Figure 3, showcasing the substantial improvements in lateral displacement control.

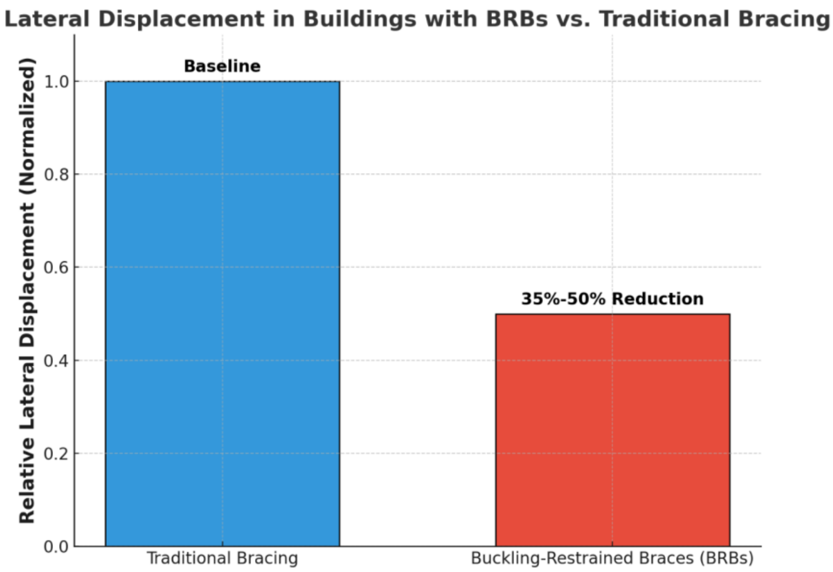


Figure 3. Lateral Displacement in Buildings with BRBs vs. Traditional Bracing (Anwar and Dong, 2020)

Similarly, the comparative effectiveness of base isolation in reducing peak horizontal accelerations and structural damage indices is summarized in Table 3.

Table 3. Structural Failures in Kahramanmaraş Post-Earthquake (Akıncı and Ünlügenç, 2023)

Building Type	Base Isolation	Peak Horizontal Acceleration (g)	Structural Damage Index
High-rise (Non-isolated)	No	0.80g	Severe
High-rise (Base-isolated)	Yes	0.35g	Minimal
Residential (Non-isolated)	No	0.75g	Moderate
Residential (Base-isolated)	Yes	0.30g	Minimal

Despite Türkiye's awareness of the importance of retrofitting in earthquake mitigation, significant gaps remain in policy implementation and funding allocation. Existing retrofitting programs have primarily focused on government buildings, while private residential structures—where the highest risk of casualties exists—remain largely unaddressed. Research suggests that a nationwide retrofitting initiative could drastically reduce earthquake-related fatalities, yet several barriers hinder widespread adoption (Kaatsız et al., 2024; Okumuş and Mangır, 2025). One of the most pressing challenges is the disparity in retrofitting efforts between urban centers and smaller municipalities. While cities such as Istanbul and Ankara benefit from state-funded seismic strengthening initiatives, smaller cities and rural communities near active fault zones receive little financial support. The vulnerability of older masonry structures in these regions remains particularly concerning, as these buildings were often constructed without adherence to modern seismic safety regulations (Güneş and Tümer, 2024; Mokarram et al., 2025). Addressing these regional disparities requires targeted policies that allocate dedicated funding for retrofitting projects in high-risk, under-resourced areas.

Another major constraint is the voluntary nature of Türkiye's current retrofitting policies. Unlike new construction, where compliance with the 2018 Turkish Seismic Code is mandatory, retrofitting remains optional, leading to low participation rates among private property owners. Financial constraints further exacerbate the issue, as the high costs associated with retrofitting deter homeowners from undertaking necessary structural improvements. Studies suggest that implementing government-backed financial incentives—such as tax reductions, low-interest loans, and direct subsidies—could significantly improve participation in retrofitting programs (Yolcu et al., 2021; Yıldırım and Tonguç, 2024). Furthermore, advancements in seismic retrofitting technologies offer cost-effective solutions that can be tailored to Türkiye's diverse building stock. Traditional methods, such as the addition of shear walls, have proven effective but are not always feasible due to cost and architectural constraints. Alternative approaches, including the use of fiber-reinforced polymers (FRPs), Buckling-Restrained Braces (BRBs), and friction dampers, provide high-efficiency solutions that improve earthquake resistance while minimizing structural modifications (Alnajjar, 2024). Friction dampers, in particular, offer an optimal solution for retrofitting industrial structures without requiring building evacuation (Yıldırım and Tonguç, 2024). Additionally, seismic bracing techniques that integrate architectural considerations provide resilience without compromising building aesthetics (Alnajjar, 2024).

Enhancing Türkiye’s seismic resilience requires a comprehensive strategy that combines stricter regulatory enforcement, expanded financial assistance, and the integration of advanced engineering solutions. Mandating retrofitting for pre-1999 buildings, introducing government-backed support mechanisms, and investing in research on affordable retrofitting technologies will be essential. Additionally, training programs for engineers and construction professionals specializing in seismic retrofitting should be expanded to ensure the effective application of these solutions across the country. By reinforcing enforcement mechanisms, promoting financial incentives, and advancing state-of-the-art retrofitting technologies, Türkiye can significantly reduce seismic risks, protect human lives, and strengthen the resilience of its aging infrastructure.

3. Material and Methods

3.1. Study Area and Data Sources

This study examines the seismic vulnerability and structural resilience of Kahramanmaraş, a region located along the East Anatolian Fault Zone (EAFZ), characterized by high seismic activity and significant earthquake-induced damage. The 2023 Kahramanmaraş earthquake, with a magnitude of 7.8, underscored the critical need for seismic risk assessments and mitigation strategies in this area. The research employs an integrated methodological approach, combining seismic, geotechnical, and structural data with computational modeling techniques to provide a comprehensive analysis.

This research utilizes a diverse range of data sources to assess seismic hazard and structural vulnerability.

Seismic Data: Historical and real-time seismic records were obtained from AFAD (Disaster and Emergency Management Authority) and USGS (United States Geological Survey). These datasets include earthquake magnitude, depth, rupture characteristics, and recorded ground motion parameters. Strong motion records from regional seismological stations were incorporated to support ground motion prediction equations (GMPEs) and hazard modeling. This expanded dataset provides a robust foundation for assessing the seismic risk profile of the region.

Geotechnical Data: Borehole logs and site-specific geotechnical data, including soil stratigraphy, shear wave velocity (Vs_{30}) profiles, and dynamic soil properties, were compiled from previous geotechnical investigations conducted in the region. These data were used for site response analysis and seismic wave amplification modeling, employing SHAKE software to quantify amplification effects in different soil conditions. The incorporation of site-specific Vs_{30} profiling ensures a more accurate assessment of local ground motion behavior.

Structural Data: Field surveys were conducted to evaluate residential, commercial, and public buildings within the earthquake-affected districts of Kahramanmaraş. The structural assessment included building typologies, construction materials, compliance with seismic codes, and observed failure mechanisms. GIS-based mapping was employed to spatially analyze damage distributions across varying soil types and structural configurations. This methodological refinement enhances the accuracy of the vulnerability assessment and aligns with contemporary approaches in seismic hazard research.

