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Seismic Hazard Assessment and Building Vulnerability in Qom City

Mahdi Moradi [a*], Mohammad Sadegh Torkaman [b], Seyed Mohammad Reza Hasani [c]

[a] *Department of Civil Engineering, Qo.C., Islamic Azad University, Qom, Iran*
[b] *Faculty of Management and Accounting, Qazvin Branch, Islamic Azad University, Qazvin, Iran*
[c] *Department of Civil Engineering, Faculty of Civil Engineering, Babol Noshirvani University of Technology, Babol, Mazandaran, Iran*

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A B S T R A C T

Qom city, owing to its location on several active faults, is a sensitive area exposed to seismic hazards. Therefore, damage reduction, crisis management, and enhancement of the city's resilience are essential. The aim of this study is to evaluate Qom's resilience against earthquakes. This objective includes producing practical maps such as seismic soil classification, peak ground acceleration (PGA) for 475 and 2475 year return period earthquakes, and assessing building performance under these seismic scenarios. To this end, soil data from previous studies were collected and analyzed using ArcGIS. PGA values for the 475 and 2475 year return period earthquakes were obtained using OpenQuake software. Finally, the results were compiled using Excel and ArcGIS. The assessments showed that the mean probability of building failure in Qom under earthquakes with 475 and 2475 year return periods is 66.5% and 80.5%, respectively, which is mainly due to the prevalence of masonry buildings lacking adequate lateral load resisting systems. These findings highlight the necessity of retrofitting and renewing deteriorated buildings, improving construction standards, and prioritizing urban resilience enhancement.

1. Introduction

Qom city holds great religious significance as the site of Iran's largest seminary and the shrine of Hazrat Masoumeh, making it the country's second most important pilgrimage city. It also serves as a major transportation corridor connecting the northern, southern, eastern, and western provinces. The population of Qom has increased markedly over the past two decades and currently stands at approximately 1,292,283 people [1]. Seddighi and Seddighi [2], through a statistical review of natural hazards over the past 100 years, reported the frequency of these hazards. According to their analysis, floods, earthquakes, and droughts were the most frequent hazards in Qom, respectively. Among these, earthquakes can be considered one of the most hazardous natural disasters. Qom is located close to several extensive active faults. The principal faults affecting the city include the Indes, Koushk Nosrat, Kashan, and Alborz faults, which confirm the high seismic hazard potential in the region [3]. Most buildings in Qom are old and structurally vulnerable, and past earthquakes have produced extensive damage in the city [4]. In 1386, an earthquake of approximately magnitude 5 on the Richter scale occurred in the town of Kahak, causing public alarm, damage to the Valiasr metro tunnel, and harm to residential units. The event resulted in several fatalities and injuries. Damage to provincial infrastructure and 156 residential units was reported at approximately sixty billion rials [5].

Seismic risk assessment requires accurate data on seismicity, the location and distribution of buildings, and the resident population. In addition, exposure models and the structural characteristics of buildings play a fundamental role in estimating their vulnerability. However, at large scales, particularly in developing countries, such data may not be readily available [6]. Seismic vulnerability of structures is commonly estimated using damage curves that relate ground-motion intensity to the probability of loss [7]. These curves are constructed from parameters such as earthquake peak ground intensity, acceleration, or velocity (PGA/PGV),

* Corresponding author.
E-mail addresses: mahdi.moradi@iau.ac.ir (M. Moradi).

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among which, peak ground acceleration (PGA) is more widely used [8]. Fragility curves are also employed to estimate the probability of exceeding specified damage states for buildings based on seismic intensity measures [9]. These curves are typically developed using empirical, analytical, and structural simulation approaches [9]. Empirical methods rely on past damage data and are particularly practical in regions where structural information is limited [10]. Numerous studies have advanced these methodologies, including analytical investigations of industrial structures in Italy [11] and numerical simulations of reinforced-concrete buildings in Turkey [12]. In Iran, despite the occurrence of destructive earthquakes, comprehensive records of damage and associated seismic parameters have often not been documented [7]. Initiatives such as JICA [13] and GEM EMME [14] have sought to improve these assessments. In this context, Fallah Tafti et al. [9] employed an Analytic Hierarchy Process (AHP)–based analytical approach to develop fragility curves for 19 different building typologies in Iran. They combined domestic and international data, using 39 local fragility curves and 481 curves from other countries. This methodology forms the primary basis for the seismic-hazard assessment in the present study.

Few studies have addressed the seismic resilience of Qom city. Kamalian et al. [15] took an important step toward assessing Qom's seismic vulnerability by collecting and analyzing data from 160 boreholes at 60 stations to conduct a detailed soil microzonation study for the city. They also presented a seismic hazard analysis for a 475-year return period and produced a peak ground acceleration (PGA) map for Qom based on those results. It should be noted that these studies were not based on local fault earthquakes and fault behavior, and no study has been conducted to quantify the vulnerability of Qom's buildings. Ghafoori et al. [16] applied an optimization-based probabilistic seismic scenario method to determine the minimum number of scenarios required to estimate urban losses. Using prior seismological and geological data, they evaluated and analyzed seismic hazards, although their work was limited to optimizing a methodology for seismic assessment and did not produce PGA maps or estimates of potential earthquake losses for Qom. Khorasani Zadeh et al. [5] examined Qom's seismic vulnerability based on a scenario for the Alborz fault. They derived fragility curves from the fault's seismic activity and calculated the probability of building failure in Qom accordingly. Their results indicated that the northeastern blocks and the southern Qomrud area sustain the greatest damage, with an estimated complete collapse of about 25%. However, this study was confined to only one of the multiple faults surrounding Qom. Therefore, more comprehensive studies that account for the effects of all faults around Qom appear necessary. Vaseghi et al. [17] investigated the seismic resilience of Districts 3 and 4 in Qom, using the Analytic Hierarchy Process (AHP) to weight resilience indicators. Their study showed that District 3 exhibits high vulnerability due to factors such as narrow passages, weak urban infrastructure, and low occupant awareness of building safety, whereas District 4 demonstrated better resilience indicators. Shirvani Harandi et al. [18] assessed the physical and social vulnerability of District 4 of Qom County under a 475 year return period earthquake scenario, employing the PGA values reported by Kamalian et al. [15]. Their results indicated that the northern half of District 4 is more vulnerable owing to higher building density, poorer construction quality, larger population, and narrower streets, while the southern half, characterized by newer buildings, lower density, and wider streets, would experience fewer losses and casualties. It should be noted that these studies do not cover the entire city of Qom, addressing only one of its seven districts, and the PGA used was based on Kamalian et al. [15]. Previous geotechnical studies of Qom and its soil classification were based on the work of Kamalian et al. [15]. Maghami et al. [19] demonstrated that earlier velocity measurements had errors of approximately 10-15%, with the $\bar{V}_{S30}$ velocity being overestimated in deeper deposits. Maghami et al. [19] presented a shear-wave velocity distribution map to bedrock in their study. However, a dedicated $\bar{V}_{S30}$ map and soil classification for Qom, which are crucial for seismic analysis, were not provided in their research.

