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Original Research Article

Uncertainties in Seismic Hazard Assessment of Metropolitan Tehran

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Abstract

Probabilistic seismic hazard analysis (PSHA) is a foundational element for determining design forces for new buildings and assessing the safety of existing structures. Consequently, decisions regarding the protection of urban infrastructures hinge on the outcomes of the PSHA. In recent years, numerous seismic hazard analyses have been conducted in Tehran, often yielding significantly divergent results. Such discrepancies can mislead analysts and stakeholders involved in urban safety. This article investigates the primary causes of variability in hazard results and quantitatively expresses the uncertainty associated with these findings. To achieve this, the Cornell-McGuire approach for PSHA is employed. The study's results indicate that the selection of ground motion prediction equations (GMPE or attenuation relationships), seismicity parameters(λ), and minimum magnitude(mmin) are critical factors contributing to this variability. Therefore, it is recommended that greater care be taken in selecting these parameters for PSHA conducted in Tehran.

Keywords: Seismic hazard analysis inputs, Seismicity parameters, Parameter distribution, Model selection.

Nomenclature

APE	Annual probability of exceedance
b-value	Slope of Gutenberg–Richter law
GMPE	ground motion prediction equations or attenuation relationship
GR	Gutenberg–Richter law
IM	Intensity measure
m_{max}	Maximum magnitude
m_{min}	Minimum magnitude
NEPSHA	Non-Extensive Probabilistic Seismic Hazard Analysis
PDF	probability density function
PGA	peak ground acceleration
PSHA	probabilistic seismic hazard analysis
SA	spectral acceleration

1. Introduction

In any statistical analysis, it is essential to periodically reassess the overarching objectives of the project to ensure that the collected data and proposed analyses align with these objectives. One of the primary aims of probabilistic seismic hazard analysis (PSHA) is to mitigate financial and human losses resulting from earthquakes. In PSHA models, data are incorporated into hazard calculations based on three fundamental distributions: time distribution (assumed stationary rate), spatial distribution (kernel methods and kriging), and frequency distribution (histograms and frequency distributions) [1].

In the Cornell-McGuire approach to PSHA, the mean annual rate at which a specific threshold value x of a ground motion intensity measure (IM) is exceeded can be calculated using an equation developed by Cornell in 1968 [2]. This equation incorporates various factors, including the frequency of earthquake occurrences and

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their associated ground motion characteristics. (Cornell, 1968).

$$\lambda_{IM}(x) = \sum_{i=1}^{n_{flt}} \upsilon \int_m \int_r G_{IM|M,R}(IM \geq x \mid m,r) f_M(m) f_{R|M}(r|m) dmdr \qquad (1)$$

where,

n_{flt}: represents the number of causative faults contributing to seismic activity in the region under study.

v: denotes the average annual frequency of earthquakes with magnitudes within a specified range, defined by a lower threshold m_{min} and an upper threshold m_{max}.

M: The moment magnitude of the earthquake, which provides a measure of the earthquake's size.

R: The distance from the earthquake source to the site of interest which influences the intensity of ground shaking experienced at that location.

$G_{IM|M,R}$: represents the probability that an IM exceeds a value of xx, given that an earthquake of magnitude mm occurs at a distance R. This probability is determined using ground motion prediction equations (GMPEs), which predict ground shaking based on various factors, including magnitude and distance.

f_M: signifies the probability density function (PDF) for earthquake magnitudes, indicating how likely different magnitudes are to occur.

$f_{R/M}$: is the PDF of distance r conditional on magnitude mm, reflecting how distances vary for earthquakes of different sizes.

The Cornell-McGuire method's capacity to integrate seismicity and geological information has led to its widespread adoption globally [3]. Geological data play a crucial role in defining seismic sources, provided that sufficient and reliable information is available. However, research indicates that varying definitions of seismic sources can significantly impact earthquake hazard analysis outcomes [4]. When multiple experts or groups are tasked with identifying seismic sources independently, substantial discrepancies often emerge between their findings, leading to considerable variations in the resulting earthquake hazard analyses [5]. This issue is less pronounced in regions such as the western United States, where surface faults are well-documented [6].