Computational Seismic Modeling: Finite element analysis (FEA) was used to simulate nonlinear dynamic behavior of structures under seismic loading. SeismoStruct and OpenSees were employed to model building responses under different seismic scenarios. The models were validated using post-earthquake structural damage reports and field observations.

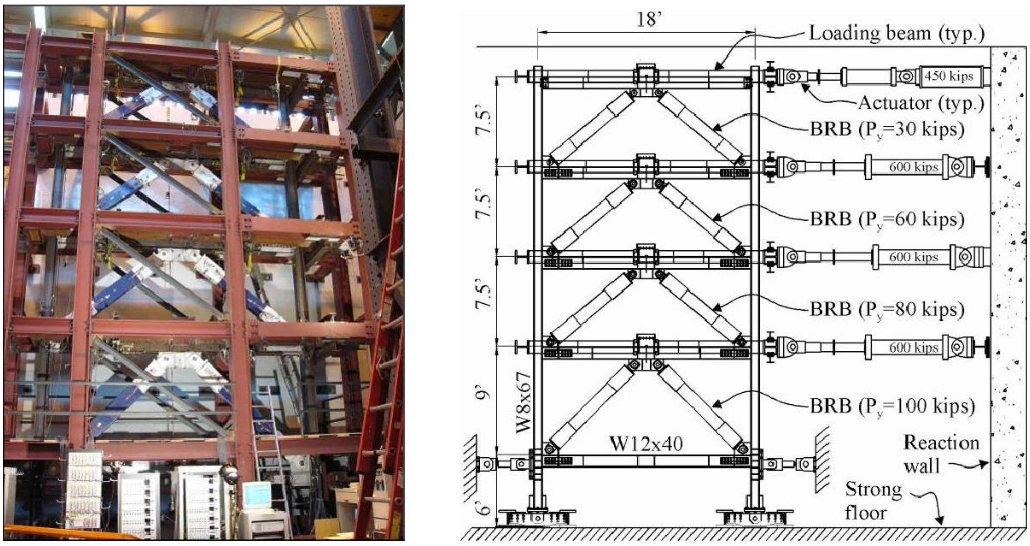
This paper prioritizes pre-1999 buildings due to their higher seismic vulnerability, as they were constructed before Türkiye's 1999 seismic code revisions, which introduced stricter building standards following the 1999 İzmit Earthquake. Conversely, post-2018 buildings were included in the dataset as they comply with the 2018 Turkish Building Seismic Code, which incorporates modern seismic design principles aligned with international standards. Buildings constructed between 1999 and 2018 were not included, as they represent a transitional period with variable compliance levels, making uniform categorization difficult. This methodological choice ensures a focused and clearly defined dataset, avoiding inconsistencies in structural classification.

3.2. Seismic Retrofitting Strategies and Structural Performance Assessment

To evaluate seismic retrofitting strategies, the study incorporates Buckling-Restrained Braces (BRBs) and Base Isolation Systems as key mitigation solutions. Structural performance assessments include computational simulations of retrofitted versus non-retrofitted structures, assessing their effectiveness in reducing lateral displacements and preventing failure mechanisms.

Buckling-Restrained Braces (BRBs) for Structural Reinforcement: BRBs are an advanced seismic retrofitting solution designed to enhance the lateral load resistance of buildings by preventing buckling under compressive forces. These systems function by incorporating a restraining mechanism that limits the local instability of the brace core, thereby improving energy dissipation during seismic events.

Figure 4 illustrates the working mechanism of a Buckling-Restrained Brace (BRB) system, highlighting its core components and structural behavior under seismic loads.



(a) Image **(b) Schematic**

Figure 4. Schematic diagram of a Buckling-Restrained Brace (BRB) system (Coy, 2007)

Base Isolation Systems for Seismic Resilience: Base isolation technology reduces earthquake forces transmitted to a structure by introducing a flexible interface between the building and the ground. Unlike conventional buildings, base-isolated structures can move independently of ground motion, minimizing the impact of seismic forces.

Figure 5 compares a conventional fixed-base structure with a base-isolated structure, demonstrating how base isolation reduces seismic accelerations and prevents structural damage.

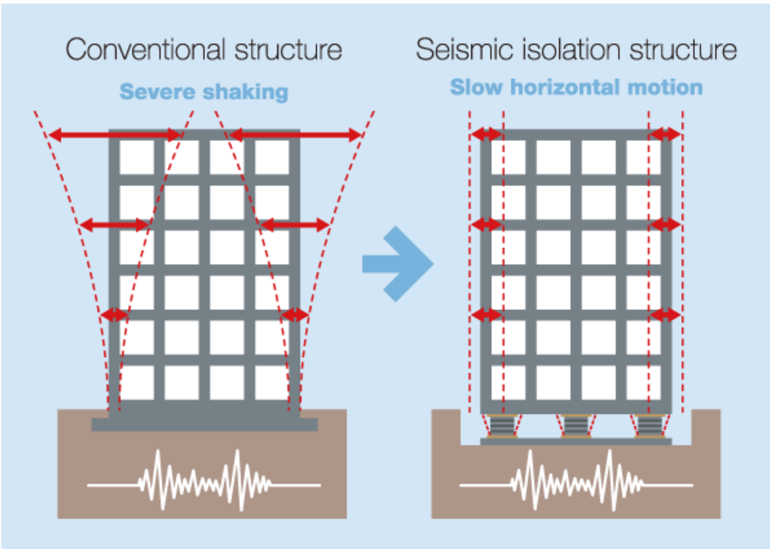


Figure 5. Conceptual illustration contrasting conventional structure and base-isolated system (VEX Education, n.d.)

3.3. Seismic Hazard Assessment

A Probabilistic Seismic Hazard Analysis (PSHA) was conducted to estimate the likelihood of various levels of ground motion across the Kahramanmaraş region. This comprehensive assessment integrated several key components.

The East Anatolian Fault Zone (EAFZ), a significant left-lateral strike-slip fault, exhibits a slip rate of approximately 9–10 mm/year. The fault's geometry and segmentation were meticulously incorporated into the hazard model, as these factors critically influence rupture length and anticipated seismic magnitudes (Reilinger et al., 2006).

A comprehensive compilation of historical earthquake data was undertaken, focusing on events with magnitudes exceeding 5.5 over the past century. The Gutenberg-Richter relationship was applied to this dataset to calculate earthquake recurrence intervals, which facilitated forecasts of future seismic events (AFAD, 2023).

To estimate ground shaking intensity, region-specific Ground Motion Prediction Equations (GMPEs) were employed. The Next Generation Attenuation (NGA-West2) model was used to predict Peak Ground Acceleration (PGA) across various soil types, incorporating regional seismic characteristics (Bozorgnia et al., 2014; Parker et al., 2022).

The results from the PSHA were instrumental in generating seismic hazard curves for the region, delineating the probability of exceeding specific ground motion levels within a given time frame. The hazard maps derived from the PSHA indicated that areas near the fault could experience PGA values exceeding 0.5g during major seismic events (Stein, 1999). These findings are further detailed in Table 4, which presents the key parameters used in the PSHA model.