Recognizing significant data gaps in Qom's seismic assessment, this research introduces a novel integrated framework. The study begins by introducing the Earthquake Potential Index (EPI) for Qom, followed by the development of a new explicit $\bar{V}_{S30}$ map and soil classification for the city derived to correct known overestimations in prior literature. Subsequently, the analysis proceeds to compute site-specific Peak Ground Acceleration (PGA) for critical return periods (475 and 2475 years). Finally, by employing regionally calibrated fragility curves for 19 Iranian building types, the percentage probability of building failure in Qom is produced and subjected to statistical analysis.

2. Earthquake potential index (EPI)

Earthquakes are inherently unpredictable and may occur without significant prior warning. The likelihood of an earthquake depends on multiple factors, including proximity to tectonic plate boundaries, historical seismic activity, the nature of existing geological formations, and others. To assess the seismicity of a region and to enable comparison of the resulting values, it is necessary to employ a model that proportionally accounts for the influence of each factor and defines an index accordingly. Ahmad et al. [20], aiming to identify key factors in spatial data analysis through Geographic Information Systems (GIS), introduced a method for determining the Earthquake Potential Index (EPI). Their approach consists of the following steps.

- Selection of variables influencing earthquake occurrence
- Generation of information layers within the GIS environment
- Numerical weighting of variables
- Integration of layers
- Calculation of the Earthquake Potential Index
- Zonation of the region based on earthquake potential

- Preparation of a seismic hazard map

For determining the EPI of Qom Province, the effects of influential factors within a radius of 150 km from the city center were considered. Fig. 1 illustrates the faults located within this 150 km radius relative to the center of Qom. Additionally, the seismic moment magnitudes of historical earthquakes around Qom were obtained from the Institute of Geophysics, University of Tehran [21]. These data are presented in Fig. 2.

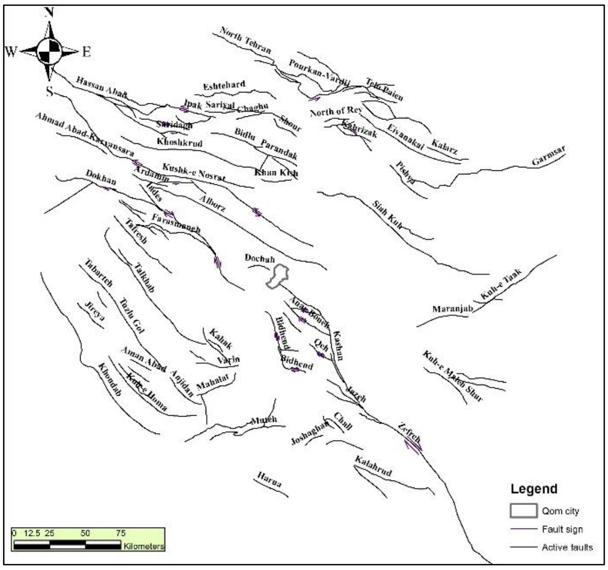


Fig. 1. Faults within a 150 km radius around Qom (adapted from the findings of Mirzaei et al. [21]).

The principal variables of the model proposed by Ahmad et al. [20] include the Digital Elevation Model (DEM), slope angle in degrees (SLOP), density of active faults (Den_F), earthquake epicenter density map (Den_{Ev}), earthquake magnitude in the region (M_L), distance from the city center to active faults (Dis_F), and distance from the city center to earthquake epicenters (Dis_{epi_ev}). For the preparation of the digital model, a map of Iran with 30-meter resolution was employed, while fault data and the earthquake catalog of the region were obtained from the Geophysics Center of the University of Tehran [21]. Ultimately, based on Eq. 1, the Earthquake Potential Index (EPI) map was generated, as illustrated in Fig. 3.

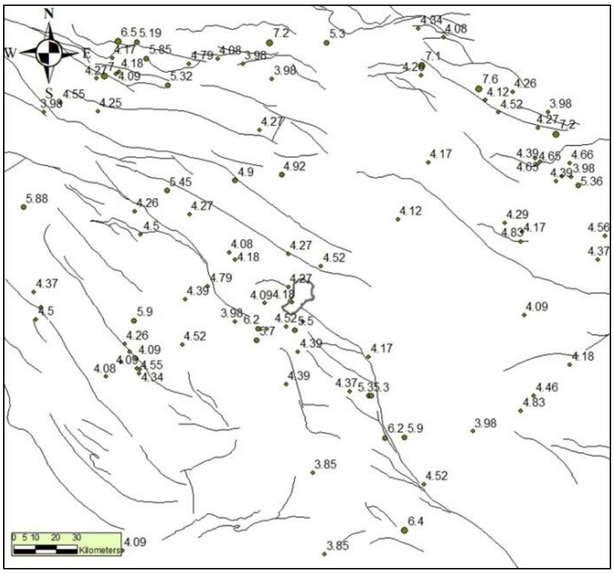


Fig. 2. Moment magnitude of earthquakes around the city of Qom (adapted from the findings of Mirzaei et al. [21]).

$$EPI = 0.1DEM + 0.1Slop + 0.15Den_F + 0.2M_L + 0.15Dis_{epi\_ev} + 0.15Den_{Ev} + 0.15Dis_F \quad (1)$$

In Fig. 3, the EPI index map is depicted within a 150 km radius around Qom. According to this map, the city of Qom exhibits high seismicity and is among the most seismically active areas within the delineated region. With an EPI index of 3.5, Qom requires special consideration in seismic design of buildings. This issue has also been addressed in Standard 2800 [22], which classifies Qom as a high-seismicity zone. It is noteworthy that the absence of a historical record of major earthquakes in Qom has somewhat reduced attention to this matter. Nevertheless, the high density of faults in this area indicates significant earthquake hazard potential. The lack of a major historical earthquake, in fact, serves as a warning signal, suggesting the accumulation of seismic energy in this region.