In contrast, areas like Tehran, where fault knowledge is incomplete, face far greater challenges in accurately defining seismic sources [7-8-9]. The maximum magnitude of a potential earthquake can typically be estimated based on historical seismicity; however, this estimation carries substantial uncertainty [10]. In conventional PSHA methods, the selected attenuation relationships involve spatial smoothing. These models have some challenges in accounting for site-to-site variability and event-specific characteristics [11].

In this paper, various factors affecting the variability of seismic hazard predictions are discussed. The variations in seismic hazard analysis results for Tehran are evaluated, and the range of hazard changes is quantified using a written Matlab-based code.

2. The PSHA uncertainties

Based on the PSHA literature study [12, 13], the most important causes of uncertainty are as follows.

2.1 Model Selection and Uncertainty

Choosing event models that align with regional realities is crucial in seismic hazard analysis. Uncertainty in these models often arises from simplifying assumptions that may later prove incorrect. Therefore, employing more accurate assumptions can help reduce this uncertainty [14].

2.2 Role of the Poisson Assumption

The Poisson assumption is fundamental in determining several outputs in seismic hazard analysis, particularly for estimating return periods. While complex earthquake occurrence models may not significantly improve risk estimates, the Poisson model remains essential for calculating confidence intervals for return rates [15].

2.3 Non-stationarity in Regional Seismicity

Risk calculations are often based on rates of occurrence, which require some stability in tectonic processes. The assumption of stationarity must ensure that past seismicity can guide future predictions. However, long-term instrumental data is often lacking, leading researchers to rely on historical and geological data, which come with high uncertainties [16].

2.4 Geological Data Contribution

Geological factors such as fault depth and earthquake occurrence can significantly impact hazard analysis results by altering event rates. Modern seismic hazard assessments often rely on computational methods that require dividing study areas into seismic sources [17].

2.5 Seismic Zone Delineation

The delineation of seismic zones has been a topic of ongoing debate. Different approaches exist for defining these zones, including probabilistic and deterministic methods based on tectonic information or actual seismic patterns [18].

2.6 Data Catalogs and Extraction

Various local and global catalogs provide differing reports on past earthquakes, especially historical events. The accuracy and completeness of these catalogs are critical for effective risk analysis [19].

2.7 Magnitude Measurement Units

Selecting appropriate conversion relationships for magnitude measurements is essential, with regional relationships preferred when sufficient data is available [20].

2.8 Methods for Aftershock Removal

Several methods exist for removing aftershocks from catalogs, including the Gardner- Knopoff method, which defines spatial and temporal windows around main shocks to categorize aftershocks. The definition of these windows is associated with great uncertainty [21].

2.9 Geological Characteristics in Aftershocks

The geological characteristics of faults are considered in some methods for determining aftershock potential and behavior. Some researchers have questioned the reason for and method of removing aftershocks.

2.10 Frequency-Magnitude Law Issues

To effectively combine historical and instrumental data, attention must be paid to unit conversions, completeness of catalogs over time and space, and the credibility of these catalogs. The methods used for data integration can significantly influence risk analysis outcomes by altering the coefficients in the Gutenberg-Richter relationship [22].

Analysts must be aware of the risks associated with extrapolating magnitude-frequency laws due to a lack of high-magnitude data in regional catalogs. The main errors arise from using extreme value distributions, which may not be more suitable than other distributions. This is critical since these distributions assign more weight to higher magnitudes. In the absence of direct data on large earthquakes, geological evidence such as plate movement rates and fault activity should be prioritized for assessing maximum possible magnitudes.

2.11 Variability in Attenuation Relationships

Variability in attenuation relationships can shift hazard curves vertically. This variability arises from differing definitions of key parameters in ground motion equations. When combining equations from different sources, it is crucial to standardize these parameters to ensure accurate hazard calculations [23].

Aleatory uncertainty in PSHA models is quantified through integration or summation processes. When additional uncertainties are identified within this category, the integration order is elevated, resulting in hazard models with double, triple, or higher-order integrations as documented in the literature [7,8]. Epistemic uncertainty, conversely, is addressed through logic tree frameworks that systematically propagate input parameter uncertainties via probability distributions. This process can be completed by employing sampling techniques such as Monte Carlo simulations or bootstrap methods to replicate and analyze the uncertainty space comprehensively.

2.12 Parameter Matching for Local Applications

Ensuring that equations used in logical trees are compatible is essential for effective hazard assessment. This may involve transformations that consider both the region where the equations were derived and where they will be applied. The lack of appropriate matching can lead to inaccurate epistemic uncertainties.