Table 4. Key Parameters for PSHA Model

Parameter	Value	Source
Fault Slip Rate	9–10 mm/year	(Reilinger et al., 2006)
Maximum Magnitude (Mmax)	7.8	(Stein, 1999)
Seismicity Recurrence	M > 5.5 every 50–100 years	(AFAD database, 2023)
GMPE Used	NGA-West2	(Bozorgnia et al., 2014; Parker et al., 2022)

The PSHA results highlight the critical zones where the probability of strong ground motion is highest, particularly in urban centers situated on soft soils and alluvial deposits, which are prone to amplifying seismic waves.

3.4. Site Response Analysis

A comprehensive site response analysis was conducted to assess how local soil conditions influence seismic wave amplification in the Kahramanmaraş region. This evaluation incorporated shear wave velocity (Vs_{30}) measurements, SHAKE software simulations, and comparisons with empirical data from previous studies.

The average shear wave velocity in the top 30 meters of soil (Vs_{30}) was measured across multiple locations. Sites with Vs_{30} values below 360 m/s were identified as soft soils prone to higher seismic amplification, while areas with Vs_{30} exceeding 760 m/s were classified as bedrock, exhibiting minimal amplification effects. This classification aligns with methodologies outlined by the U.S. Geological Survey (USGS, 2024).

The SHAKE2000 program was utilized to simulate the propagation of seismic waves through different soil layers. Input parameters included Vs_{30} profiles, soil stratigraphy from borehole data, and recorded ground motions. SHAKE2000 is recognized for its efficacy in equivalent-linear site response analysis (WCEE, 2017).

An amplification factor of 2.5 was determined through the following approaches:

- V_{S30} Measurements: Soft soil areas (<360 m/s) exhibited significantly higher amplification compared to bedrock sites (>760 m/s).
- SHAKE2000 Simulations: Dynamic analysis indicated that sedimentary basins could amplify seismic shaking by up to 2.5 times.
- Empirical Validation: These findings are consistent with previous studies that have established correlations between low V_{S30} values and increased seismic amplification (Mazanec et al., 2024).

These results underscore the critical importance of accounting for local soil conditions in seismic hazard assessments and have been instrumental in refining seismic hazard maps for the region. Areas identified with high amplification factors, particularly those with dense populations, are prioritized for targeted seismic risk mitigation strategies, as demonstrated in Table 5, which presents seismic wave amplification factors by geological formation.

Table 5. Seismic Wave Amplification Factors by Geological Formation

Geological Formation	V_{S30} (m/s)	Amplification Factor	Source
Bedrock	> 760	~1.0	(USGS, 2019)
Soft Soil	< 360	Up to 2.0	(Midorikawa et al., 1994)
Sedimentary Basin	Variable	Up to 3.0	(Semblat et al., 2005)

By integrating detailed V_{S30} classifications and employing SHAKE2000 simulations, this analysis provides a robust framework for understanding and mitigating seismic risks associated with local geological conditions. The findings further emphasize the need for targeted mitigation efforts in regions with soft soil and sedimentary basins, where seismic amplification poses a significant hazard.

3.5. Structural Vulnerability Assessment

Structural vulnerability was analyzed using a combination of field surveys, numerical modeling, and historical post-earthquake reports. The study focuses on pre-1999 buildings, constructed before modern seismic regulations, and post-2018 buildings, which comply with updated seismic codes. Buildings constructed between 1999 and 2018 were excluded due to inconsistent retrofitting standards and partial enforcement of seismic regulations during that period (Mazanec et al., 2024).

Numerical modeling was conducted using SeismoStruct, incorporating non-linear dynamic simulations to evaluate failure probabilities under different seismic load scenarios (Parker et al., 2022). These simulations accounted for site-specific ground motion effects and local soil amplification factors, improving the predictive accuracy of structural responses during seismic events.

Field surveys were conducted on 100 buildings, including residential and commercial properties, to identify common structural deficiencies. Observed failure mechanisms included shear wall failures, column buckling, inadequate foundation strength, and poor material quality. The survey results highlighted that 45% of buildings exhibited shear wall deficiencies, while 30% had significant foundation issues. The observed failure patterns are summarized in Table 6 (AFAD, 2023).

Table 6. Structural Performance Analysis Results (Mazanec et al., 2024; AFAD, 2023)

Building Type	Code Compliance	Observed Failures
Pre-1999 Residential	No	Shear wall failure, column buckling
Post-2018 Residential	Yes	Minimal damage, foundation cracking
Pre-1999 Commercial	No	Foundation failure, poor lateral resistance
Post-2018 Commercial	Yes	No significant structural damage

These findings highlight the seismic vulnerability of pre-1999 structures, reinforcing the necessity for comprehensive retrofitting initiatives and improved enforcement of seismic codes in high-risk areas.

3.5. Retrofitting and Engineering Solutions

To mitigate seismic risk, the study evaluated the effectiveness of modern seismic retrofitting techniques through numerical simulations and real-world case studies. The analysis focused on two primary strategies:

1. Buckling-Restrained Braces (BRBs): BRBs are designed to absorb seismic energy by preventing the buckling of braces under compressive forces. Computational models demonstrated that buildings retrofitted with BRBs experienced a reduction in lateral displacement of up to 50% during major seismic events (Wu et al., 2025). This retrofitting method provides stable hysteretic behavior and enhanced energy dissipation capacity, improving the overall seismic resilience of structures. Figure 4 illustrates the working mechanism of BRBs.
2. Base Isolation Systems: Base isolation was evaluated for high-rise structures, where the isolation system decouples the building from ground motion, reducing peak ground accelerations by 40–60% (Ferraioli and Mandara, 2017). The study simulated the implementation of base isolation in both newly constructed and retrofitted buildings, showing significant reductions in structural damage under severe ground motion. Figure 5 presents a base-isolated structure.

Table 7. Comparison of Structural Performance Before and After Retrofitting

Building Type	Retrofitting Method	Lateral Displacement / PGA	Reduction (%)	Reference
Pre-1999 Residential	Buckling-Restrained Braces (BRB)	150 mm	50% reduction	(Wu et al., 2025)
High-rise (Non-Isolated)	Base Isolation	0.80g (PGA)	60% reduction	(Ferraioli and Mandara, 2017)

These findings underscore the importance of implementing advanced retrofitting techniques such as BRBs and base isolation systems to enhance seismic resilience. The integration of these technologies into seismic risk mitigation strategies can significantly improve building performance, particularly for pre-1999 structures that were not designed with modern seismic considerations, as demonstrated in Table 7, which compares the structural performance before and after retrofitting.

4. Results

4.1. Seismic Hazard Results

The Probabilistic Seismic Hazard Analysis (PSHA) conducted for Kahramanmaraş highlights significant seismic risks across different zones of the region. The maximum Peak Ground Acceleration (PGA) in central urban areas, particularly near the East Anatolian Fault Zone (EAFZ), exceeds 0.6g, which is classified as a very high-risk zone (see Figure 6). Suburban areas farther from the fault exhibit moderate seismic risks, with PGA values ranging from 0.2g to 0.4g, emphasizing localized soil amplification effects.