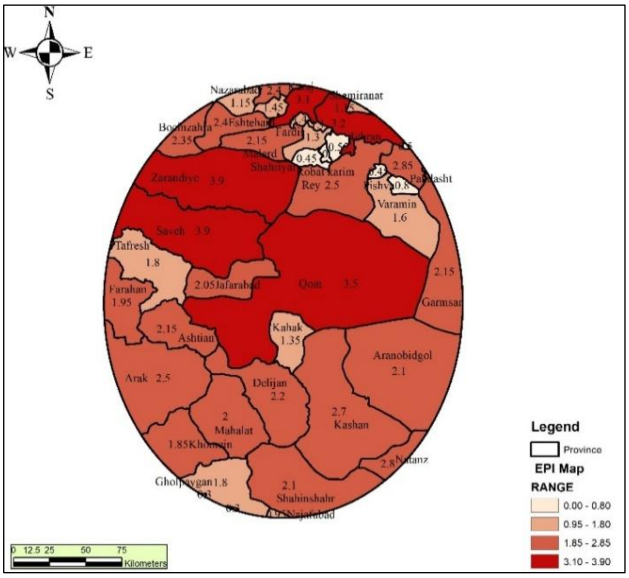


Fig. 3. Earthquake Potential Index (EPI) map of Qom Province.

3. Geology and geotechnical engineering in the city of Qom

Buildings in Iran are designed against earthquakes in accordance with Standard 2800 [22]. According to this standard, soils are classified based on the average shear-wave velocity to a depth of 30 meters ($\bar{V}_{S30}$). The standard divides soils into four types. Type I with shear-wave velocity greater than 750 m/s (most suitable for construction), Type II with shear-wave velocity between 375 and 750 m/s (moderate quality), Type III with shear-wave velocity between 175 and 375 m/s (medium density), and Type IV with shear-wave velocity less than 175 m/s (weak and requiring improvement).

In 2002, Ramazi [23] conducted a seismic hazard zoning study of Qom Province. He estimated the peak horizontal acceleration of bedrock without considering soil types, based on the tectonics and seismicity of Qom Province, using Cornell's approach. His findings indicated that the seismicity of Qom is influenced not only by the major known faults between Tehran and Kashan but also by smaller, yet active or potentially active faults beneath the city itself. As a significant step toward assessing the seismic vulnerability of Qom, Kamalian et al. [15] carried out a microzonation study of Qom soils by analyzing data from 160 boreholes across 60 stations. They also performed seismic hazard analysis for a return period of 475 years and presented a map of peak ground acceleration across the city. To complement these results, Maghami et al. [19] constructed a three-dimensional model of the Qom sedimentary basin based on shear-wave velocity using Refraction Microtremor (ReMi) surveys. Their findings revealed new evidence of several potential faults, including the Qomrud Fault. Moreover, the analyses showed that for relatively shallow bedrock, previously obtained velocities had errors of about 10–15%, while in deeper sediments, $\bar{V}_{S30}$ values were overestimated [19]. However, most existing geotechnical reports prepared by local companies in Qom are limited to shallow depths (generally less than 30 meters) and rely on descriptive methods rather than direct use of $\bar{V}_{S30}$ [19].

Maghami et al. [19] presented shear-wave velocity distribution profiles down to bedrock in their study (Fig. 4). However, neither the $\bar{V}_{S30}$ map nor the soil classification of Qom based on it was provided. Accordingly, the results of Maghami et al. [19] were utilized to prepare a map of average shear-wave velocity to a depth of 30 meters for Qom soils ($\bar{V}_{S30}$), which is shown in Fig. 5. This map indicates that most urban areas fall within soil Types II and III, while some zones even belong to Type IV, reflecting the seismic weakness of Qom soils. A comparison of these results with the study of Kamalian et al. [15] suggests that earlier investigations may have overestimated soil conditions.

4. Seismic hazard assessment and zoning of Qom

In this study, the OpenQuake software was employed for seismic hazard assessment and zoning of the city of Qom. OpenQuake is an open-source software designed for earthquake hazard evaluation. It has been developed by the Global Earthquake Model (GEM) Foundation. The software is widely used for conducting seismic analyses and assessing earthquake hazards. Acting as a comprehensive tool, OpenQuake provides capabilities for Probabilistic Seismic Hazard Analysis (PSHA), Deterministic Seismic Hazard Analysis (DSHA), and overall seismic hazard evaluation [11].

To initiate the process, OpenQuake relies on a set of input data. These data include identification of seismic sources, earthquake Ground-Motion Prediction Equations (GMPEs), target points for output results, the type of response of interest (peak ground acceleration (PGA), spectral acceleration (SA) for different probabilities), and average shear-wave velocity at 30 m depth ($\bar{V}_{S30}$), and selection of Ground Motion Prediction Equations (GMPEs) to define ground motion hazard. Seismic hazard analysis and earthquake zoning with this software involve four stages. These stages include identification of seismic sources, determination of the controlling earthquake (the largest probable earthquake for each source), selection of an appropriate GMPE for strong ground motion, and calculation of strong ground-motion parameters and seismic hazard estimation [24].

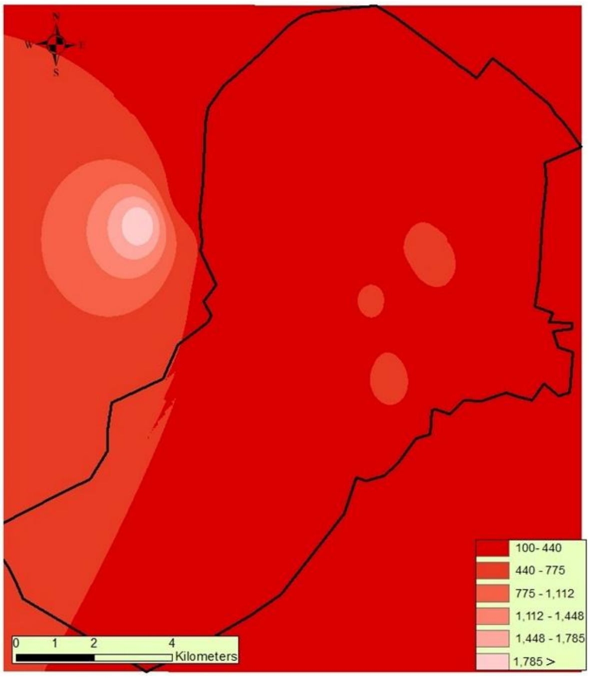


Fig. 4. $\overline{V}_{S30}$ in the soils of Qom (in meters per second) (adapted from the study of Maghami et al. [19]).

