

Urban-Scale Geographic Deaggregation of Seismic Hazard in Tehran Using Probabilistic Modeling

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Abstract

Tehran is a seismically active megacity with a complex network of faults. While conventional deaggregation methods provide statistical insight, they lack spatial resolution regarding the contribution of seismic sources.

In this study, standard $M_w-R-\epsilon$ deaggregation was performed using EZ-FRISK at three representative sites across northern, central, and southern Tehran. We then developed customized coded spatial logic algorithms to generate geographic deaggregation maps for peak ground acceleration (PGA) and spectral acceleration (SA) at each structure's fundamental period. The results reveal that the northern site (Saman Bank Tower) is predominantly influenced by near-field sources, notably the North Tehran and Mosha faults, while the southern site (Kashani Hospital) is mainly affected by high-magnitude, moderate-to-far field events. Site-to-site variation in source contributions reflects differences in fault proximity, soil conditions, and structural periods. Our approach enables spatially resolved hazard characterization, offering a robust foundation for seismic design, retrofitting prioritization, and building code development in urban-scale seismic risk assessment. These findings support targeted retrofitting and zoning policies for fault-dense megacities such as Tehran.

Key Points

- This study addresses geographic deaggregation of seismic hazard at the urban scale in Tehran.
- Geographic source contribution varies significantly across closely located sites.
- The approach supports microzonation-based mitigation in seismically active megacities.

1 Introduction

1–1 Problem Context & Motivation

Earthquakes are among the most destructive natural hazards, causing considerable human and economic losses each year. Seismic hazard analysis plays a vital role in earthquake engineering, disaster risk management, and urban planning by estimating the likelihood of various ground motion levels over specific time intervals (Cornell, 1968; McGuire, 2004). Among available approaches, Probabilistic Seismic Hazard Analysis (PSHA) is widely used due to its capacity to incorporate uncertainties in seismic sources and local site effects (Bazzurro & Allin Cornell, 1999). To enhance the interpretation of PSHA outcomes, seismic hazard deaggregation techniques have been developed, allowing the dissection of contributions by magnitude, distance, and other critical parameters (Harmsen & Frankel, 2001; Harmsen, Perkins, & Frankel, 1999). Recent studies have emphasized that geographic deaggregation, which maps the spatial contributions of different seismic sources, provides a clearer and more comprehensive understanding of hazard distribution (Harmsen, 2001; Petersen et al., 2014). This geographic perspective is particularly crucial in regions characterized by complex fault systems, playing an essential role in improving seismic design practices, optimizing resource allocation, and formulating

effective risk mitigation strategies (Aagaard et al., 2008; Sharp et al., 1989). Traditional seismic hazard analyses commonly rely on disaggregating hazard into magnitude, distance, and epsilon ($M-R-\epsilon$). While these methods yield important insights into the characteristics of contributing events, they lack direct geographic information on the spatial distribution of hazard. In cities like Tehran, characterized by complex geological structures, numerous active faults, and diverse geomorphology, a detailed understanding of the spatial contribution of hazard sources becomes critically important. In such regions, the absence of spatially explicit analyses can lead to inaccuracies in decision-making related to structural design, disaster management, and resource allocation (Abdi, Mirzaei, & Shabani, 2013; Ghodrati, Khoshnevis, & Razavian, 2013). Consequently, the need for methodologies capable of explicitly mapping the geographic distribution of seismic hazard is increasingly recognized in advanced hazard assessment practices.

Given its complex geological structures, the presence of multiple active faults, and the high density of population and critical infrastructure, Tehran is considered one of the most seismically vulnerable megacities in the world. Under such circumstances, obtaining a precise understanding of the spatial contribution of seismic sources is crucial for enhancing urban safety, seismic-resistant design, and earthquake risk management. Traditional seismic hazard disaggregation methods based on magnitude, distance, and epsilon fail to provide explicit spatial information, thus falling short of addressing the needs of detailed risk analyses at the urban scale. Employing geographic deaggregation offers a clearer depiction of the actual distribution of seismic hazard, playing a fundamental role in optimizing engineering and disaster management decisions. Accordingly, developing geographic deaggregation analyses for Tehran constitutes both a scientific and practical necessity that this study seeks to address.

1–2 Brief Literature Review

Systematic efforts to develop seismic hazard deaggregation began with the work of Harmsen and colleagues in the United States. Harmsen and Frankel (Harmsen & Frankel, 2001) introduced geographic deaggregation, a novel method to map spatial contributions of seismic sources beyond the standard magnitude–distance–epsilon ($M-R-\epsilon$) framework. Previously, Harmsen et al. (Harmsen et al., 1999) had applied traditional deaggregation in central and eastern U.S. hazard studies. Geographic deaggregation was later incorporated—partially—into the U.S. National Seismic Hazard Maps (Petersen et al., 2014). In Iran, researchers such as Abdi et al. (Abdi et al., 2013), Ghodrati et al. (Ghodrati et al., 2013), and Firuzi et al. (Firuzi, Ansari, Amini Hosseini, & Rashidabadi, 2019) performed PSHA studies focused on magnitude–distance metrics, with limited attention to spatial source mapping. Jarahi and colleagues (H. Jarahi, 2016, 2017; H. Jarahi, Madadi, Nadalian, & Bandar, 2015) also contributed to regional hazard assessments for Tehran and Karaj, but their work similarly remained within conventional $M-R-\epsilon$ analysis. Overall, the literature suggests that geographic deaggregation—despite its utility—has seen minimal application in urban-scale assessments outside the United States, particularly in complex environments like Tehran.

1–3 Regional Tectonic Framework and Seismotectonic Context

Tehran, Iran's most populous and strategically vital city, lies between 35°34'–35°50' N and 51°00'–51°36' E. The metropolitan area spans diverse geological units, ranging from the southern alluvial plains to the northern foothills of the Central Alborz Mountains. The North Tehran Fault marks the city's northern edge and is one of its most seismically active structures (Fig. 1). In contrast, southern features such as the Rey and Kahrizak faults—historically considered active—have been reinterpreted as stabilized paleo-shorelines of a Quaternary lake (H Jarahi, 2021; H. Jarahi et al., 2015). This reinterpretation reduces their seismic significance. The geomorphological contrast between the flat southern plains and the rugged northern terrain causes pronounced spatial variability in ground motion and hazard levels. The convergence of high population density, critical infrastructure, and complex tectonics reinforces the need for advanced hazard assessment strategies, particularly those that incorporate spatially explicit modeling such as geographic deaggregation.

1–4 Objective and Contribution of the Study

This study introduces a novel framework for the geographic deaggregation of seismic hazard across the city of Tehran. The methodology begins with a probabilistic seismic hazard analysis (PSHA) and conventional $M-R-\epsilon$ deaggregation, followed by the generation of spatial deaggregation maps using customized post-processing. This approach reveals the geographic contributions of seismic sources to local hazard levels and enables detailed, site-specific interpretation—crucial for urban-scale applications. Unlike prior studies, this work represents the first implementation of geographic deaggregation at an urban scale outside the United States. By integrating conventional deaggregation outputs with spatial modeling techniques, we produced high-resolution maps that directly attribute seismic hazard to specific faults. This framework accounts for Tehran's complex fault network and heterogeneous geology, offering practical insights for seismic design, risk mitigation, and urban planning. The emphasis on spatial attribution at the fault level marks a methodological advancement in seismic hazard modeling and enhances the precision of hazard assessment in densely populated, tectonically active cities.