2.13 Uncertainties in Matching

If proper matching is not achieved, epistemic uncertainties cannot be accurately calculated. Since empirical relationships used for matching carry their uncertainties, relying on them can exacerbate overall uncertainty. Analysts must consider both epistemic uncertainty and inherent variability when developing risk estimates.

2.14 Lack of Attention to Different Failure Modes

Structural failures often result from a lack of precise information regarding the structure's response to seismic forces and ground movements. The occurrence of various types of ground motion can trigger different failure modes, leading to significant deviations in hazard assessment [24-26].

2.15 Seismic Hazard Maps

Hazard maps are the oldest tools used for risk analysis but have not been thoroughly discussed in terms of their preparation basis. Generally, these maps are created using non-general smoothing methods without assessing or improving their accuracy [27-28].

2.16 Averaging Issues and Logical Trees

In the current PSHA, logical trees are employed to calculate average hazard, which is crucial for engineering design. Uncertainties in models regarding earthquake magnitude, location, and GMPE must be managed carefully. Two types of uncertainty exist: inherent variability (aleatory) and epistemic uncertainty. These uncertainties affect the shape of the hazard curves differently [29-32].

2.17 Selection of hazard Curves

Choosing the appropriate hazard curve in engineering design is essential for safety levels and uncertainty management. Using average curves in projects with long return periods may lead to significant risks, necessitating careful model selection and weighting in logic trees [33-35].

3. Tehran's Past Hazard Analyses

In order to assess the earthquake hazard of Tehran based on past studies, a number of hazard analyses have been reviewed in this section. The reviewed studies report various peak ground acceleration (PGA) values and spectral acceleration (SA) estimates for different return periods. Yazdani et al. (2015) present an artificial statistical method for estimating seismicity parameters from incomplete earthquake catalogs in metropolitan Tehran, Iran. The hazard values are greater than the classic method for Annual probability of exceedance (APE) larger than 0.0021 [9].

Ghodrati Amiri et al. (2003) found similar PGA values but noted that these were likely underestimations due to limited high-magnitude data [36]. Yazdani et al. (2012) provided a range of PGA values from their Monte Carlo simulations, indicating potential ground shaking from 0.3g to 0.7g depending on the scenario [37]. Wang & Taheri (2014) reported PGA values around 0.4g for a 10% probability of exceedance in 50 years [38]. Yazdani & Kowsari (2017) produced maps showing spectral accelerations varying significantly across Greater Tehran, with some areas experiencing accelerations exceeding 0.5g under severe scenarios [39]. Mahsuli et al. (2019) emphasized the variability in hazard estimates, with PGA values ranging from 0.4g to 0.8g based on different reliability methods applied [40]. Alikhanzadeh & Zafarani (2023) presented higher PGA estimates, reaching up to 0.6g for similar return periods due to their advanced modeling techniques [41]. The non-extensive approach resulted in higher estimates of PGA compared to traditional PSHA methods, which often rely on extensive catalogs that may not fully capture the seismicity of the region. Motaghed et al. 2024 For instance, while traditional PSHA studies might estimate PGA values around 0.4g for a 10% probability of exceedance in 50 years, the non-extensive method could yield values closer to 0.5g or higher, reflecting a more comprehensive understanding of seismic hazard [34]. NEPSHA (Non-Extensive Probabilistic Seismic Hazard Analysis) enhances traditional PSHA by substituting the Gutenberg–Richter power law with the SCP (Sotolongo-Costa and Posadas) non-extensive model for earthquake size distribution. This approach explicitly accounts for the irregular geometry of tectonic plate interactions and fragmented crustal structures within its numerical framework. The SCP model demonstrates superior statistical fit to regional seismicity data compared to the Gutenberg–Richter law, evidenced by a residual sum of squares of **0.01453 vs. 0.03563**. Applied to the Tehran region, NEPSHA predicts **20–30% higher hazard levels** than classical PSHA, particularly for medium-rise structures (common in urban areas), with spectral accelerations exceeding **0.5g** under severe scenarios.