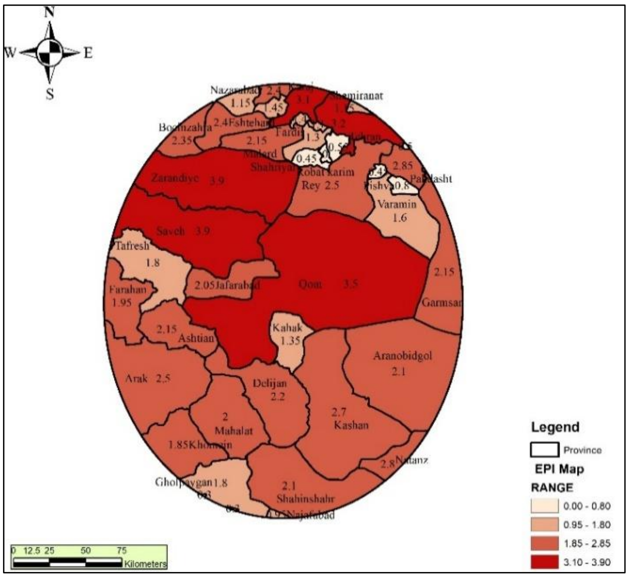


Fig. 5. Oil classification map of Qom province.

In this study, faults affecting the city of Qom within a radius of 100 km from the city center were considered. Information on these faults (including geographic location, length, moment magnitude scale, orientation, and type) was obtained from the Geophysics Institute of the University of Tehran [21]. The moment magnitude (M_w) of these faults was estimated using Eqs. 2-4, based on subsurface rupture length. In these equations, (L) and (M_w) represent the subsurface rupture length (in kilometers) and the moment magnitude of the fault, respectively. Eq. 2 applies to strike-slip faults, Eq. 3 to reverse faults, and Eq. 4 to normal faults [25].

$$M_w = 4.33 + 1.49Log(L) \quad (2)$$

$$M_w = 4.49 + 1.49Log(L) \quad (3)$$

$$M_w = 4.34 + 1.54Log(L) \quad (4)$$

The faults influencing Qom within a 100 km radius, along with their calculated (M_w) values, are compiled in Table 1. It should be noted that for unspecified fault types, Eq. 3 was applied.

Table 1. Faults affecting the city of Qom within a 100 km radius.

Fault Name	Fault Type	Wells–Coppersmith [25] Relation Eqs. 2-4	Distance to Qom City Center (km)	Fault Length (km)
Kashan	Approximate / Concealed / Inferred	6.86	3.93	39.01
Dochah	Reverse or Thrust Fault	6.32	7.52	16.79
Alborz	Reverse or Thrust Fault	7.67	15.53	136.77
Anar Boneh	Left-lateral Strike-slip	6.90	17.59	41.36
Mehrabad	Reverse and Right-lateral Fault	6.49	24.49	21.91
Indes	Reverse and Right-lateral Fault	7.53	25.63	109.36
Myam	Unspecified	6.37	26.18	18.38
Bidehend	Right-lateral Fault	6.73	26.40	31.68
Kushk Nosrat	Reverse and Left-lateral Fault	7.82	29.12	221.01
Kashan	Reverse or Thrust Fault	7.26	38.05	71.78
Farasmaneh	Reverse or Thrust Fault	7.18	47.24	64.06
Bidehand	Reverse and Right-lateral Fault	6.72	49.42	31.38
Rahagh	Unspecified	6.14	51.28	12.72
Gheh	Right-lateral Fault	6.44	52.43	20.26
Khoreh	Reverse or Thrust Fault	6.77	64.07	33.77
Kahak	Reverse or Thrust Fault	6.18	64.30	13.68
Zard Rang	Unspecified	6.61	64.35	26.45
Siah Kouh	Reverse or Thrust Fault	7.69	65.14	140.91
Ravand	Unspecified	6.50	65.78	22.42
Khan Kish	Unspecified	6.49	66.48	21.83
Varin	Reverse or Thrust Fault	6.69	68.80	29.95
Nazarabad	Approximate / Concealed / Inferred	6.53	69.39	23.50
Talkhab	Reverse or Thrust Fault	7.56	69.87	114.23
Khoshk Rud	Approximate / Concealed / Inferred	7.33	73.46	80.26
Mahallat	Unspecified	6.76	74.46	33.60
Tafresh	Reverse or Thrust Fault	7.12	74.87	58.00
Payvand	Unspecified	6.14	75.24	12.81
Ghermez Aghash	Right-lateral Fault	6.21	77.14	14.17
Sang Khorideh	Reverse or Thrust Fault	6.16	78.43	13.12
Parandak	Approximate / Concealed / Inferred	6.77	78.53	33.80
Jaze	Reverse or Thrust Fault	6.73	80.35	31.83
Zorjin	Reverse or Thrust Fault	6.36	81.38	17.90
Goujar	Unspecified	6.66	87.74	28.66
Nashveh	Reverse and Left-lateral Fault	6.62	88.57	26.72
Azdin	Reverse or Thrust Fault	6.27	90.51	15.58
Bidlou	Unspecified	6.85	91.43	38.13
Dozdeh Emam	Reverse or Thrust Fault	6.62	91.49	27.00
Nobaran	Approximate / Concealed / Inferred	6.88	92.94	40.43
Shour	Unspecified	6.46	99.25	21.11

A crucial element in seismic hazard evaluation is the selection of appropriate ground-motion prediction equations (GMPEs), which model the variation in peak ground motion (such as acceleration) based on magnitude and distance. To address the epistemic uncertainty associated with using a single GMPE, this study employs a logic tree approach incorporating three widely used horizontal ground-motion models supported in OpenQuake [26-28]. The Campbell and Bozorgnia [26] model is a comprehensive NGA-West2 equation with high sensitivity to site conditions and near-fault effects, making it suitable for shallow crustal earthquakes like those in Qom. The Chiou and Youngs [27] model complements it by emphasizing near-fault behavior and soil-dependent amplification, improving accuracy in areas with soft soils. The Akkar and Bommer [28] model, developed from European and Middle Eastern data, provides a more regionally appropriate representation of seismic behavior in Iran, offering a better fit for the local tectonic regime compared to North American models. This combination ensures robust coverage of key physical phenomena and regional applicability, while the weighting reflects the relative confidence in each model's performance for the study area. The GMPEs were weighted as 40, 30, and 30% for Campbell and Bozorgnia [26], Chiou and Youngs [27], and Akkar and Bommer [28], respectively. This weighting reflects their relative reliability and applicability to the regional seismic context. This weighting scheme adheres to standard PSHA practices and enhances the robustness of the hazard assessment.