2 Methodology

Section 1: Probabilistic Seismic Hazard Analysis Framework

This study employs the probabilistic seismic hazard analysis (PSHA) framework originally proposed by (Cornell, 1968) and further advanced by McGuire (McGuire, 2004). PSHA serves as the standard methodology in both national and international seismic hazard modeling. Its goal is to estimate the probability of exceeding specified ground motion intensities—such as peak ground acceleration (PGA) and spectral acceleration (SA)—over defined time intervals, while incorporating uncertainties in source characteristics and site response. Within this framework, seismic hazard deaggregation dissects the total hazard into contributions from individual seismic sources. Initial deaggregation was performed using the standard magnitude–distance–epsilon ($Mw-R-\epsilon$) approach via EZ-FRISK software. These

outputs formed the foundation for the subsequent spatial analysis and development of geographically resolved deaggregation maps.

Section 2: **Site Selection and Structural Characteristics**

To represent the spatial and structural diversity of Tehran in an urban-scale hazard assessment, three sites were selected from the city's northern, central, and southern zones. Site 1 corresponds to the Saman Bank Central Tower—a modern high-rise building in northern Tehran. Site 2 is the Toqrol Historical Tower, a centuries-old heritage structure in the Rey district. Site 3 is Kashani General Hospital, a key healthcare facility located in southern Tehran and critical for post-earthquake emergency response. The fundamental period (T) of each structure was estimated using the empirical relation(Goel & Chopra, 1997) $T = 0.08H^{0.75}$, where H denotes building height in meters. Site-specific parameters—such as shear-wave velocity (Vs30) from downhole testing, geographic coordinates, structure height, and year of construction—are summarized in Table 1. These data were directly integrated into the hazard model to reflect local soil and structural conditions with high fidelity.

Table 1

Site-specific characteristics including location, structural parameters, and shear-wave velocity (Vs30) values used in the seismic hazard analysis.

Site	Name	Latitude (N)	Longitude (E)	Height (m)	Floors	Year Built	Estimated T (s)	Vs30 (m/s)
1	Saman Bank Central Tower	35.75°	51.45°	100	32	2015	4.75	360–490
2	Toqrol Historical Tower	35.60°	51.44°	20	1	~1100	1.42	240–300
3	Kashani General Hospital	35.64°	51.42°	10	4	1962	0.85	< 180

Section 3: **Seismic Source Modeling**

Eight active faults with significant seismic potential were selected to represent the primary sources affecting seismic hazard in the study area. These include the North Tehran, North Karaj, Taleqan, Mosha, Firuzkuh, Parchin, Pishva, and Robat Karim faults. Geometric and seismotectonic parameters—such as rupture length, slip rate, slip sense, maximum magnitude, and most recent surface rupture—were compiled from authoritative paleoseismic and regional tectonic studies (see Table 2). Each fault was modeled independently, and recurrence rates were derived from a combination of historical seismicity, trench investigations, and slip-rate data. To quantify their relative contributions, weights were assigned to fault sources based on the product of rupture length and average slip rate. This physically grounded approach aligns with practices used in regional hazard frameworks such as UCERF3 (Field et al., 2014) and avoids the complexity of full logic-tree modeling. Given the sensitivity of spatial hazard modeling,

fault geometries were carefully calibrated within the PSHA environment and preserved during spatial deaggregation. Multiple scenarios were considered to account for parametric and behavioral uncertainties across fault sources.

Table 2

Geometric and seismotectonic characteristics of active faults considered in the seismic source model, including rupture length, slip sense, slip rate, estimated maximum magnitude (Mw), and last known seismic event.

Fault source	Rupture length (km)	Sense of slip	Slip rate (mm/yr)	Characteristic or maximum magnitude (Mw)	Date of last event	References
North Karaj	70	Reverse	0.3 ± 0.05	7.2	312 – 280 BC 1177 AD	(J.-F. Ritz et al., 2012)
North Tehran	70	Reverse	0.3 ± 0.05	7.4	312 – 280 BC 1177 AD	(J.-F. Ritz et al., 2012)
Taleqan	50	Strike slip	0.6–1.6	7.2	80 AD	(Nazari et al., 2009)
Mosha	80	Strike slip	2.0	7.1	1665 AD 1830 AD	(Allen, Vincent, Alsop, Ismail-zadeh, & Flecker, 2003; Bachmanov et al., 2004; J.-F. Ritz et al., 2003; J. F. Ritz et al., 2006)
Firuzkuh	80	Strike slip	1.1–2.2	7.4	1321 AD	(J.-F. Ritz et al., 2009; J. F. Ritz et al., 2006)
Pishva	50	Reverse	0.12–0.14	7.2	1384 AD	(Majidi Niri, Nazari, Qarashi, & Talebian, 2011)

Section 4: **Ground Motion Prediction Equations (GMPEs)**

Ground motion estimation in this study utilized the NGA-West2 suite of ground motion prediction equations (GMPEs), which are developed from extensive empirical analyses of strong-motion datasets in active tectonic regions. To capture the epistemic uncertainty in ground motion modeling, four widely used NGA-West2 models were selected: (Abrahamson, Silva, & Kamai, 2014; Boore, Stewart, Seyhan, & Atkinson, 2014; Campbell & Bozorgnia, 2014; Chiou & Youngs, 2014). Equal weighting was assigned to each model to prevent bias from any single GMPE. Model selection was based on their relevance to the seismotectonic and site conditions in Tehran, where Vs30 values generally range from 180 to 760 m/s,

and expected magnitudes fall within Mw 6.5–7.5—consistent with the characteristics of major faults such as North Tehran, Taleqan, and North Karaj. Site-specific input parameters were derived from local downhole geotechnical investigations to ensure consistency with observed subsurface conditions.

Section 5: Standard Probabilistic Deaggregation and Data Preparation for Spatial Analysis

Standard probabilistic deaggregation was performed for each of the three selected sites using EZ-FRISK, based on moment magnitude (Mw), source-to-site distance (R), and standardized residual (ϵ). Intensity measures included peak ground acceleration (PGA) and spectral acceleration (SA) at the fundamental period of each structure, evaluated for return periods of 475, 975, and 2475 years—corresponding to exceedance probabilities of 20%, 10%, and 4% in 50 years, respectively. For spatial integration, a radial grid of points was constructed around each site. Fault-intersecting points were identified, and their coordinates, radial distances, and fault associations were cataloged in a structured spreadsheet. EZ-FRISK outputs—including Mw–R– ϵ matrices and fault-specific contribution tables—were reorganized according to the radial grid. For each distance band, the magnitude–epsilon contribution from each fault was computed using tabulated percentages, and the data were structured pointwise. The processed results were exported as a formatted text file for used as input to a Python-based disaggregation pipeline.

Section 6: Development of Geographic Deaggregation and Spatial Mapping

The disaggregation outputs (Mw, R, ϵ) were processed using a purpose-built Python-based algorithm. This algorithm transforms tabular scenario-based data into fault-resolved hazard contributions through coded spatial association. Each radial point around a site is programmatically matched to intersecting fault traces, enabling assignment of individual hazard components to specific faults. The result is a structured matrix of hazard contributions categorized by magnitude bin and return period, resolved at the fault level. The full workflow—from input parsing through computational fault-tagging—is summarized in Fig. 2 as a structured schematic. Implementation details are provided in Appendix A.

Section 7: Uncertainty Considerations in Seismic Hazard Analysis

Recognizing the inherent uncertainties in probabilistic seismic hazard analysis (PSHA), this study explicitly considered both aleatory and epistemic sources of variability. Key contributors to uncertainty include:

- (i) ground motion prediction models (GMPEs),
- (ii) fault geometry and rupture dimensions,
- (iii) earthquake recurrence intervals, and
- (iv) heterogeneity in site conditions (e.g., Vs30 values).