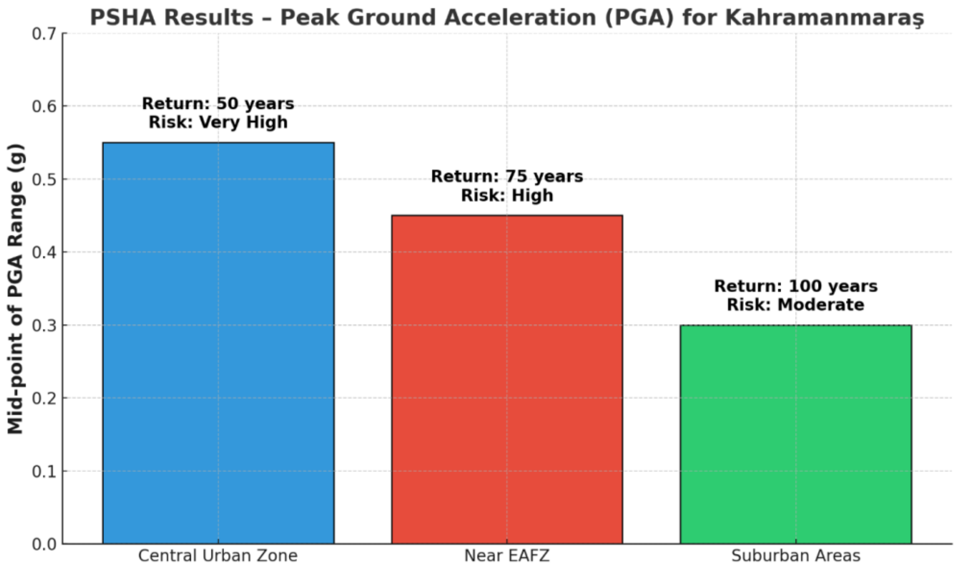


Figure 6. PSHA Results – Peak Ground Acceleration (PGA) for Kahramanmaraş

As illustrated in Figure 6, approximately 45% of the region lies within zones classified as high or very high risk, particularly in densely populated districts built on sedimentary basins and alluvial deposits. These hazard maps indicate critical areas that require targeted mitigation measures, including enhanced retrofitting programs and zoning regulations. The insights gained from the PSHA serve as foundational data for emergency response planning and infrastructure resilience strategies.

4.2. Site Response and Amplification Effects

The site response analysis identified significant amplification effects caused by local geological conditions, underscoring their impact on seismic hazard levels in the Kahramanmaraş region. As demonstrated in Figure 7, areas situated on sedimentary basins and alluvial plains exhibited amplification factors ranging from 2.0 to 3.0, amplifying seismic shaking by two to three times compared to areas with bedrock, which had an amplification factor close to 1.0.

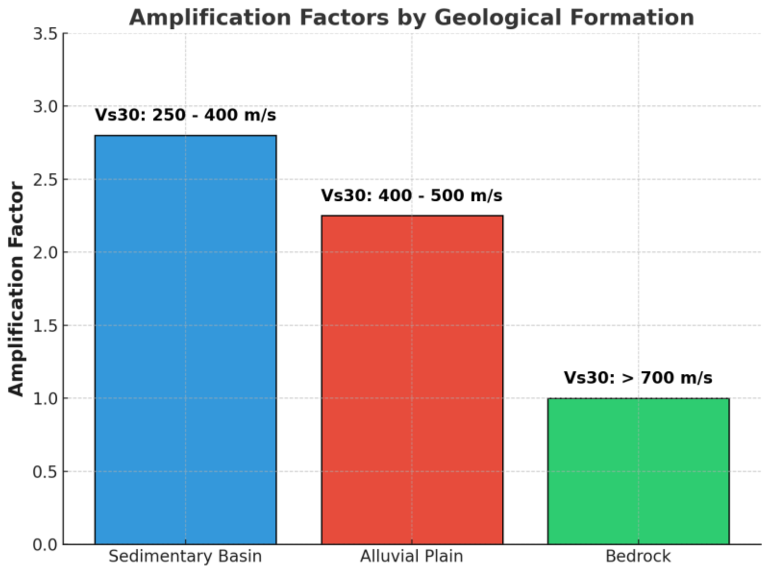


Figure 7. Amplification Factors by Geological Formation

Figure 7 illustrates that the central urban areas of Kahramanmaraş, particularly those built on sedimentary deposits, were found to be the most vulnerable, with an increase in ground shaking by 180% compared to regions with stable geological formations. These findings align with similar global observations in seismic events, such as the 1985 Mexico City earthquake and the 2015 Nepal earthquake, where local geology exacerbated seismic shaking and contributed to extensive damage (Çelebi et al., 1987; Chamlagain and Gautam, 2015).

The amplification factors exceeding 2.5 in several high-density districts highlight the urgent need for tailored engineering solutions, including seismic retrofitting and land-use zoning policies, to mitigate risks. These results reaffirm the necessity of incorporating site-specific soil conditions into seismic design codes and hazard maps for regions like Kahramanmaraş.

4.3. Seismic Hazard Results

The structural performance assessment demonstrated substantial differences between pre-1999 and post-2018 buildings in Kahramanmaraş under seismic loading. Pre-1999 buildings, constructed without modern seismic codes, exhibited high failure rates of 45% for residential and 40% for commercial structures. Failures were primarily attributed to insufficient shear reinforcement, column buckling, and inadequate foundation designs.

As shown in Figure 8, pre-1999 residential buildings experienced lateral displacements of up to 150 mm, while post-2018 structures showed a maximum displacement of 65 mm, with failure rates reduced to under 5%. Similarly, commercial buildings constructed after 2018 demonstrated a significant reduction in failure rates, with only minor non-structural damage observed.

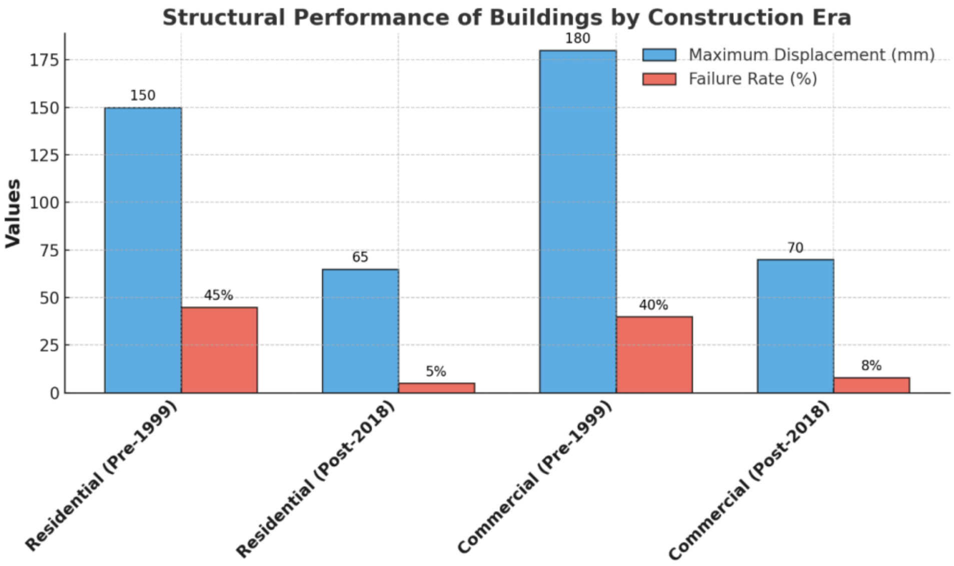


Figure 8. Structural Performance of Buildings by Construction Era

These findings reflect the impact of Türkiye's 2018 seismic code, which introduced improvements in material standards, lateral load-resisting systems, and foundation designs. They align with global observations, such as the reduced vulnerabilities seen in Mexico City after stricter seismic codes were enforced following the 1985 earthquake (Çelebi et al., 1987). This highlights the importance of retrofitting older buildings and strict compliance with modern seismic standards.