In probabilistic seismic hazard assessment (PSHA), analyses are conducted based on all possible scenarios of earthquake magnitudes from seismic sources within the study area and across all possible distances from the site under investigation. In this research, the latest version of the OpenQuake software was utilized. The objective of this type of analysis is to evaluate the probability that an intensity measure type (IMT) will exceed a specified intensity measure level (IML). The software inputs are defined in such a way that they encompass all possible rupture scenarios for the identified sources. The principal equation used in OpenQuake is expressed as follows (Eq. 5).

$$Prob(IMT \geq IML|site.Forecast) = 1 - \prod_{i=1}^{I}(1 - \sum_{n=1}^{N(i)} Prob(IMT \geq IML|site.Rup_{n.i})Prob(Rup_{n.i}) \tag{5}$$

The Forecast module of the software computes earthquake rupture predictions. In this approach, probabilities are directly incorporated, unlike earlier methods that relied on the summation of average annual rates. As shown in Fig. 6, the study area was discretized into 1296 grid points (36×36) with a 0.5 km spacing to enable probabilistic modeling of seismic hazard using OpenQuake, allowing for a more accurate spatial representation of ground motion across the region. The soil classification results from previous sections were assigned to these grid points. The OpenQuake software was then executed based on the defined settings to calculate peak ground acceleration (PGA) for return periods of 475 years (10% probability of exceedance in 50 years) and 2475 years (2% probability of exceedance in 50 years). Fig. 7 presents the output of this software for the 475-year PGA. Based on these results, seismic hazard zoning maps were generated. To enhance visualization, these maps for Qom's buildings were prepared using ArcGIS and are presented in Figs. 8 and 9. According to these maps, the eastern and northern parts of Qom are more strongly affected by seismic activity.

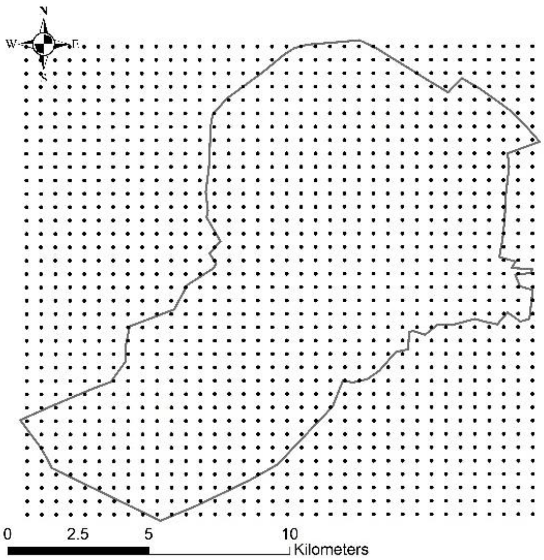


Fig. 6. Spatial discretization of the study area for OpenQuake modelling.

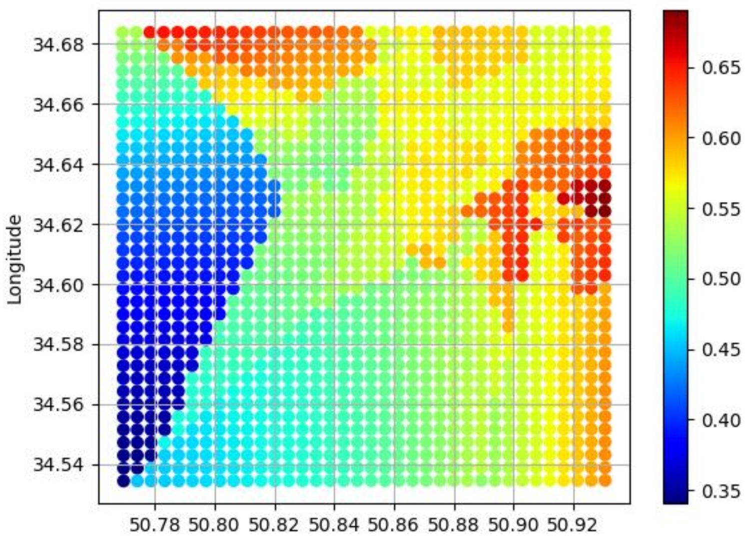


Fig. 7. PGA map for a 475-year return period (OpenQuake).

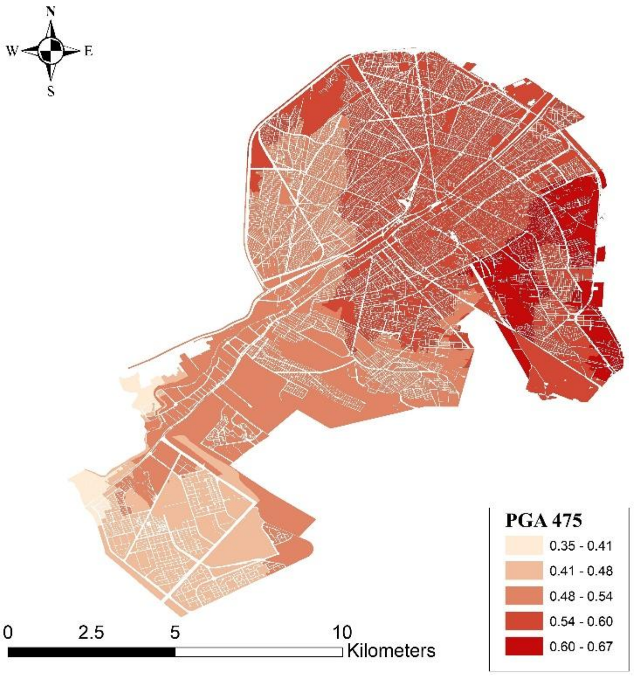


Fig. 8. PGA map for a return period of 475 years (equivalent to a 10% probability of exceedance in 50 years of structural life).