To address these, four NGA-West2 GMPEs were applied with equal weighting to capture model-to-model variability. In fault modeling, ranges of slip rate, magnitude, and segmentation were assigned to principal faults based on available paleoseismic data. Fault geometries were carefully calibrated to reduce spatial mismatch and improve accuracy during geographic deaggregation. Aleatory uncertainty—stemming from random variability in rupture and wave propagation—was inherently captured through the spectrum of GMPE outputs across different return periods. Epistemic uncertainty—reflecting incomplete knowledge of fault activity—was partially mitigated using updated datasets and localized site characterizations. However, formal quantification through Monte Carlo simulations or probabilistic logic-tree frameworks was not pursued, consistent with previous deaggregation-focused studies (Harmsen & Frankel, 2001; Petersen et al., 2014). This limitation defines a scope boundary for the present study and offers a direction for future work aiming at uncertainty propagation and sensitivity analysis in urban-scale seismic hazard modeling.

3 Result

3-1-Base Seismic Hazard Analysis

Prior to initiating the deaggregation process, a base-level seismic hazard analysis was performed for the three selected sites using the EZ-FRISK software. This analysis incorporated NGA-West2 ground motion models and the seismotectonic parameters of the region's active faults to develop hazard curves for peak ground acceleration (PGA) and spectral acceleration (SA) at the fundamental period of each structure (Fig. 3). Examination of the hazard spectra indicates that Site 1 (Saman Bank Tower) exhibits the highest seismic hazard, particularly at shorter periods, reflecting the strong influence of the North Tehran and Mosha fault systems. Site 2 (Toqrol Tower) displays a relatively uniform hazard profile with elevated risk at longer periods compared to Site 3. Finally, Site 3 (Kashani Hospital) presents the lowest seismic hazard across all periods, likely due to its greater distance from major active faults and its location within softer sedimentary deposits. These hazard curves form the foundational input for subsequent standard deaggregation and spatial deaggregation analyses. The uniform hazard spectra for each site are presented in Fig. 5–20.

3-2-Summary of Site Analyses and Intensity Measures

Three sites with distinct seismic characteristics were evaluated in this study: the Saman Bank Tower (Site 1), the historical Toqrol Tower (Site 2), and the Kashani Hospital (Site 3). For each site, two seismic intensity measures—peak ground acceleration (PGA) and spectral acceleration (SA) at the fundamental period of the structure—were analyzed. The hazard evaluations were conducted for three standard return periods: 475, 975, and 2475 years. Standard probabilistic deaggregation results in terms of magnitude–distance–epsilon ($M_w-R-\epsilon$) were generated for each site–intensity–return period combination, providing the foundational inputs for the subsequent spatial deaggregation analyses.

3-3-Standard Seismic Hazard Deaggregation Results

Standard probabilistic seismic hazard deaggregation results in terms of magnitude–distance–epsilon (M_w – R – ϵ) were obtained for each site, each intensity measure (PGA and SA), and each return period (475, 975, and 2475 years) (Table 3). As summarized in Table 3, the dominant magnitude and epsilon values vary significantly across the three sites. Site A consistently exhibits higher ϵ values, especially under the 2475-year return period, which suggests increased variability in ground motion, likely due to its proximity to multiple overlapping fault sources. In contrast, Site C, located farther from the primary fault zones, shows lower ϵ and slightly lower dominant magnitudes. These contrasts illustrate the value of geographic deaggregation in capturing localized hazard heterogeneity, which cannot be inferred from conventional magnitude-distance deaggregation alone.

The observed patterns indicate that:

- **Site 1 (Saman Bank Tower)** is predominantly influenced by nearby seismic sources, particularly the North Tehran and Mosha faults, with dominant magnitudes in the M_w 6.5–7.2 range at distances less than 10 km (Fig. 4).
- **Site 2 (Toqrol Tower)** shows increased contributions from more distant events with larger magnitudes (M_w greater than 7.0) (Fig. 5).
- **Site 3 (Kashani Hospital)** is mainly affected by relatively large magnitude earthquakes occurring at greater distances, reflecting the site's more peripheral location relative to major active faults (Fig. 6).

The dominant magnitude, distance, and epsilon values for each site and intensity measure, derived directly from the deaggregation outputs, are summarized in Tables 5–8 to 5–10. These results provide the foundational basis for the subsequent spatial deaggregation analyses. The full M_w – R – ϵ deaggregation plots for each site and intensity measure are presented in Figs. 4 to 6.

Table 3

Summary of dominant magnitude, distance, and epsilon values from standard deaggregation for PGA and spectral acceleration (SA) at the fundamental periods of the selected sites, considering return periods of 475 and 2475 years.

Scenario	Dominant Mw	Dominant Distance (km)	Dominant Epsilon
Site 1 PGA in 2475y	5.05	8.75	0.5
Site 1 PGA in 475y	6.75	23.75	0.7
Site 2 PGA in 2475y	7.05	36.25	1.7
Site 2 PGA in 475y	6.95	38.75	1.1
Site 3 PGA in 2475y	7.05	33.75	1.9
Site 3 PGA in 475y	6.75	33.75	0.9
Site 1 SA in 4.75s 2475y	7.05	23.75	0.9
Site 1 SA in 4.75s 475y	6.95	23.75	0.5
Site 2 SA in 1.42s 2475y	7.05	36.25	1.3
Site 2 SA in 1.42s 475y	6.75	36.25	0.5
Site 3 SA in 0.85s 2475y	7.05	33.75	1.5
Site 3 SA in 0.85s 475y	6.55	33.75	0.7

3-4-Geographic Deaggregation Analysis

Based on the previously presented standard Mw–R– ϵ deaggregation results, spatial processing was implemented via a fully scripted Python framework to generate geographic deaggregation maps for each selected site. Following the completion of seismic hazard deaggregation using EZ-FRISK, the output data were processed through custom Python algorithms that compute radial fault associations and visualize magnitude–distance–epsilon distributions. These maps illustrate the spatial contribution of seismic sources in terms of dominant magnitude, distance, and epsilon across the three selected sites. This approach identifies geographically dominant seismic sources, evaluates fault orientation and proximity effects, and highlights site-specific hazard asymmetries on an urban scale. Results are presented for two intensity measures—PGA and spectral acceleration (SA) at each structure’s fundamental period—considering return periods of 475, 975, and 2475 years (Fig. 7–9).

Geographic Deaggregation Analysis – Site 1 (North Tehran / Saman Bank Tower)

The geographic deaggregation maps for Site 1, located in the northern region of Tehran, clearly reveal the dominant seismic contribution from the North Tehran and Mosha faults. Across all return periods and both intensity measures (PGA and SA at 4.75s), these two fault zones consistently account for the highest proportion of seismic hazard. For a return period of 475 years (10% probability in 50 years),

Mosha and North Tehran faults contribute approximately 44.5% and 53.3% of the total hazard, respectively. The corresponding dominant magnitude is around Mw 6.75 with a distance of roughly 11 km. As the return period increases (e.g., 2475 years), the dominant magnitude shifts toward Mw 7.25 and the role of close-proximity sources becomes even more pronounced. In contrast, remote sources such as Firuzkuh, Robat Karim, and Pishva exhibit negligible influence on the hazard at this site, regardless of the scenario. The deaggregation maps for spectral acceleration at $T = 4.75\text{s}$ further amplify this spatial concentration, showing significantly taller hazard bars near the northern faults, indicating increased hazard levels for structures with longer natural periods. The observed variation in contribution with return period is also reflected in the trend of positive mean epsilon values, especially for higher return periods, implying the dominance of ground motions exceeding the median estimates. These findings confirm the critical seismic role of proximal faults in northern Tehran and validate the necessity of geographically explicit deaggregation in hazard-informed urban planning.