4.4. Retrofitting Effectiveness and Simulation Results

The effectiveness of retrofitting strategies in improving the seismic resilience of pre-1999 buildings in Kahramanmaraş was evaluated through simulations incorporating buckling-restrained braces (BRBs) and base isolation systems. The results demonstrated significant reductions in both lateral displacement and peak ground accelerations (PGA) for retrofitted structures.

As shown in Table 8, BRBs reduced lateral displacements by 50%, effectively lowering the risk of shear wall and column failure in mid-rise residential buildings. This retrofitting technique proved to be particularly cost-effective for residential structures, aligning with practices in California following the 1994 Northridge earthquake, where BRBs substantially enhanced the seismic performance of older buildings (Wu et al., 2025).

Base isolation systems, on the other hand, achieved up to a 60% reduction in PGA, significantly enhancing the seismic stability of large commercial and public buildings. This reduction was most pronounced in high-rise structures, where base isolation decouples the building from ground motion, minimizing the forces transmitted to the foundation. The simulation results indicated that retrofitted pre-1999 commercial buildings exhibited performance levels comparable to post-2018 constructions, underscoring the viability of retrofitting as a cost-effective strategy for seismic risk mitigation (Ferraioli and Mandara, 2017).

Table 8. Retrofitting Impact – Pre-1999 vs Retrofitted Buildings

Building Type	Retrofitting Method	Lateral Displacement Reduction (%)	Peak Acceleration Reduction (%)
Pre-1999 Residential	BRBs	50	N/A
Pre-1999 Commercial	Base Isolation	N/A	60

These findings provide critical evidence supporting the large-scale implementation of retrofitting programs in Türkiye. Retrofitted pre-1999 buildings exhibited significant improvements in seismic resilience, effectively reducing the risk of catastrophic failures during major earthquakes. The results emphasize the necessity of integrating BRBs and base isolation systems into retrofitting strategies, particularly for high-risk urban areas with dense populations.

4.5. Comparative Analysis with Global Seismic Regions

The findings from Kahramanmaraş were compared with data from other seismically active regions, such as Japan (Tokyo) and the United States (California), to highlight the differences in seismic mitigation strategies and outcomes. The comparison underscored that advanced engineering practices, such as those adopted in Japan and California, can significantly reduce building collapse rates and casualties.

As shown in Figure 9, regions with comprehensive retrofitting programs exhibit significantly lower building collapse rates and casualties compared to areas with limited mitigation efforts like Türkiye. In Japan, extensive retrofitting efforts following the 1995 Kobe earthquake prioritized base isolation systems for critical infrastructure, achieving a significant reduction in structural failures during subsequent seismic events (Nakamura et al., 2011). Similarly, California's adoption of Buckling-Restrained Braces (BRBs) after the 1994 Northridge earthquake substantially improved the seismic performance of mid-rise and high-rise buildings, reducing building collapse rates by up to 80% (Wu et al., 2025).

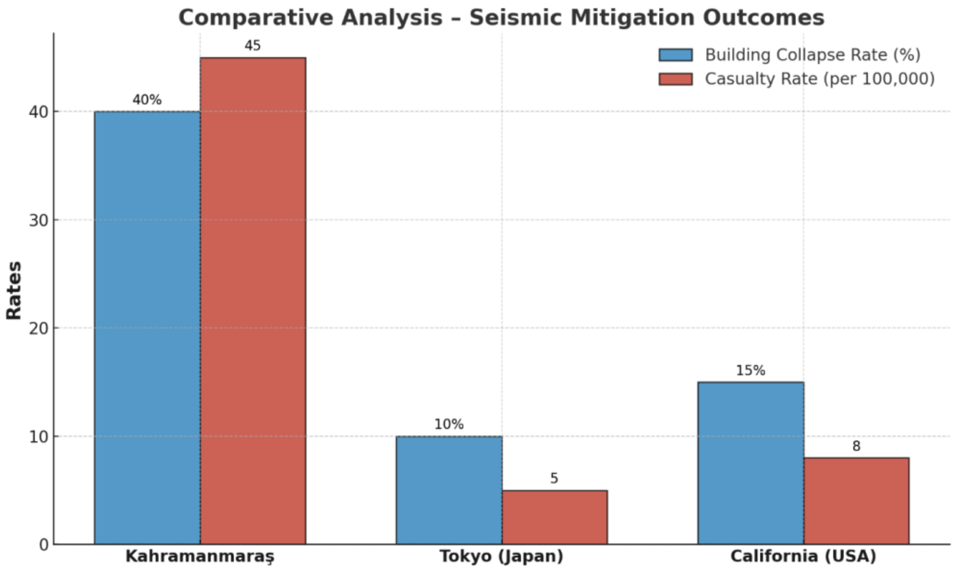


Figure 9. Comparative Analysis – Seismic Mitigation Outcomes

The comparative results also revealed that Türkiye's retrofitting initiatives remain insufficient, especially in rural areas. Unlike Tokyo and California, where government-mandated retrofitting programs have significantly enhanced building resilience, Türkiye's efforts are limited to urban centers, leaving older structures highly vulnerable. This analysis underscores the urgency for Türkiye to expand retrofitting programs nationwide to achieve seismic risk reduction on par with global benchmarks.

5. Discussion

The findings of this study provide a comprehensive evaluation of seismic hazards, structural vulnerabilities, and retrofitting strategies for Kahramanmaraş, a region that faces considerable earthquake risks due to its location along the East Anatolian Fault Zone (EAFZ). By incorporating probabilistic seismic hazard analysis, site-specific amplification modeling, and structural performance assessments, this research identifies critical weaknesses in the existing building stock while underscoring the need for immediate policy and engineering interventions to improve Türkiye's seismic resilience.

Probabilistic seismic hazard assessments indicate that central Kahramanmaraş is subject to peak ground accelerations exceeding 0.6g, comparable to those observed in major seismic events along California's San Andreas Fault (Nakamura et al., 2011; Bozorgnia et al., 2014). This highlights the necessity for stringent zoning regulations and enhanced seismic design requirements. A critical factor contributing to the region's vulnerability is local site amplification; seismic shaking in areas situated on sedimentary basins and alluvial plains is intensified compared to structures built on bedrock, exacerbating structural damage. The impact of site-specific amplification has been well-documented in other catastrophic earthquakes, such as the 1985 Mexico City and 2015 Nepal earthquakes, where soil conditions played a crucial role in the disproportionate destruction of urban districts (Çelebi et al., 1987; Chamlagain and Gautam, 2015). Türkiye's current seismic design codes do not adequately account for these site-specific effects, leaving many structures insufficiently protected. Implementing hazard models that integrate local geological conditions, as successfully done in countries like Japan and New Zealand, would improve earthquake-resistant construction and provide more precise seismic risk assessments for urban planning (Ferraioli and Mandara, 2017).