The reason for these differences in results must be sought in the data, models, and methods used. Wang & Taheri (2014) utilized a PSHA approach, incorporating historical earthquake data and local geological conditions. The study highlighted the need for updated seismic catalogs. Ghodrati Amiri et al. (2003) Similar to Wang & Taheri, this study employed PSHA but emphasized integrating both historical and instrumental data. The authors found that the hazard of large earthquakes was underestimated due to a lack of high-magnitude records, which could lead to inadequate preparedness. Alikhanzadeh & Zafarani (2023) introduced a physics-based PSHA, focusing on the complexities of the Tehran Basin's geology. Their findings indicated higher seismic hazard levels compared to previous studies due to detailed geological modeling, which accounted for local tectonic features. Yazdani et al. (2012) utilized Monte Carlo simulations to assess seismic hazards, allowing for a comprehensive evaluation of uncertainties. The simulations provided a range of ground motion predictions, highlighting the variability in potential earthquake impacts across different scenarios.

Yazdani & Kowsari (2017) developed scenario-based seismic hazard maps using probabilistic methods. Their maps illustrated varying levels of ground shaking across Greater Tehran under different earthquake scenarios, providing practical tools for urban planning. Mahsuli et al. (2019) applied reliability methods in their PSHA, focusing on uncertainties in input parameters and model predictions. The findings underscored the importance of robust methodologies that can accommodate uncertainties, leading to more reliable hazard assessments. The comparative analysis reveals that while all studies acknowledge the significant seismic risk in Tehran, they differ in methodologies and resulting hazard values due to variations in data integration, modeling approaches, and treatment of uncertainties. Table *** shows a summary of the most important results of the PSHA including the PGA of the 475-year return period.

Table 1. PSHA results in different studies

Study	Methodology	PGA	Key Findings
Ghodrati Amiri et al. (2003)	Classic PSHA	0.34–0.52g on bedrock	Highest accelerations near North Tehran Fault;
Yazdani et al. (2012)	Monte Carlo simulations	0.3g-0.7g	Wide variability in potential ground shaking across scenarios
Wang & Taheri (2014)	PSHA with local geology	~0.4g	Southern Tehran faces amplified ground motions due to soft soils and seismic gaps identified beneath the city.
Yazdani & Kowsari (2017)	Probabilistic scenario mapping	Up to 0.5g	Spatial variability in spectral accelerations across Greater Tehran
Mahsuli et al. (2019)	Reliability-based PSHA	0.4g-0.8g surface conditions	Emphasizes the importance of parameter uncertainty handling
Alikhanzadeh & Zafarani (2023)	Physics-based PSHA	Up to 0.7g - surface conditions.	Highlights the role of dynamic rupture modeling in capturing variability; identifies high hazard in southern Tehran Basin.
Non-extensive PSHA	Tsallis entropy framework	>0.5g	Captures complex seismicity patterns better than traditional PSHA

What can be concluded from these studies is that the studies employing advanced geological modeling techniques like Alikhanzadeh & Zafarani (2023) tend to yield higher hazard estimates compared to earlier works that relied more heavily on historical data without detailed geological insights. The use of Monte Carlo simulations by Yazdani et al. (2012) highlights the inherent variability in earthquake impacts, which is crucial for understanding risk in a densely populated urban environment like Tehran. Overall, these studies collectively emphasize the need for continuous updates to seismic hazard assessments as new data becomes available and methodologies evolve.

4. Tehran Seismic Hazard Uncertainty

In this section, we will explore how variations in input parameters influence the distribution of results from PSHA. In order to perform PSHA, a code has been written in Matlab software. The inputs to the analysis, including attenuation relations, seismicity coefficient (λ) and minimum magnitude, Gutenberg-Richter coefficient (b-value), maximum magnitude, fault to site distance and fault depth, have been modeled by assigning weighted, normal, uniform, normal, lognormal, normal and normal distributions, respectively.

The Monte Carlo simulation method is a computational technique used to quantify uncertainty in model outputs by statistically analyzing how input parameter variability propagates through the system. The approach involves **sampling input parameters** from their respective **probability distributions**. The **dispersion** of these distributions – quantified through metrics like variance, standard deviation, or confidence intervals – directly reflects the uncertainty associated with each input parameter. By repeating this process across multiple simulations, the method generates a statistical distribution of possible outcomes, enabling robust uncertainty quantification in model predictions.