Geographic Deaggregation Analysis – Site 2 (Toqrol Tower, Rey)

The geographic deaggregation results for Site 2, located in Rey district, reveal a more spatially distributed hazard pattern compared to Site 1. While the Mosha fault remains the primary contributor to seismic hazard across all scenarios—accounting for approximately 54% of the total in the 475-year return period—the influence of other, more distant faults becomes increasingly significant in longer return periods. Notably, faults such as Robat Karim, Taleqan, and even North Karaj display a growing share in the deaggregation results for the 2475-year scenario. Unlike the more localized concentration observed in Site 1, hazard contributions for Site 2 are distributed across a broader geographic range, particularly toward the northwest and southwest of the site. The North Tehran fault contributes around 22% in the 475-year scenario but drops below 14% in the 2475-year case. The corresponding deaggregation maps for spectral acceleration at $T = 1.42\text{s}$ exhibit increased influence from distant sources, with noticeably taller bars in western zones near Taleqan and Karaj Dam. This shift highlights the greater relevance of long-period waves, which are more effective at affecting flexible, taller structures typically associated with longer natural periods. Consistently positive epsilon values across all scenarios further indicate the contribution of ground motions exceeding the median estimates, underscoring the importance of considering rare but intense shaking scenarios in seismic design for this site.

Geographic Deaggregation Analysis – Site 3 (Kashani Hospital, Southern Tehran)

The geographic deaggregation results for Site 3, located in the southern part of Tehran, demonstrate a notable shift in seismic hazard contributions toward more distant sources. In the 475-year return period, the Mosha fault still dominates with approximately 53% contribution. However, at the 2475-year level, the North Tehran fault becomes the most influential, accounting for nearly 37% of the total hazard. Contributions from more remote faults, such as Taleqan, Firuzkuh, and Robat Karim, increase significantly with return period, indicating a broader spatial dispersion of seismic hazard. Unlike Sites 1 and 2, Site 3 shows hazard bars distributed over a much wider geographic area, including locations as far west as Karaj and Taleqan. The dominant distances typically range from 35 to over 40 km, with

corresponding magnitudes predominantly between M_w 7.05 and 7.25. This pattern highlights the impact of moderate-to-large magnitude earthquakes originating at intermediate to far distances for this southern site. For spectral acceleration at $T = 0.85s$, the spatial pattern remains largely similar, although some scenarios show elevated contributions from western sources. The hazard bars are visibly taller in zones west of the site, reflecting an increase in long-period seismic influence. The relatively low V_{s30} at this site (less than 200 m/s) further elevates its seismic vulnerability, despite its distance from the city's main active faults. These results suggest that seismic hazard at Site 3 is governed by a broader set of distant seismic sources, and emphasize the importance of regional fault systems even for peripheral urban areas.

3-5-Comparative Summary of Geographic Deaggregation Results

The comparative analysis of geographic deaggregation results across the three selected sites in Tehran reveals significant spatial and structural variations in dominant seismic sources. At Saman Bank Tower (Site 1), located in northern Tehran, the hazard is highly concentrated along nearby sources—specifically the North Tehran and Mosha faults. In all return period scenarios, over 90% of the hazard contribution stems from these two faults, with dominant magnitudes around M_w 6.8 and distances less than 15 km, indicating strong near-field effects. In contrast, Toqrol Tower (Site 2) in Rey exhibits a broader spatial distribution of seismic contributions. While the Mosha fault continues to play a major role, distant sources such as Taleqan and Robat Karim begin to contribute more prominently, especially in the 2475-year return period. Dominant distances increase to the 25–35 km range, and consistently positive epsilon values suggest that above-median shaking events are critical for this site. At Kashani Hospital (Site 3) in southern Tehran, the spatial pattern is even more dispersed. Distant faults, including North Tehran, Taleqan, and Firuzkuh, not only contribute but occasionally dominate, particularly in longer return period scenarios. Dominant distances often exceed 35 km, with magnitudes between M_w 7.0 and 7.3. The spectral deaggregation maps at $T = 0.85s$ show taller hazard bars in western regions such as Karaj and Taleqan, reflecting an increased influence of long-period waves. The site's low V_{s30} (< 200 m/s) further amplifies its vulnerability despite its relative distance from active faults. Collectively, these results underscore the critical importance of incorporating geographic deaggregation alongside traditional M_w – R – ϵ methods in seismic hazard modeling. The spatial asymmetry observed from north to south across the city provides essential input for urban-scale seismic risk planning, site-specific design, and prioritization of retrofitting strategies.

4 Discussion

Traditional seismic hazard deaggregation based on magnitude, distance, and epsilon (M_w – R – ϵ) has long served as the standard method for characterizing dominant ground motion scenarios. While standard deaggregation approaches have been widely applied across seismic hazard models in Italy (Barani, Spallarossa, & Bazzurro, 2009), Japan (De Risi & Goda, 2016), and New Zealand (Stirling et al., 2012), these studies generally focus on magnitude–distance–epsilon outputs without mapping the

geographic contribution of sources. In contrast, geographic deaggregation, as formally conceptualized by Harmsen and Frankel (Harmsen & Frankel, 2001), has been implemented primarily in the United States. This study represents one of the first applications of this method in a megacity outside the U.S., incorporating spatial source attribution at the fault scale. While effective for statistical analysis, such models lack the spatial resolution required for urban-scale risk assessment. In this study,

We introduced a geographic deaggregation methodology built upon standard outputs from EZ-FRISK and extended it via a structured Python-based analysis pipeline that algorithmically handles spatial source contributions. This approach replaces earlier spreadsheet-based processing workflows. Our findings align with earlier efforts by Harmsen and Frankel (Harmsen & Frankel, 2001) and Petersen et al. (Petersen et al., 2014), but differ fundamentally in terms of implementation strategy and automation.

Unlike previous studies that presented only regional or continental-scale maps, our method integrates radial fault-intersection mapping and localized spatial clustering, allowing fault-specific contribution mapping with much greater detail—an advantage critical for a fault-dense environment like Tehran. Another key insight involves the behavior of the epsilon component, particularly at long return periods. Sites like Kashani Hospital, with soft soil and shorter fundamental periods, display significantly positive epsilon values under higher hazard levels. This suggests the presence of long-period ground motions with enhanced amplification, consistent with conclusions from Field et al. (2015) in the context of UCERF3 hazard modeling. Technically, our method offers high adaptability, spatial precision, and scenario customization. Nonetheless, the method remains subject to certain limitations, including simplified fault geometry representations and the absence of explicit uncertainty quantification—both of which warrant further methodological refinement. In summary, geographic deaggregation, as implemented here through direct algorithmic processing, provides a robust framework for seismic hazard assessment in complex megacities. Its application can significantly inform urban resilience planning, targeted retrofitting, and the development of seismic design policies in high-risk regions.

5 Conclusion

This study introduced a comprehensive framework for the geographic deaggregation of seismic hazard in Tehran, integrating probabilistic seismic data and NGA-West2 ground motion prediction equations with a scripted post-processing workflow. Departing from conventional spatial mapping approaches, the proposed method applies algorithmic processing of deaggregation outputs to identify localized hazard contributions with high spatial resolution.

Three distinct urban sites—Saman Bank Tower, Toqrol Tower, and Kashani Hospital—were analyzed using both peak ground acceleration (PGA) and spectral acceleration (SA) at their respective fundamental periods, across standard return periods of 475, 975, and 2475 years. Results demonstrate clear differences in hazard patterns:

- Site A exhibited high ϵ values across all return periods, indicating greater variability near fault intersections.

- Spatial deaggregation clarified the fault-specific contribution to hazard, which traditional $M_w-R-\epsilon$ plots could not resolve.
- The method was executed through open-source Python-based algorithm, enhancing transparency and replicability.
- This workflow supports seismic design and emergency planning with higher locational resolution. Future research should integrate nonlinear site response and rupture dynamics for increased modeling accuracy.