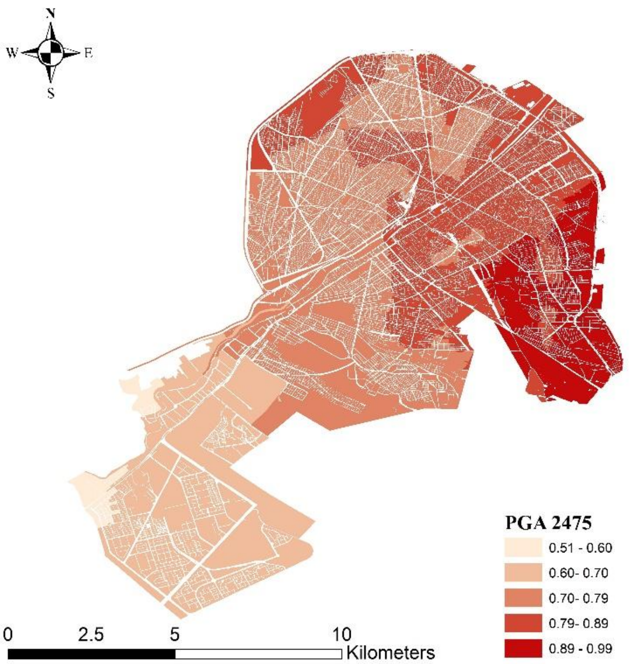


Fig. 9. PGA map for a return period of 2475 years (equivalent to a 2% probability of exceedance in 50 years of structural life).

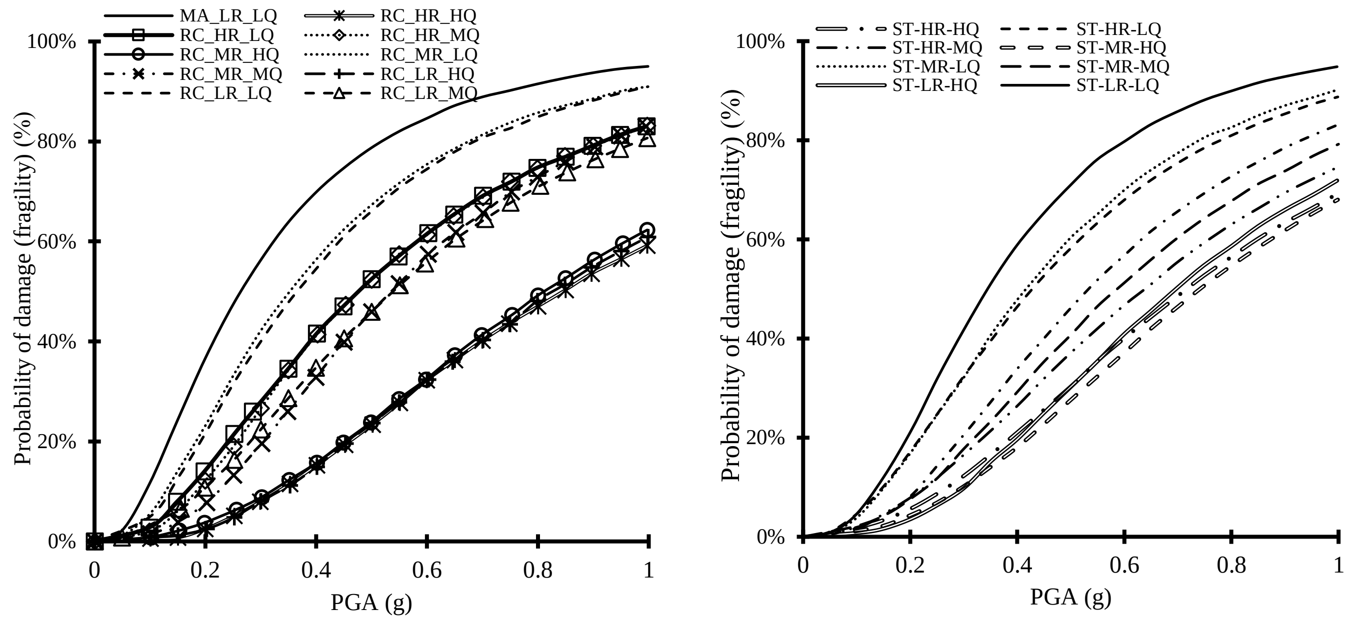
5. Building vulnerability and probability of damage in Qom

As noted earlier, in this study the fragility curves developed by Fallah Tafti et al. [9] were employed. They prepared fragility curves for 19 building types in Iran, with their classification presented in Table 2. The fragility curves based on PGA are shown in Fig. 10. It should be emphasized that the building classification of Qom used in this study is consistent with the classification adopted by Fallah Tafti et al. [9], which ensures greater accuracy in the evaluation.

Table 2. Building classification according to the criteria of Fallah Tafti et al. [9].

Building Type	Structural Type	Building Height	Construction Quality (Year of Construction)	Building Type Code
1	Masonry	Low-rise (1–3 stories)	Low quality	MA_LR_LQ
2	Reinforced Concrete	Low-rise (1–3 stories)	Low quality (before 1987)	RC_LR_LQ
3	Reinforced Concrete	Low-rise (1–3 stories)	Medium quality (1987–2007)	RC_LR_MQ
4	Reinforced Concrete	Low-rise (1–3 stories)	High quality (after 2007)	RC_LR_HQ
5	Reinforced Concrete	Mid-rise (4–7 stories)	Low quality (before 1987)	RC_MR_LQ
6	Reinforced Concrete	Mid-rise (4–7 stories)	Medium quality (1987–2007)	RC_MR_MQ

7	Reinforced Concrete	Mid-rise (4–7 stories)	High quality (after 2007)	RC_MR_HQ
8	Reinforced Concrete	High-rise (>7 stories)	Low quality (before 1987)	RC_HR_LQ
9	Reinforced Concrete	High-rise (>7 stories)	Medium quality (1987–2007)	RC_HR_MQ
10	Reinforced Concrete	High-rise (>7 stories)	High quality (after 2007)	RC_HR_HQ
11	Steel Structure	Low-rise (1–3 stories)	Low quality (before 1987)	ST_LR_LQ
12	Steel Structure	Low-rise (1–3 stories)	Medium quality (1987–2007)	ST_LR_MQ
13	Steel Structure	Low-rise (1–3 stories)	High quality (after 2007)	ST_LR_HQ
14	Steel Structure	Mid-rise (4–7 stories)	Low quality (before 1987)	ST_MR_LQ
15	Steel Structure	Mid-rise (4–7 stories)	Medium quality (1987–2007)	ST_MR_MQ
16	Steel Structure	Mid-rise (4–7 stories)	High quality (after 2007)	ST_MR_HQ
17	Steel Structure	High-rise (>7 stories)	Low quality (before 1987)	ST_HR_LQ
18	Steel Structure	High-rise (>7 stories)	Medium quality (1987–2007)	ST_HR_MQ
19	Steel Structure	High-rise (>7 stories)	High quality (after 2007)	ST_HR_HQ



(a) **(b)**

Fig. 10. Fragility curves against PGA, adapted from Fallah Tafti et al. [9] (a) Curves for reinforced concrete and masonry buildings (b) Curves for steel buildings.