Structural simulations reveal that pre-1999 buildings in Kahramanmaraş exhibit severe deficiencies, making them particularly susceptible to collapse during major seismic events. Common failure mechanisms include excessive lateral displacements, shear wall collapse, column buckling, and weak foundation designs. These vulnerabilities are consistent with those observed in the 1999 İzmit earthquake, where thousands of buildings suffered catastrophic failures due to outdated seismic construction practices (Ferraioli and Mandara, 2017). Given that 35–40% of Türkiye's building stock predates modern seismic regulations, these vulnerabilities present a major public safety concern. Without targeted retrofitting efforts, future earthquakes could result in large-scale destruction and human casualties (Tesfamariam and Saatcioglu, 2010; Akıncı and Ünlügenç, 2023).

Retrofitting older buildings has proven effective in reducing earthquake-induced fatalities and economic losses. Various international case studies highlight the success of large-scale government-led retrofitting programs in mitigating seismic risks. For example, California's seismic retrofit program mandates structural reinforcement for high-risk buildings, significantly reducing post-earthquake collapse rates (Parker et al., 2022). Japan has invested heavily in base isolation for public infrastructure, resulting in a substantial reduction in structural damage during major earthquakes (Nakamura et al., 2011). Similarly, New Zealand enforces mandatory retrofitting for critical infrastructure, which has improved overall urban seismic resilience (Ferraioli and Mandara, 2017). Despite growing awareness of the importance of retrofitting, Türkiye's efforts remain limited, with initiatives primarily focused on public buildings, while private residential and commercial structures remain largely unaddressed. Expanding retrofitting programs to target pre-1999 residential buildings, particularly in high-risk urban areas, must become a national priority.

However, the adoption of retrofitting in Türkiye faces significant economic and policy-related barriers. The high costs of structural strengthening make retrofitting financially inaccessible for many property owners, particularly in lower-income urban districts. Additionally, while Türkiye's seismic code mandates strict compliance for new construction, retrofitting remains voluntary, resulting in low participation rates among homeowners (Yıldırım and Tonguç, 2024). Major cities such as Istanbul and Ankara benefit from government-funded retrofitting programs, but rural and smaller urban areas receive minimal financial support, exacerbating regional disparities (Güneş and Tümer, 2024). To address these challenges, Türkiye should implement a structured financial assistance program that includes government-backed subsidies, low-interest loans, and tax incentives for property owners who undertake retrofitting measures. Public-private partnerships could also be leveraged to fund large-scale infrastructure retrofitting, while phased implementation strategies prioritizing the most at-risk structures would allow for a more cost-effective and efficient allocation of resources. These financial strategies have been successfully implemented in other countries, leading to widespread adoption of retrofitting and long-term cost savings in post-disaster recovery (Wu et al., 2025).

A comparative analysis of global seismic risk reduction measures provides key lessons for Türkiye's earthquake preparedness strategies. Japan's government-mandated base isolation technology has played a crucial role in reducing seismic damage to critical infrastructure (Nakamura et al., 2011). California's strict enforcement of seismic strengthening for mid-rise and high-rise buildings has led to a significant reduction in failure rates (Wu et al., 2025). New Zealand introduced comprehensive building code revisions following the 2011 Christchurch earthquake, mandating retrofitting for all pre-code buildings, which significantly improved urban seismic resilience (Ferraioli and Mandara, 2017). For Türkiye to achieve similar levels of risk reduction, the government must take decisive steps toward making retrofitting a mandatory requirement for pre-1999 structures. Expanding financial support mechanisms would make retrofitting more accessible to a wider range of property owners, while revising zoning regulations to integrate local seismic amplification data would ensure that new and existing buildings meet the necessary structural demands. Public awareness campaigns on earthquake safety and disaster preparedness should also be prioritized to increase community participation in seismic risk reduction efforts.

In conclusion, addressing Türkiye's seismic risk requires a comprehensive, multi-disciplinary approach that combines engineering innovation, regulatory enforcement, and financial investment in retrofitting. By learning from successful international mitigation strategies, Türkiye can significantly reduce the risks associated with future earthquakes and protect both lives and infrastructure in high-risk regions such as Kahramanmaraş. The inevitability of future seismic events underscores the urgent need for proactive measures, ensuring that urban centers and vulnerable communities are adequately prepared for the next major earthquake.

6. Conclusion

This study provides a comprehensive evaluation of seismic hazards, structural vulnerabilities, and retrofitting strategies in Kahramanmaraş, a region at high risk due to its proximity to the East Anatolian Fault Zone. By integrating probabilistic seismic hazard analysis, site-specific amplification modeling, and structural performance simulations, this research offers valuable insights into how Türkiye can enhance its seismic resilience. The findings contribute to the broader discourse on earthquake risk mitigation by identifying key engineering and policy interventions necessary for reducing the risks associated with major seismic events (Nakamura et al., 2011; Bozorgnia et al., 2014; AFAD, 2023).

The results confirm that central Kahramanmaraş experiences peak ground accelerations exceeding 0.6g, placing it among the most seismically active regions in Türkiye (Bozorgnia et al., 2014; AFAD, 2023). In addition to inherent tectonic hazards, the region’s geological characteristics, particularly its sedimentary basins and alluvial plains, further amplify ground shaking. This amplification effect significantly increases the risk of structural damage, particularly for older buildings that were not designed to withstand such forces. Similar amplification effects were observed in the 1985 Mexico City earthquake, where site-specific geological conditions contributed to widespread destruction (Çelebi et al., 1987). These findings underscore the urgent need for localized seismic hazard assessments and updates to building codes that account for regional amplification effects, as successfully implemented in countries like Japan and New Zealand (Nakamura et al., 2011; Ferraioli and Mandara, 2017).

Structural vulnerability assessments reveal that a significant portion of the building stock in Kahramanmaraş remains highly susceptible to collapse in the event of a major earthquake. Buildings constructed before the implementation of Türkiye's modern seismic codes in 1999 exhibit high failure rates, primarily due to inadequate lateral reinforcement, weak columns, and poor foundation strength (Tesfamariam and Saatcioglu, 2010; Akıncı and Ünlügenç, 2023). The observed structural failures during the 2023 Kahramanmaraş earthquake closely mirror those from the 1999 İzmit earthquake, which led to the collapse of approximately 60,434 buildings and resulted in over 17,000 fatalities (Wikipedia, 2025). Without targeted intervention, future earthquakes could yield similarly devastating consequences.