The geographic deaggregation method not only quantifies these differences but also visualizes the evolving role of seismic sources under varying intensity measures and return periods. This level of spatial insight is essential for site-specific hazard characterization, performance-based seismic design, and urban risk governance in seismically active megacities.

The study also demonstrates the feasibility of implementing geographic deaggregation in practice, utilizing EZ-FRISK outputs in combination with a fully scripted Python-based workflow integrating radial fault-intersection logic and Python-based faultmapping was implemented, replacing the earlier spreadsheet-based processing. Given the complexity and heterogeneity of Tehran's fault system, this methodology provides a critical advancement for seismic hazard modeling in the region and sets a replicable precedent for other high-risk urban areas worldwide.

Declarations

Author Contributions: Hadi Jarahi: formal analysis, fieldwork, methodology, investigation, and writing the first draft of the manuscript; Donya Namdar: conceptualization and design of the study, review, and editing. All authors have read and agreed to the published version of the manuscript. All authors contributed to the research and preparation of the manuscript and approved the submitted version.

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Data and Resources: All seismic source parameters were obtained from published sources listed in the references. Ground-motion prediction equations (GMPEs) were accessed via EZ-FRISK v8.0 (licensed software). No new data were generated for this study

Conflicts of Interest: The authors declare no competing interests.

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Figures

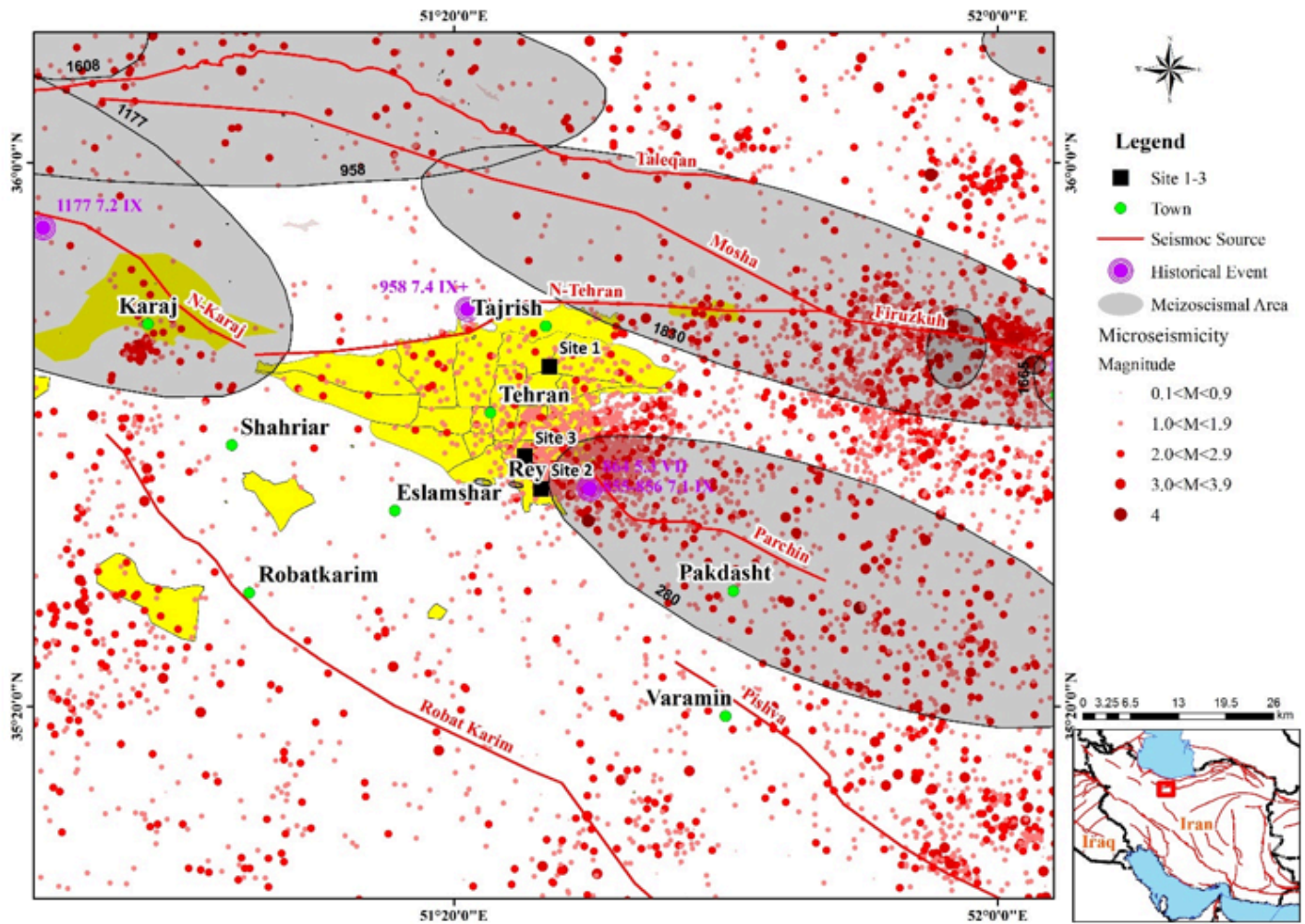


Figure 1

Seismotectonic map of the Tehran region showing active faults, historical and instrumental earthquake epicenters, and the location of three selected study sites. Fault traces are based on regional neotectonic studies; historical and instrumental seismicity is compiled from Berberian (Berberian, 2014) and BHRC databases. Epicentral clustering highlights zones of seismic potential relevant to hazard modeling.