The outcomes of this evaluation are depicted in Figures 1 through 7. This methodology enables us to assess the degree of confidence necessary in selecting input values to achieve a desired level of certainty in the output results. Figure 1 illustrates that variations in hazard levels at a specific probability of exceedance are highly inconsistent and cannot be reliably depended upon. For example, at an annual exceedance probability of 0.0021, the peak ground acceleration (PGA) values show considerable fluctuation, ranging from approximately 0.08 g to 0.6 g. Similarly, at an annual exceedance probability of 0.0004, the PGA values vary between about 0.15 g and 0.8 g.

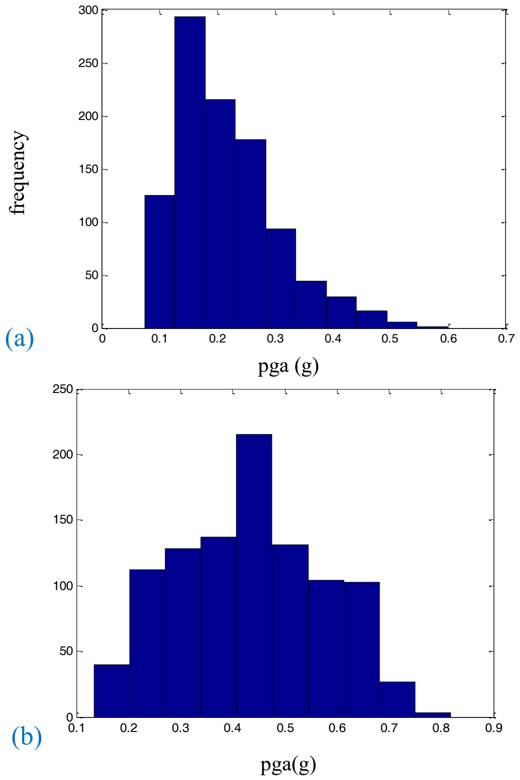

Figure 1. The distribution of PSHA with all input variables change (a) 10% probability of exceedance in 50 years; (b) 2% probability of exceedance in 50 years

The attenuation relationships utilized in this analysis are derived from various studies focusing on seismic hazards in different regions. These relationships help to inform the uncertainty analysis by providing a framework for understanding how attenuation relationships can influence hazard outcomes. The GMPEs are:

- Ghodrati et al. (2007) - Central Alborz region [42]
- Yazdani and Kowsari (2013) - Northern Iran [43]
- Zafarani & Soghrat (2012) - Zagros (recommended by the Code) [44]
- Ambraseys et al. (2005) - Middle East data used in Tehran risk analysis [45]
- Campbell and Bozorgnia (1994) - Middle East [46]
- Zare & Bard (1999) - Alborz and central Iran [47]
- Ramazi (1999) - Tehran specific [48]
- Nowroozi (2005) - Tehran specific [49]
- Sarma & Srbulov (1996) - Middle East, used in Tehran risk analysis [50]
- Ambraseys and Bommer (1991) - Middle East, used in Tehran risk analysis [51]

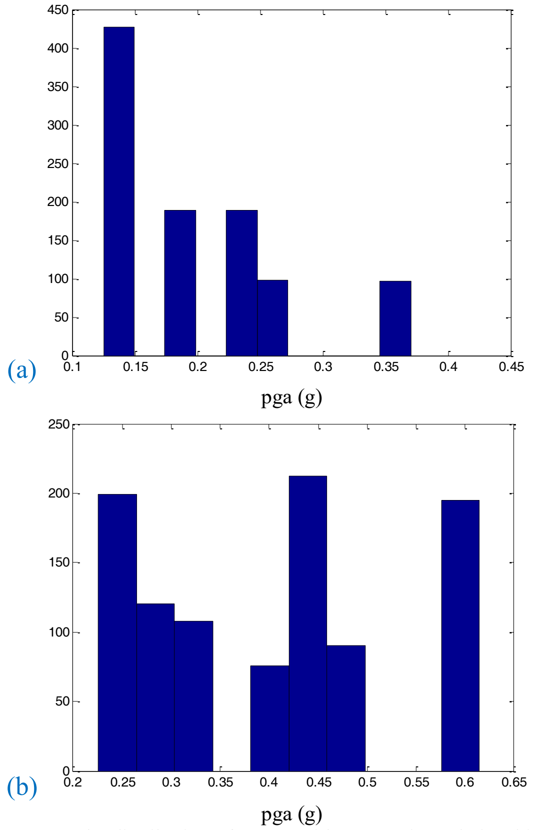

Figure 2. The distribution of PSHA with attenuation relationships change (a) 10% probability of exceedance in 50 years; (b) 2% probability of exceedance in 50 years

GMPEs are typically selected by **subjective judgment, expert opinion**, or **systematic ranking frameworks [5,52].** In this study, the **expert-based approach** was adopted as the criterion for selecting the GMPEs. The experts in this field are researchers who have applied these relationships in their studies.