One of the most critical takeaways from this research is the necessity of large-scale retrofitting initiatives, particularly for mid-rise residential buildings and critical infrastructure such as hospitals, schools, and emergency response facilities. Global case studies have demonstrated the effectiveness of retrofitting in reducing structural failures and human casualties. For example, California's seismic retrofit program has significantly reduced building collapse rates in high-risk areas (Parker et al., 2022). Likewise, Japan's widespread adoption of base isolation systems has resulted in a 90% reduction in structural damage during major seismic events (Nakamura et al., 2011). However, Türkiye faces considerable economic and logistical barriers to the widespread implementation of these strategies (Nakamura et al., 2011; Ferraioli and Mandara, 2017). To overcome these challenges, a multi-faceted approach is necessary. Government-backed financial incentives, including subsidies, low-interest loans, and public-private partnerships, could make retrofitting more accessible, particularly in lower-income urban areas (Yolcu et al., 2021; Yıldırım and Tonguç, 2024). Additionally, fostering public engagement and awareness is essential for promoting a culture of earthquake preparedness and encouraging private property owners to invest in structural resilience (Nakamura et al., 2011; Wu et al., 2025).

Beyond engineering solutions, seismic resilience is also a function of governance and policy enforcement. Lessons from countries with advanced earthquake mitigation frameworks emphasize the importance of integrating seismic risk reduction strategies into urban planning. Following the 1995 Kobe earthquake, Japan implemented extensive retrofitting mandates and base isolation requirements, significantly improving building performance in subsequent seismic events (Nakamura et al., 2011). Similarly, California's seismic retrofitting regulations for mid-rise and high-rise buildings have reduced failure rates by up to 80% (Wu et al., 2025). Türkiye can benefit from adopting similar measures, particularly by making retrofitting mandatory for pre-1999 structures and ensuring that financial support mechanisms enable compliance. Expanding research into cost-effective retrofitting alternatives, such as fiber-reinforced polymers, could provide practical solutions for under-resourced communities, ensuring that seismic resilience efforts are both effective and financially viable (Mokarram et al., 2025).

In addition to structural interventions, Türkiye must explore the integration of early warning systems and real-time seismic monitoring as part of a broader disaster risk reduction strategy (Parker et al., 2022). Advances in sensor technology and real-time data analytics have proven effective in mitigating casualties and improving emergency response in regions with mature earthquake preparedness frameworks (AFAD, 2023). Implementing similar measures in Türkiye could significantly enhance the country's ability to detect and respond to seismic events, thereby reducing the potential for large-scale human and economic losses (Hayes et al., 2024).

This study underscores the urgent need for Türkiye to strengthen its earthquake preparedness through a combination of policy enforcement, targeted retrofitting programs, and informed urban planning (Tan and Eyidoğan, 2019). The inevitability of future earthquakes necessitates a shift from reactive disaster response to proactive risk mitigation. By integrating best practices from leading earthquake-prone countries, expanding financial support for retrofitting, and fostering a culture of preparedness, Türkiye can significantly reduce the threat posed by seismic hazards. Immediate action is essential to ensure that high-risk regions like Kahramanmaraş are better protected against future earthquakes, ultimately safeguarding lives and critical infrastructure for future generations.

Acknowledgment

We extend our sincere gratitude to all individuals and organizations that provided aid and support to the victims of the Kahramanmaraş earthquake. The devastation caused by this disaster highlighted the urgent need for improved seismic resilience and motivated us to conduct this study. Through this research, we aim to contribute to the development of more effective mitigation strategies, ensuring that future earthquakes do not result in similar losses.

Conflict of Interest Statement

The authors declare that there is no conflict of interest among them.

Statement of Author Contributions

The authors declare that they have contributed equally to this manuscript.

References

AFAD (Disaster and Emergency Management Authority). 2023 Kahramanmaraş earthquake report: Seismic Impact, Structural Failures, and Policy Recommendations. Retrieved from https://tdth.afad.gov.tr. 2023.

AFAD. Türkiye Deprem Tehlike Haritaları İnteraktif Web Uygulaması. https://tdth.afad.gov.tr/. 2024

Akıncı AC., Ünlügenç UC. 6 Şubat 2023 Kahramanmaraş depremleri: Sahadan jeolojik veriler, değerlendirme ve Adana için Etkileri. Çukurova Üniversitesi Mühendislik Fakültesi Dergisi 2023; 38(2): 553–569. https://doi.org/10.21605/cukurovaumfd.1334155

Akkuş HT., Kışlalıoğlu V. Investigating the effects of natural disasters on the stock market on a sectoral basis: The case of 2023 Kahramanmaraş/Türkiye Earthquake. International Journal of Business and Economic Studies 2023; 5(2): 141–151. https://doi.org/10.54821/uiecd.1296562

Alnajjar A. Seismic bracing for earthquake-resistant design: Architectural integration strategies. Journal of Design and Built Environment 2024; 13(1): 25–42. Retrieved from https://dergipark.org.tr/en/download/article-file/3005568

Anwar GA., Dong Y. Seismic resilience of retrofitted RC buildings. Earthquake Engineering and Engineering Vibration 2020; 19(3): 561–571. https://doi.org/10.1007/s11803-020-0580-z

Balkaya M., Özden S., Akyüz HS. Morphometric and morphotectonic characteristics of Sürgü and Çardak faults (East Anatolian Fault Zone). Journal of Advanced Research in Natural and Applied Sciences 2021; 7(2): 1–15. https://doi.org/10.28979/jarnas.939075

Bilham R. The amplification of seismic shaking by soft sediments: Lessons from Mexico City and Kathmandu. Seismological Research Letters 2019; 90(2A): 405–417. https://doi.org/10.1785/0220180232

Bozorgnia Y., Abrahamson NA., Atik LA., Ancheta TD., Atkinson GM., Baker JW., Youngs RR. NGA-West2 research project. Earthquake Spectra 2014; 30(3): 973–987. https://doi.org/10.1193/072113EQS209M

Cárdenas M., Chávez-García FJ., Gusev A. Regional amplification of ground motion in central Mexico: Results from coda-length magnitude data and preliminary modeling. Journal of Seismology 1997; 1(4): 341–355. https://doi.org/10.1023/A:1009738406881

Chamlagain D., Gautam D. Seismic hazard in the Himalayan intermontane basins: An example from Kathmandu Valley, Nepal. In: Nibanupudi H., Shaw R., editors. Mountain Hazards and Disaster Risk Reduction. Springer; 2015. p. 83–96. https://doi.org/10.1007/978-4-431-55242-0_5

Çelebi M., Dietel C., Prince J., Onate M., Chavez G. Site amplification in Mexico City (Determined from 19 September 1985 strong-motion records and from recordings of weak motions). In: Cakmak AS, editor. Developments in Geotechnical Engineering. Elsevier; 1987. Vol. 44, pp. 141–151. https://doi.org/10.1016/B978-0-444-98956-7.50013-1

Cilek A., Ergün M. The impact of the 2023 Kahramanmaraş earthquake on BIST100 and BIST bank index: Evidence from Toda-Yamamoto causality test. Pressacademia 2023; 10(1): 1–10. https://doi.org/10.17261/Pressacademia.2023.1760

Coy BB. Buckling-restrained braced frame connection design and testing. In: Proceedings of a Conference; 2007. Retrieved from https://www.semanticscholar.org/paper/Buckling-Restrained-Braced-Frame-Connection-Design-Coy/9f485c3ebcb9a6198fc076a1072f7275ade01d58

Ferraioli M., Mandara A. Base isolation for seismic retrofitting of a multiple building structure: Design, construction, and assessment. Mathematical Problems in Engineering 2017. https://doi.org/10.1155/2017/4645834