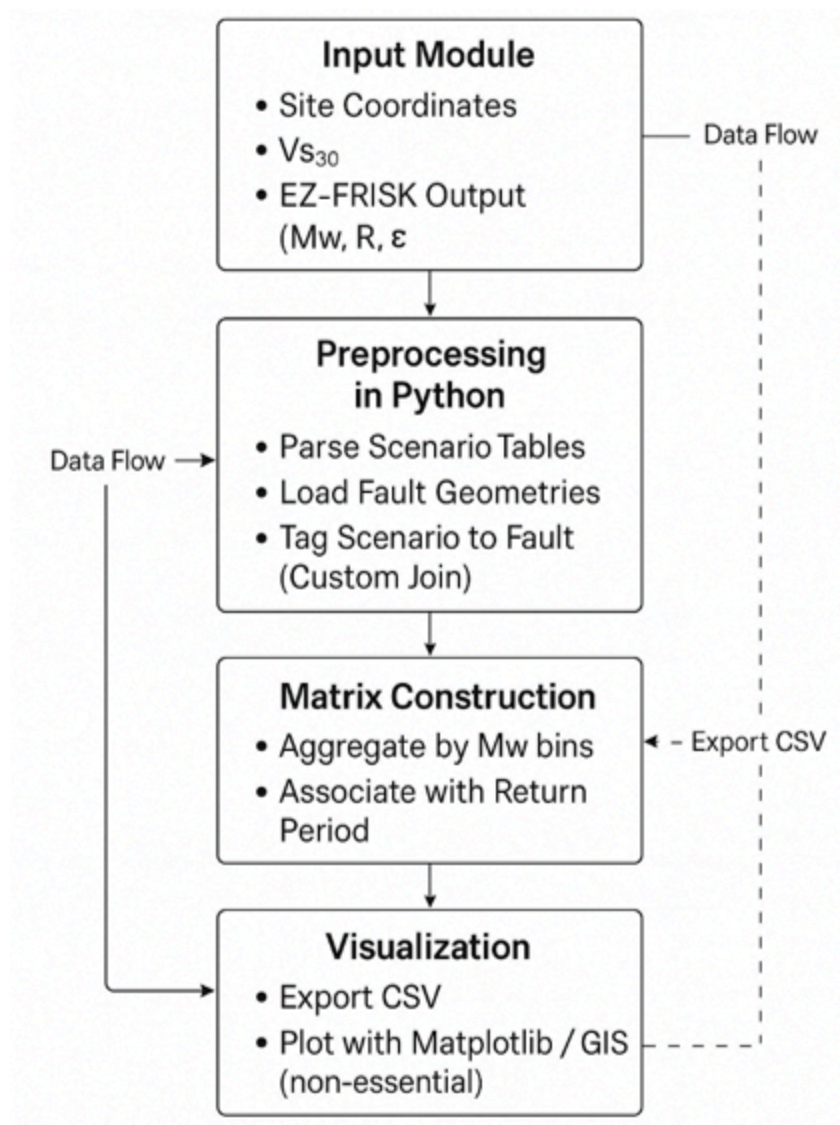


Figure 2

Structured computational pipeline for fault-resolved seismic hazard disaggregation. The framework receives scenario-based outputs from EZ-FRISK and applies a fully scripted pipeline to associate each contribution with specific fault segments. The flowchart distinguishes the coded algorithmic stages—scenario parsing, fault-tagging, and contribution matrix assembly—from optional visualization steps.

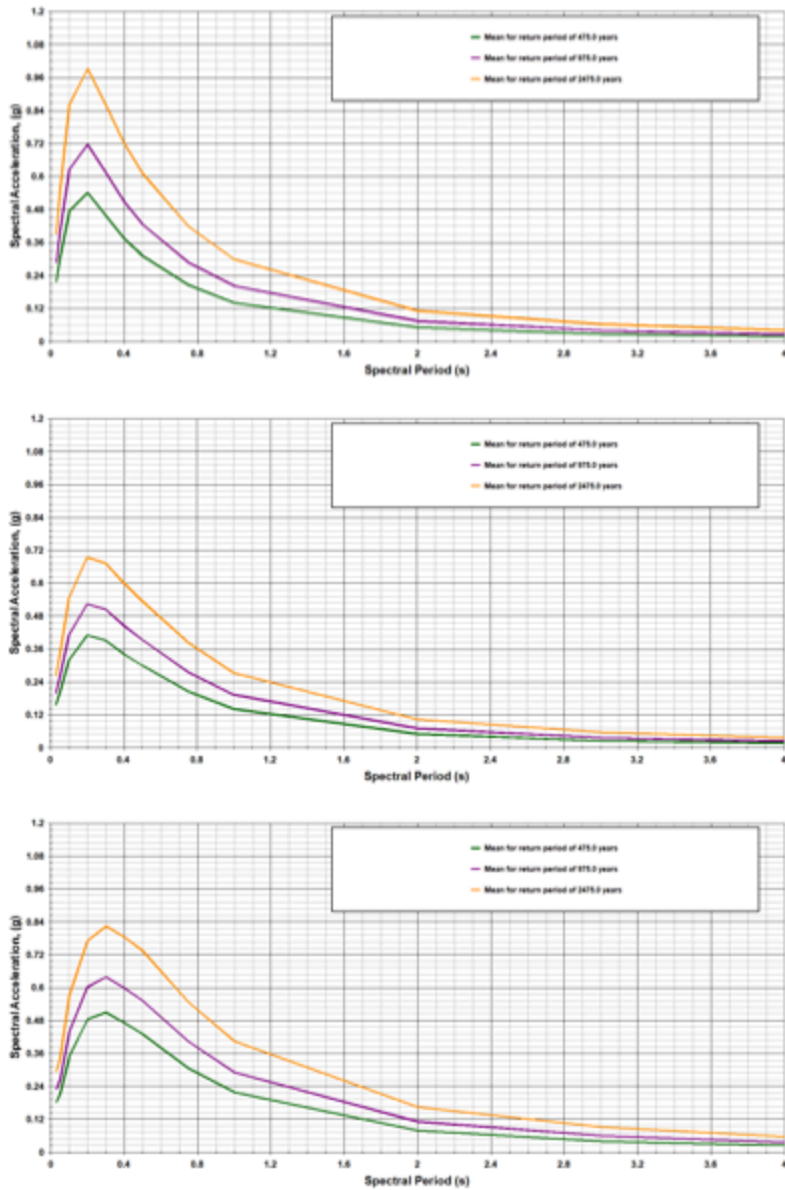


Figure 3

Uniform hazard spectra for PGA and spectral acceleration (SA) at the fundamental period of each structure, computed for three selected sites. The curves correspond to return periods of 475, 975, and 2475 years, illustrating variations in seismic hazard levels from north to south across the urban domain.

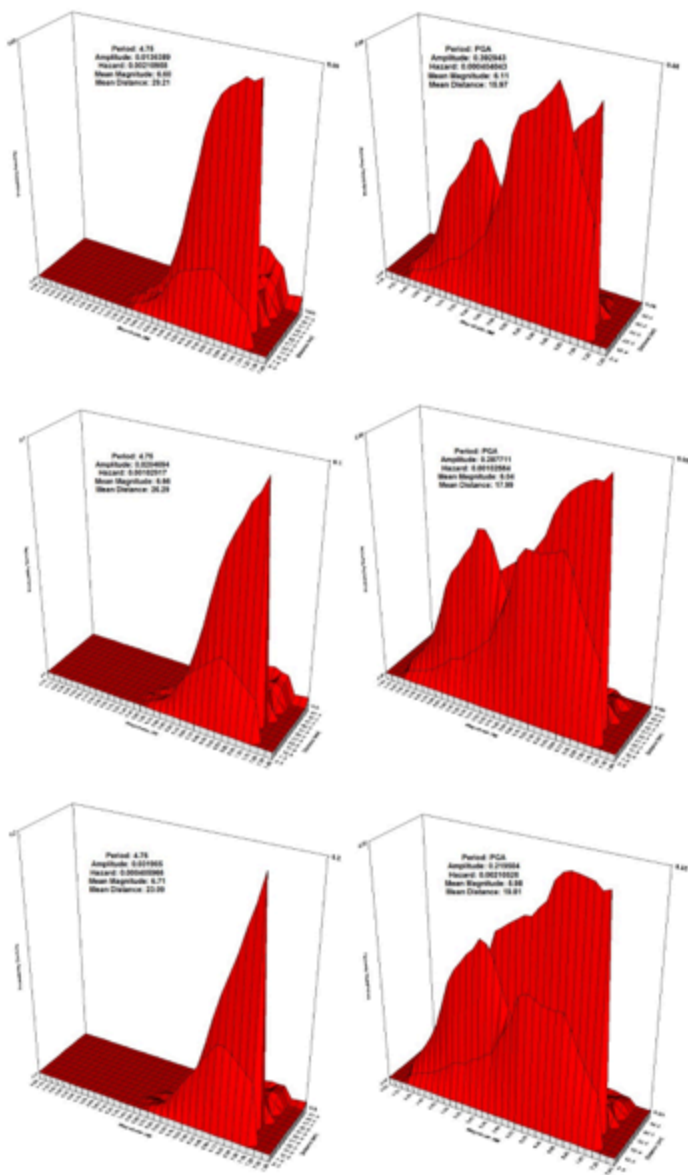


Figure 4

Standard Mw–R– ϵ deaggregation plots for Site 1 (Saman Bank Tower) for PGA and SA ($T = 4.75$ s), 475-year return period.