For damage assessment of Qom's buildings, a database of buildings was compiled based on data provided by the Municipality of Qom. Subsequently, the buildings of Qom were classified according to the criteria of Fallah Tafti et al. [9]. Fig. 11 illustrates the classification of building types in Qom. Certain land uses (including vacant lots, parks and green spaces, agricultural lands, and similar categories) were considered as "type 0" and excluded from the evaluation. Interpretation of results is facilitated by numerical values. Accordingly, the statistical outcomes of this classification are presented in Table 3.

Table 3. Statistical assessment of existing buildings in Qom.

Building Type	Number	Percentage	Building Type	Number	Percentage
Dilapidated buildings (over 50 years old)	32,894	14.76%	Type 9 buildings	0	0.00%
Masonry buildings	182,289	81.80%	Type 10 buildings	1,088	0.49%
Reinforced concrete structures	18,686	8.39%	Type 11 buildings	369	0.17%
Steel structures	21,865	9.81%	Type 12 buildings	5,653	2.54%
Type 1 buildings	182,289	81.80%	Type 13 buildings	13,462	6.04%
Type 2 buildings	25	0.01%	Type 14 buildings	13	0.01%
Type 3 buildings	561	0.25%	Type 15 buildings	182	0.08%
Type 4 buildings	8,980	4.03%	Type 16 buildings	2,043	0.92%
Type 5 buildings	1	0.00%	Type 17 buildings	0	0.00%
Type 6 buildings	37	0.02%	Type 18 buildings	1	0.00%
Type 7 buildings	7,994	3.59%	Type 19 buildings	142	0.06%
Type 8 buildings	0	0.00%			

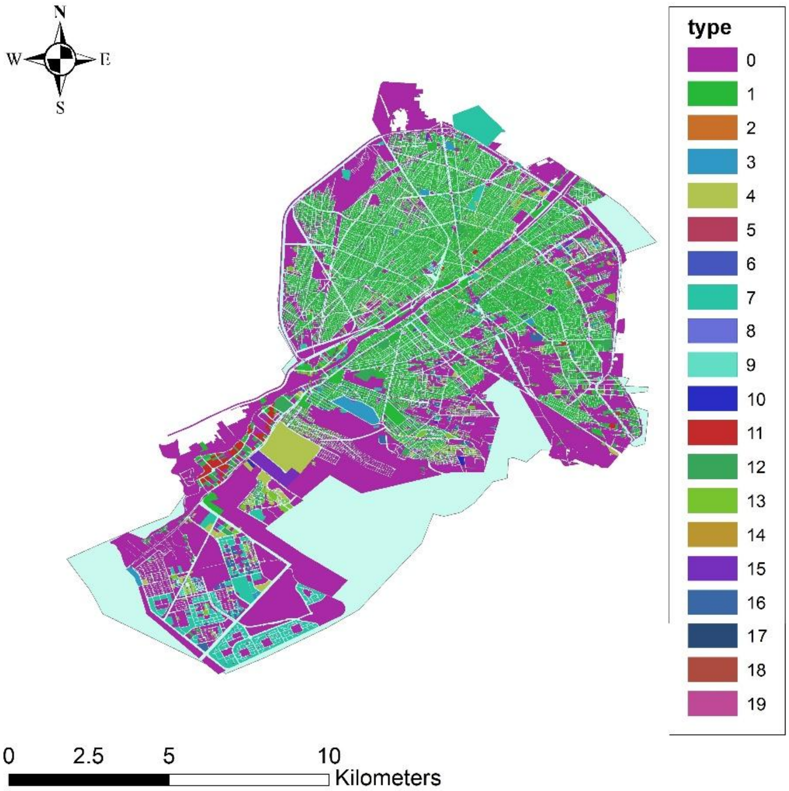


Fig. 11. Classification of building types in Qom.

The results indicate that 14.76% of Qom's buildings are over 50 years old and have reached the end of their service life (Table 3). Furthermore, 81.80% of Qom's buildings are masonry structures (including vaulted brickwork, adobe, and brick buildings). These structures lack adequate lateral load-bearing systems and are highly vulnerable to earthquakes. Based on these findings, it can be concluded that the primary challenge for Qom in terms of seismic resilience lies in the building stock, highlighting an urgent need for renovation and retrofitting.

For each building, PGA values corresponding to earthquakes with return periods of 475 and 2475 years were extracted using ArcGIS (Figs. 8 and 9). To estimate damage probabilities, the fragility curves developed by Fallah Tafti et al. [9] were parameterized through nonlinear regression. Building usage data for the city of Qom were exported into Microsoft Excel, where the buildings were classified according to Table 2. The equations were then applied to the classified building types in Excel, and the probability of damage was calculated. Table 4 presents the mean probability of damage for buildings under 475 and 2475 year return period earthquakes. For a more accurate evaluation of mean building damage, the number of units within each building was considered as an important indicator. Each floor was treated as one building unit (since the significance of a 10-story building is not equivalent to that of a single-story building when calculating mean damage). Table 4 shows the number of reinforced concrete, steel, and masonry buildings, along with the product of their counts and corresponding number of floors.

Table 4. Mean probability of building damage under earthquakes.

Category	Total Buildings	Reinforced Concrete	Steel Structures	Masonry Buildings
Number of buildings	222,840	18,686	21,865	182,289
Number of building units	276,567	65865	28268	182,434
Mean probability of damage (%) – 475 years	66.5	32.2	39.6	83.1

The mean probability of damage for building units in Qom under 475 and 2475 year return period earthquakes was estimated at 66.5% and 80.5%, respectively. These results are alarming. The primary reason lies in the prevalent building type in Qom, which is masonry construction with poor seismic performance. The mean probability of damage for masonry buildings under the 475 year earthquake was calculated at 83.1%, while steel and reinforced concrete buildings had mean probabilities of 39.6% and 32.2%, respectively (Table 4). Although the performance of framed buildings is not ideal, it is significantly better than that of masonry structures. As noted earlier, certain land uses) including vacant lots, parks, and agricultural lands(were excluded from the analysis. Figs. 12 and 13 illustrate the mean probability of building damage in Qom under 475 and 2475 year return period earthquakes. These figures show that the northern and central areas of Qom are in poor condition, whereas Pardisan and, more broadly, the western part of Qom Province exhibit better seismic performance. This is attributed to the newer construction in these areas and the use of earthquake-resistant structural systems. Furthermore, PGA values in western Qom were lower, consistent with the observed results.