Güneş O., Tümer R. Performance-based seismic retrofit design for RC frames using FRP composite materials. Mühendislik Bilimleri ve Tasarım Dergisi 2024; 12(4): 627–642. https://doi.org/10.21923/jesd.1372646

Güzel F., Sarp G. Evaluation of the tectonic activity of faults with mineral alterations: A case of the East Anatolian Fault-Palu segment, Türkiye. Bulletin of the Mineral Research and Exploration 2024; 171: 1–15. https://doi.org/10.19111/bulletinofmre.1518855

Hayes GP., Sundstrom ASB., Barnhart WD., Blanpied ML., Davis LA., Earle PS., Wolfe CJ. U.S. geological survey earthquake hazards program decadal science strategy, 2024–33. U.S. Geological Survey Circular 1544 2024. https://doi.org/10.3133/cir1544

Kaatsız K., Alıcı FS., Erberik MA. Seismic assessment of electrical equipment in power substations: A case study for circuit breakers. Turkish Journal of Civil Engineering 2024; 35(4): 49–68. https://doi.org/10.18400/tjce.1241107

Mazanec M., Valenta J., Málek J. Does VS_{30} reflect seismic amplification? Observations from the West Bohemia Seismic Network. Natural Hazards 2024; 120: 12181–12202. https://doi.org/10.1007/s11069-024-06679-x

Midorikawa S., Matsuoka M., Sakugawa K. Site effect on strong-motion records observed during the 1987 Chiba-ken-toho-oki, Japan earthquake. In: Proceedings of the 9th Japan Earthquake Engineering Symposium; 1994. 3: 85–90. Retrieved from https://iisee.kenken.go.jp/lna/download.php?cid=S1-090-2012andf=20130319cdbec86d.pdfandn=1_geomorphology_Vs30.pdf

Mokarram V., Banan MR., Kheyri A. A critical evaluation of the coefficient method, capacity spectrum method, and modal pushover analysis for irregular steel buildings in seismic zones. Turkish Journal of Civil Engineering 2025; 36(1): 75–108. https://doi.org/10.18400/tjce.1422919

Nakamura Y., Hanzawa T., Hasebe M., Okada K., Kaneko M., Saruta M. Report on the effects of seismic isolation methods from the 2011 Tohoku–Pacific earthquake. Seismic Isolation and Protection Systems 2011; 2(1): 57–74. https://doi.org/10.2140/siaps.2011.2.57

Okumuş V., Mangır A. Earthquake performance analysis of a masonry school building's retrofitted state by the equivalent frame method. Turkish Journal of Civil Engineering 2025; 36(1): 29–49. https://doi.org/10.18400/tjce.1392529

Özyazıcıoğlu M., Hancılar U., Selçuk SS. Site response analysis for Kahramanmaraş, Türkiye: A seismic hazard study. Journal of Seismology 2020; 24(1): 17–29. https://doi.org/10.1007/s10950-019-09884-7

Pala M., Başsürücü M. 6 Şubat 2023 Kahramanmaraş merkezli depremler sonrasında Adıyaman İlindeki betonarme yapılarda oluşan hasarların malzeme ve işçilik problemlerine bağlı olarak incelenmesi.

Adıyaman Üniversitesi Mühendislik Bilimleri Dergisi 2024; 11(24): 415–427. https://doi.org/10.54365/adyumbd.1550346

Palermo A., Wotherspoon L., Wood J., Chapman H., Scott A., Hogan L., Chouw N. Lessons learnt from 2011 Christchurch earthquakes: Analysis and assessment of bridges. Bulletin of the New Zealand Society for Earthquake Engineering 2011; 44(4): 319–333. https://doi.org/10.5459/bnzsee.44.4.319-333

Parker GA., Stewart JP., Boore DM., Atkinson GM., Hassani B. NGA-subduction global ground-motion models with regional adjustment factors. Earthquake Spectra 2022; 38(1): 456–493. https://doi.org/10.1177/87552930211034889

Reilinger R., McClusky S., Vernant P., Lawrence S., Ergintav S., Özgür E. GPS constraints on continental deformation in the Africa–Arabia–Eurasia continental collision zone and implications for the dynamics of plate interactions. Journal of Geophysical Research: Solid Earth 2006; 111(B5): B05411. https://doi.org/10.1029/2005JB004051

Semblat JF., Duval AM., Dangla P. Seismic site effects in a deep sedimentary basin: Numerical analysis and field experiment results. Journal of Seismology 2005; 9(2): 107–131. Retrieved from https://hal.science/hal-00107884/document

Stein RS. The role of stress transfer in earthquake occurrence. Nature 1999; 402: 605–609. https://doi.org/10.1038/45144

Tan A., Eyidoğan H. The kinematics of the East Anatolian Fault Zone, Eastern Turkey and seismotectonic implications. International Journal of Engineering and Applied Sciences 2019; 11(4): 494–506. https://doi.org/10.24107/ijeas.649330

Tesfamariam S., Saatcioglu M. Seismic vulnerability assessment of reinforced concrete buildings using hierarchical fuzzy rule base modeling. Earthquake Spectra 2010; 26(1): 235–256. https://doi.org/10.1193/1.3280115

U.S. Geological Survey. V_{S30} Models and Data. USGS 2019. Retrieved from https://earthquake.usgs.gov/data/vs30

U.S. Geological Survey. Seismic hazard assessment and site response analysis methods. U.S. Geological Survey Publications 2024. Retrieved from https://pubs.usgs.gov/publication/70041709

VEX Education. San Francisco and seismic isolators. VEX Robotics Education [no date]. Retrieved from https://education.vex.com/stemlabs/iq/stem-labs/tallest-tower/san-francisco-and-seismic-isolators

Wikipedia. 1999 İzmit earthquake. Wikipedia 2025. Retrieved from https://en.wikipedia.org/wiki/1999_%C4%B0zmit_earthquake

World Conference on Earthquake Engineering. SHAKE2000: Equivalent-linear site response analysis and its applications. 16WCEE, Paper #798. 2017. Retrieved from https://www.wcee.nicee.org/wcee/article/16WCEE/WCEE2017-798.pdf

Wu K., Wei G., Lin C., Zhang L., Yu W., Lan X. Experimental study on the seismic performance of buckling-restrained braces with different lengths. Buildings 2025; 15(2): 154. https://doi.org/10.3390/buildings15020154

Yıldırım S., Tonguç Yİ. An innovative retrofitting technique of an industrial prefabricated building without evacuation. Academic Platform Journal of Natural Hazards and Disaster Management 2024; 5(1): 1–29. https://doi.org/10.52114/apjhad.1328346

Yilmaz DG. Geçmiş depremlerden 2023 Kahramanmaraş depremlerine: Neden afete karşı hazır değiliz? Afet ve Risk Dergisi 2023; 6(3): 1009–1023. https://doi.org/10.35341/afet.1258947

Yolcu A., Tanırcan G., Tüzün C. Acceleration displacement response spectra for design of seismic isolation systems in Turkey. Teknik Dergi 2021; 32(2): 10629–10644. https://doi.org/10.18400/tekderg.511798