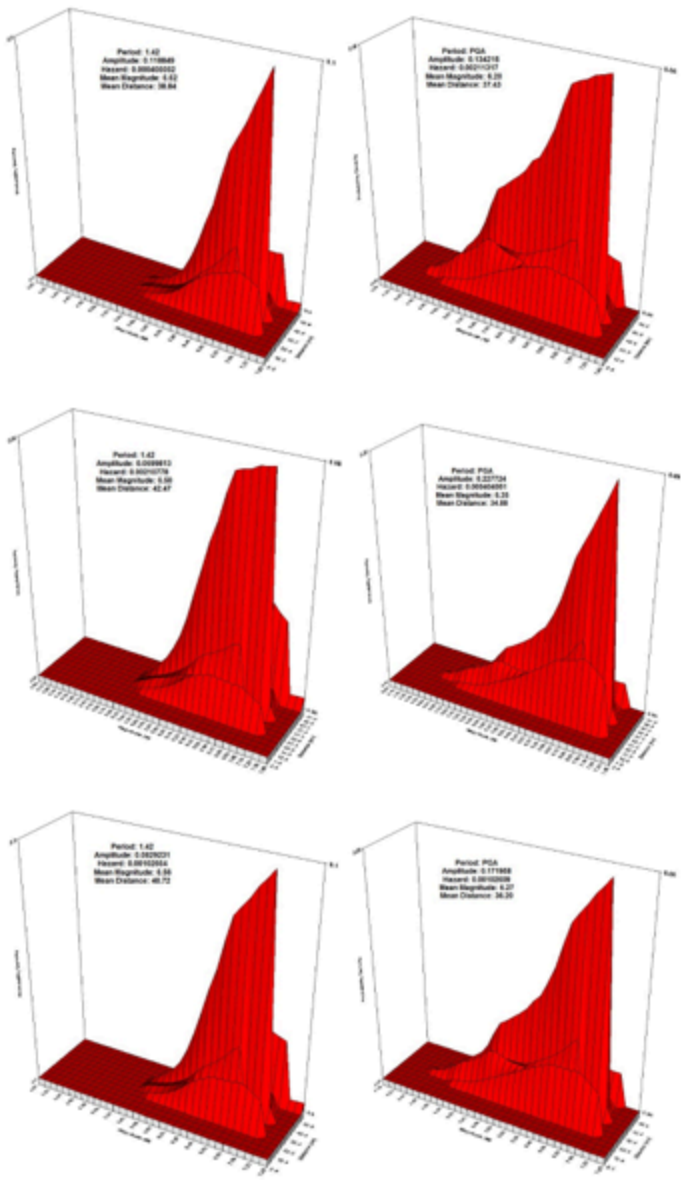


Figure 5

Standard deaggregation results for Site 2 (Toqrol Tower), showing magnitude–distance–epsilon distributions for PGA and SA at $T = 1.42$ s.

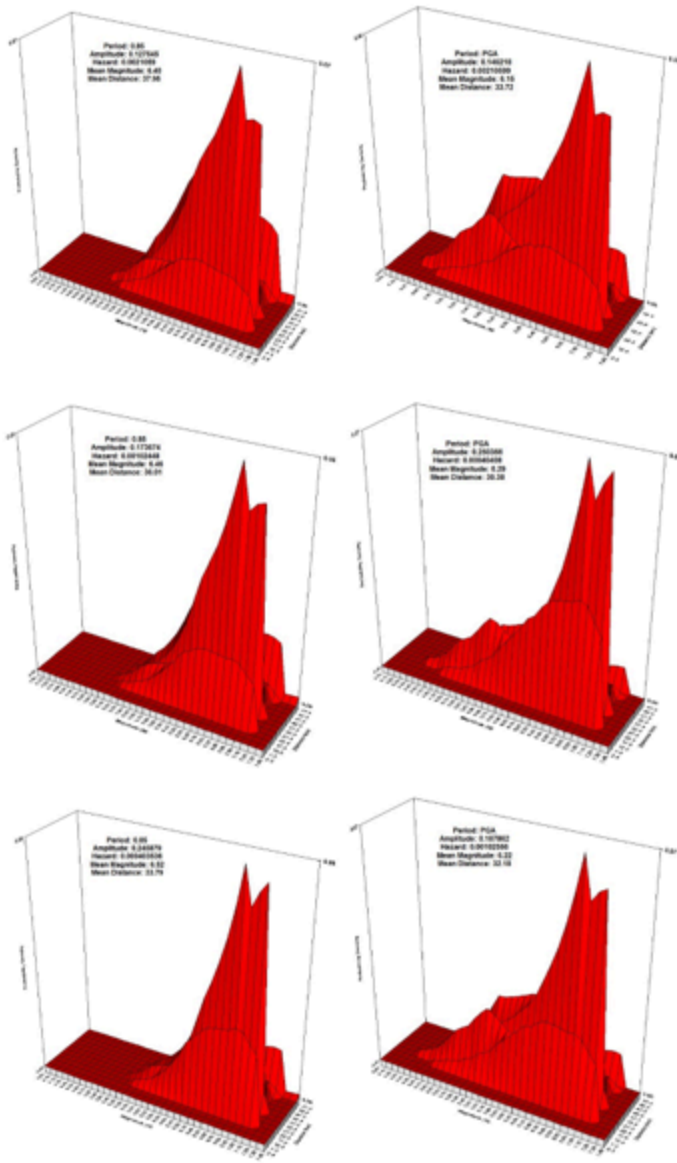


Figure 6

Standard deaggregation results for Site 3 (Kashani Hospital), illustrating the dominant magnitude, distance, and epsilon values for PGA and SA (T = 0.85s).

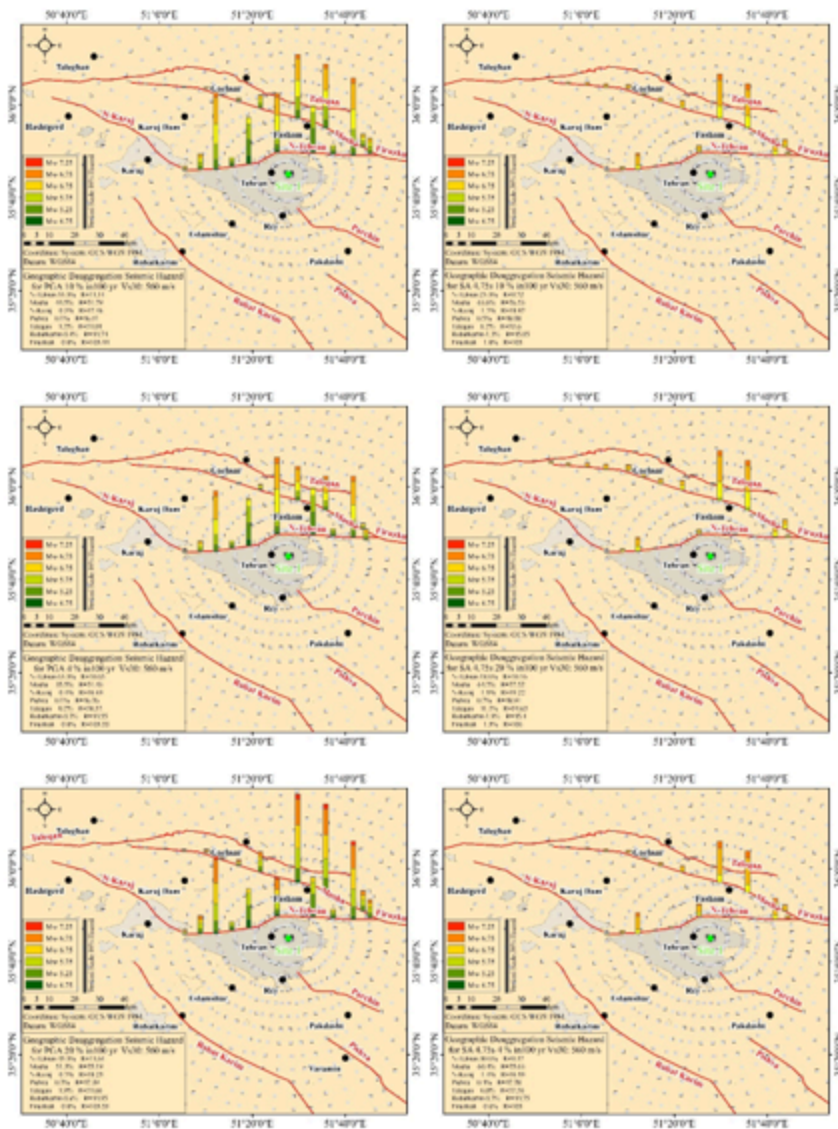


Figure 7

Geographic deaggregation maps for Site 1 (Saman Bank Tower) showing hazard contributions for PGA and SA at $T = 4.75s$ under 475-, 975-, and 2475-year return periods.