The cited editions align with the **Standard**, which prioritizes consistency in curriculum-aligned resources. While newer editions of some works exist [53-56], we adhered to the specified editions to maintain compliance with institutional guidelines for selection and validation.

In Figure 2, the primary changes observed in the PSHA curve are mainly due to variations in the attenuation relationships. The discrete modeling of these relationships results in multiple curves, specifically showing 10 distinct relationships in the figure. Figures 3 to 8 illustrate the distribution of seismic hazard at annual probabilities of exceedance of 0.0021 and 0.0004 for various parameters.

These figures provide additional insights into how different parameters influence seismic hazard estimates and emphasize the variability of hazard outcomes based on the selected models.

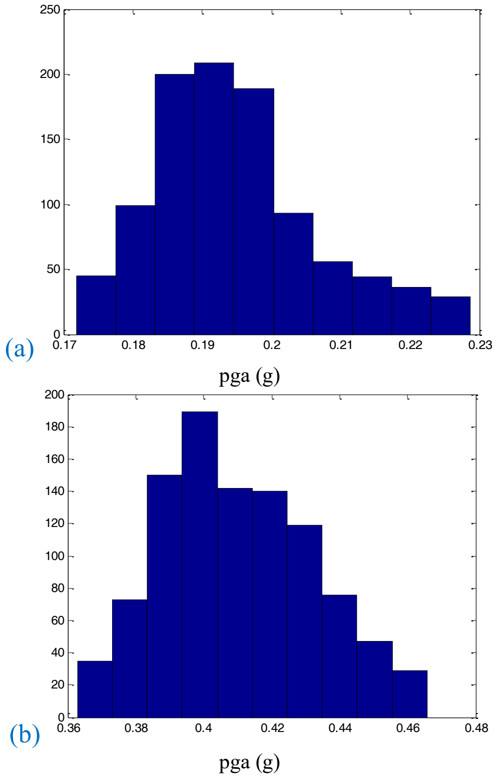

Figure 3. The distribution of PSHA with b-value change (a) 10% probability of exceedance in 50 years; (b) 2% probability of exceedance in 50 years

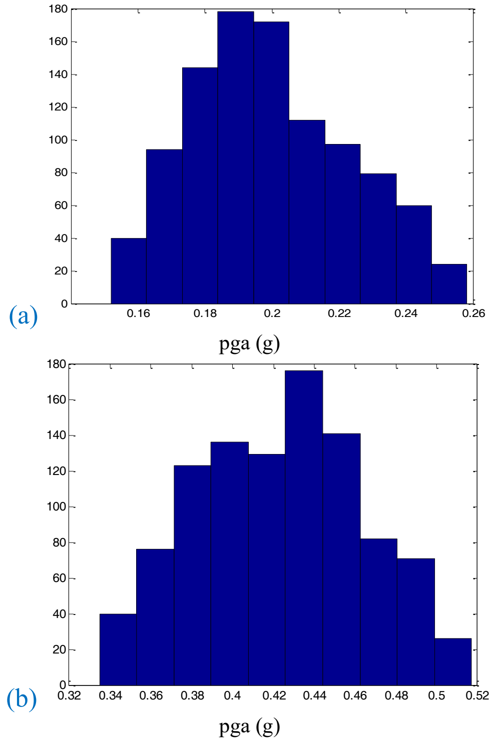

Figure 4. The distribution of PSHA with minimum magnitude change (a) 10% probability of exceedance in 50 years; (b) 2% probability of exceedance in 50 years