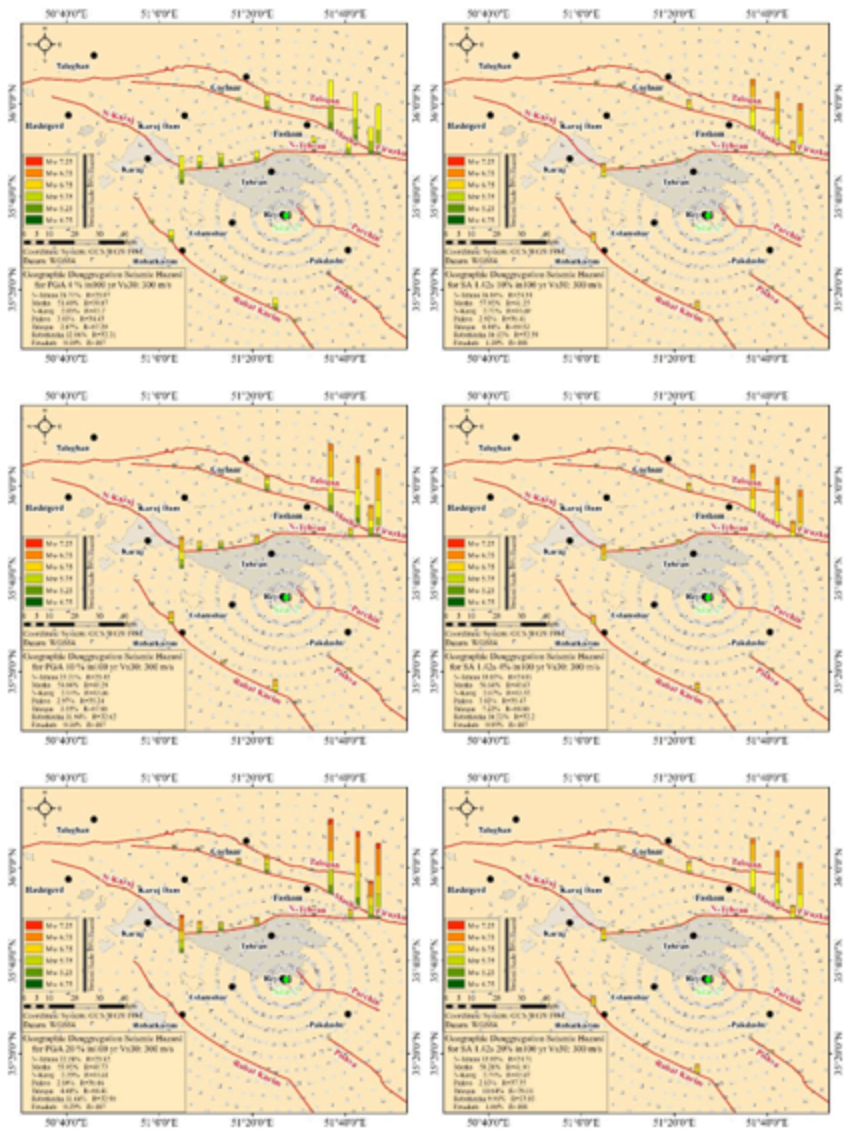


Figure 8

Geographic deaggregation maps for Site 2 (Toqrol Tower) for PGA and SA at $T = 1.42s$ across three standard return periods. Contributions from both nearby and remote fault sources are visualized.

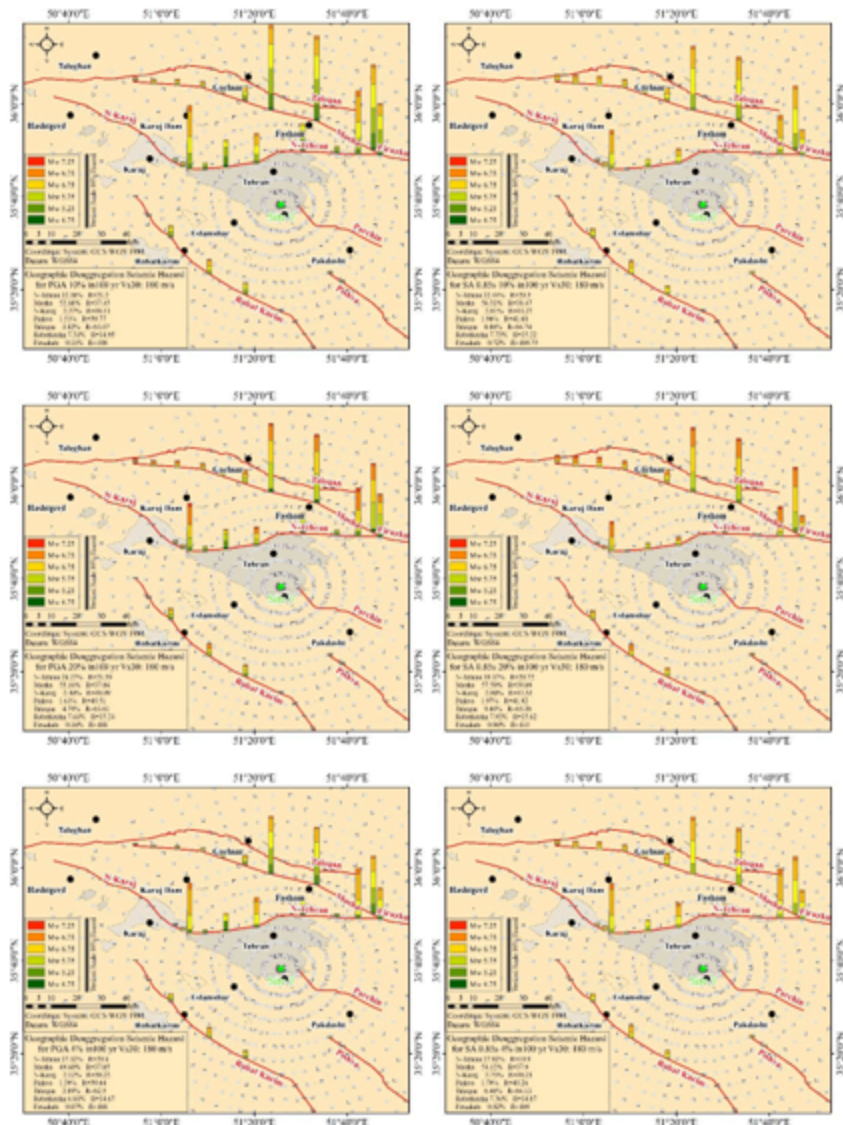


Figure 9
 Geographic deaggregation maps for Site 3 (Kashani Hospital), depicting the spatial distribution of dominant seismic sources affecting PGA and SA at $T = 0.85s$.

Supplementary Files

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

- [AppendixAGeographicDeaggregationPython.docx](#)