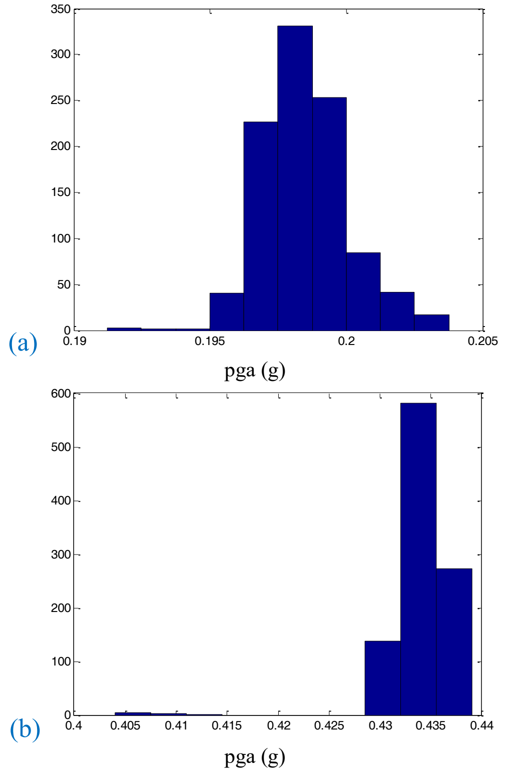

Figure 5. The distribution of PSHA with maximum magnitude change (a) 10% probability of exceedance in 50 years; (b) 2% probability of exceedance in 50 years

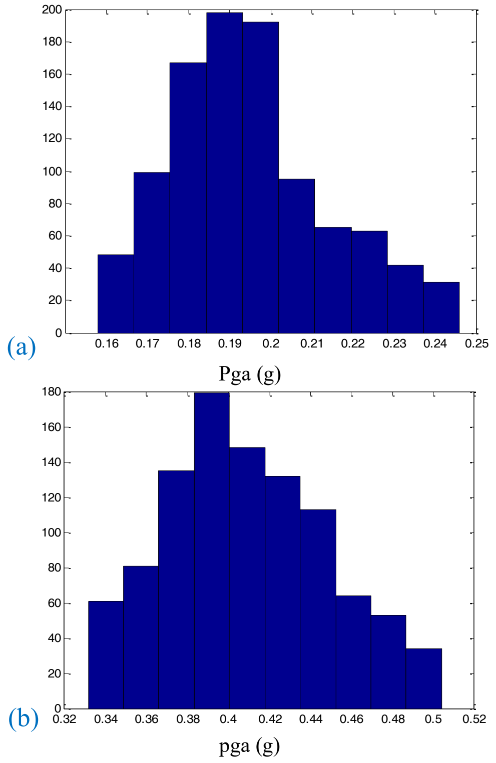

Figure 7. The distribution of PSHA with fault position change (a) 10% probability of exceedance in 50 years; (b) 2% probability of exceedance in 50 years

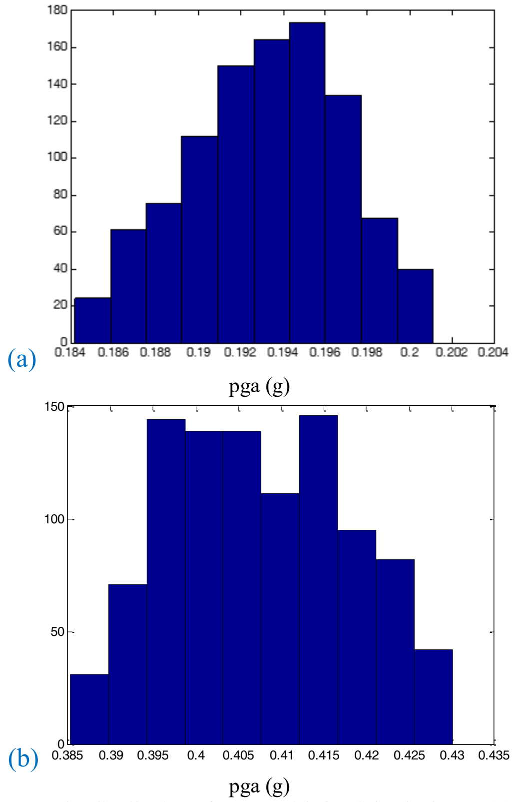

Figure 6. The distribution of PSHA with focal depth change (a) 10% probability of exceedance in 50 years; (b) 2% probability of exceedance in 50 years

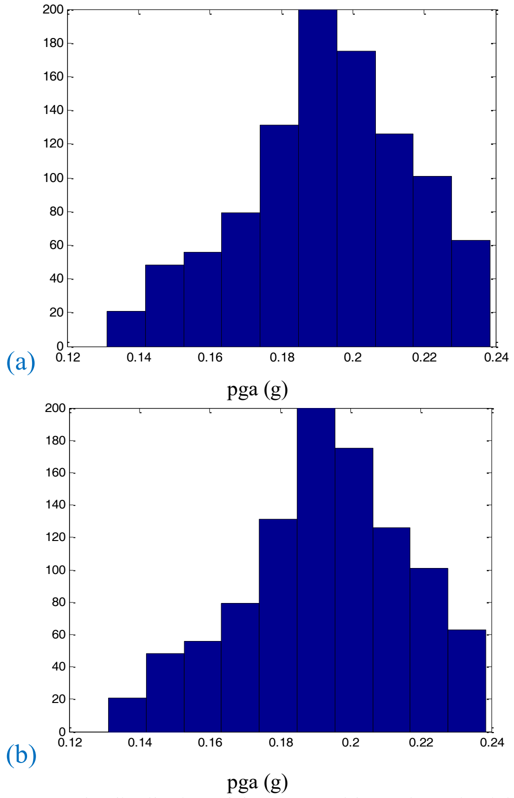

Figure 8 The distribution of the PSHA with varying seismicity coefficients (λ). A: 10% probability of exceedance in 50 years; B: 2% probability of exceedance in 50 years

5. Conclusion

This study highlights the critical importance of periodically reassessing the objectives of probabilistic seismic hazard analysis (PSHA) to ensure alignment between data collection and analytical methods. The overarching goal of PSHA is to minimize the financial and human toll of earthquakes by providing accurate hazard assessments. Through the examination of various methodologies, including the Cornell-McGuire approach, we have identified key factors that contribute to uncertainty in seismic hazard analysis. The analysis reveals that uncertainties arise from multiple sources, including model selection, non-stationarity in seismicity, geological data contributions, and the delineation of seismic zones. Each of these factors can significantly influence hazard estimates, underscoring the need for careful consideration in their application.

Furthermore, discrepancies in defining seismic sources highlight the challenges faced in regions with incomplete fault knowledge, such as Tehran, compared to areas with well-documented geological features. Our review of past seismic hazard analyses for Tehran demonstrates a range of peak ground acceleration (PGA) values and spectral acceleration (SA) estimates across different studies. Notably, newer methodologies that incorporate advanced modeling techniques tend to yield higher hazard estimates than traditional approaches. This trend emphasizes the necessity for continuous updates and improvements in seismic hazard assessments as new data and methodologies become available.

The findings from this study stress the importance of integrating various data sources and employing robust statistical methods to enhance the reliability of seismic hazard assessments.

By addressing uncertainties associated with input parameters and employing a comprehensive approach to data integration, we can achieve more accurate predictions of seismic risk. Ultimately, this research contributes to a deeper understanding of earthquake hazards in Tehran and similar regions, providing valuable insights for urban planning, risk mitigation strategies, and emergency preparedness initiatives. As cities continue to grow in seismically active areas, adopting refined methodologies for seismic hazard analysis will be crucial for safeguarding lives and infrastructure against potential earthquake impacts.

Tehran faces unique seismic challenges due to its complex geological and urban characteristics. These challenges include **incomplete fault mapping, basin amplification effects**, and **vulnerable infrastructure**. Tehran lies on six major fault lines and numerous minor ones, yet detailed mapping of these faults remains incomplete. This lack of comprehensive data hinders accurate seismic hazard assessment and preparedness efforts. The Tehran basin's deep sedimentary layers significantly amplify ground motion during earthquakes, particularly at low frequencies (0.4–3 Hz). This amplification is further exacerbated by strong lateral discontinuities within the basin, leading to multidimensional site effects that increase seismic risks across the city. Many buildings in Tehran, especially in informal settlements, are constructed with unreinforced masonry and heavy materials without lateral load designs. These structures are highly susceptible to collapse during earthquakes. Addressing these challenges requires improved fault mapping, enhanced seismic modeling to account for basin effects, stricter building regulations, and community-based preparedness programs tailored to Tehran's unique risk profile. Understanding the costs and benefits associated with each hazard level is critical for both engineers and decision-makers.

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Conflict of Interests

The Authors declares that there is no conflict of interest.

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