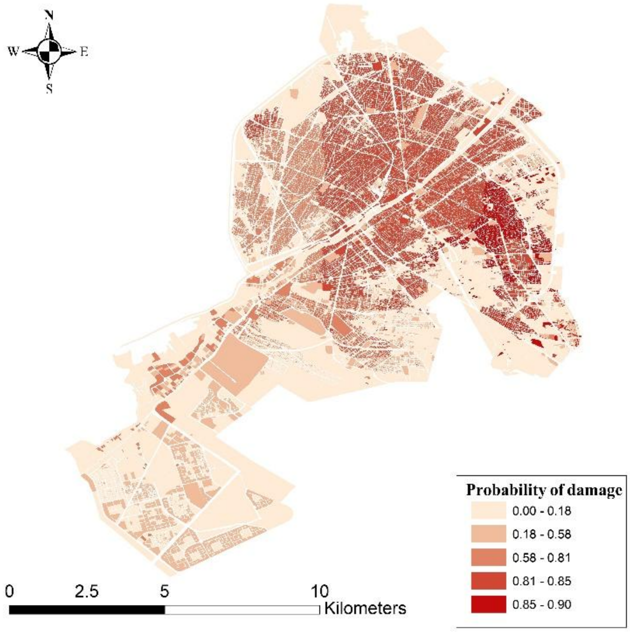


Fig. 12. Probability of building damage in Qom under a 475-year return period earthquake.

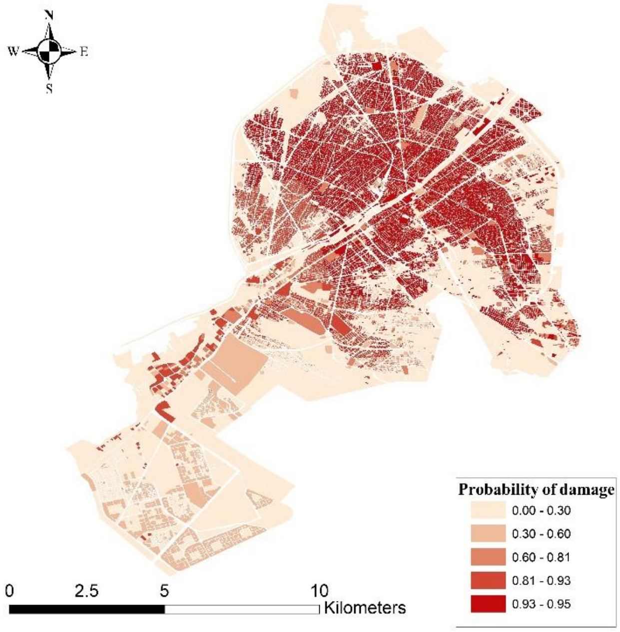


Fig. 13. Probability of building damage in Qom under a 2475-year return period earthquake.

6. Discussion

The findings of this study reveal a high seismic risk for Qom, driven by its significant seismic potential, indicated by a seismic potential index of 3.5 within 150 km, and the widespread presence of vulnerable unreinforced masonry buildings. The hazard assessment, using OpenQuake, shows substantial ground motion levels, particularly in the central and northern districts, with PGA values reaching up to 0.67 g for a 475-year return period. The soil conditions, characterized by Type II, III and IV classifications based on Vs30, suggest significant site amplification. This combination of high seismic hazard, weak soil conditions, and an extensive stock of non-ductile buildings creates a critical vulnerability, particularly in older urban areas, necessitating urgent measures to enhance the city's seismic resilience.

To mitigate this risk, a multi-faceted approach is required. The most pressing need is the retrofitting and strengthening of existing structures, particularly the extensive stock of unreinforced masonry buildings. Implementing a transparent building performance rating system, based on structural evaluation, could serve as a powerful incentive for owners to upgrade their properties. This system would empower the public to make informed decisions regarding building safety and encourage investment in seismic resilience. The municipality of Qom, as a key policy-making body in the construction sector, has a crucial role in promoting public awareness about seismic hazards and the importance of building safety through targeted educational campaigns. Financial incentives, such as tax reductions or subsidies, could further encourage property owners to undertake necessary strengthening measures. Enhancing the city's emergency response capabilities is equally important. The development of an online management system for crisis equipment, which provides real-time information on the location, quantity, and condition of available resources across municipal departments, would significantly improve operational efficiency and resource allocation during a disaster. This system would enable faster and more coordinated response efforts. Furthermore, the creation and regular updating of accurate seismic hazard maps, which clearly delineate fault lines and high-risk zones, is essential. These maps should be made accessible to the public to increase awareness and inform land-use planning and construction decisions.

The design base acceleration (A) for the city of Qom per Standard 2800 [22] is 0.30g. The elastic response spectrum is obtained as A×B, where the factor B accounts for soil type and structural period, with maximum values of 2.5 for soil types 1 and 2, and 2.75 for soil types 3 and 4 per Standard 2800 [22] for Qom. The PGA values computed in this study (0.35g to 0.67g), accounting for local soil effects, yield an equivalent base acceleration range of 0.14g to 0.268g when divided by B_max, confirming that the standard's 0.30g is conservative and consistent with probabilistic seismic hazard analysis. These results enable the development of site-specific design response spectra, which, upon comparison with Standard No. 2800 spectra, can refine local amplification factors for precise structural analysis.

7. Conclusion

This study presented a comprehensive analysis of seismic hazard and building vulnerability in the city of Qom. First, the seismic potential index of Qom was determined using ArcGIS and available data, confirming the high seismicity of the region. Subsequently, maps of average shear-wave velocity to a depth of 30 meters and seismic soil classification of Qom were prepared. To estimate peak ground acceleration (PGA), the OpenQuake software was employed, and PGA maps for return periods of 475 and 2475 years were generated. Based on fragility curves derived from a domestic study, Qom's buildings were classified, and their damage under different earthquake scenarios was estimated. The findings can be summarized as follows.

- The seismic potential index (EPI) within a 150 km radius around Qom was examined. With an EPI of 3.5, Qom is among the most seismically active areas in the region. Although no historical record of major earthquakes exists, the high density of faults indicates significant seismic hazard potential.
- Results showed that Qom is highly vulnerable due to the predominance of masonry buildings lacking adequate lateral load-bearing systems. The mean probability of building damage under 475 and 2475 year return period earthquakes was estimated at 66.5% and 80.5%, respectively.
- Northern and central areas of Qom are more vulnerable, while newer western districts (particularly Pardisan) exhibit better seismic performance due to modern construction practices and earthquake-resistant structural systems.
- To reduce seismic risk in Qom, a comprehensive, multi-faceted approach is essential, prioritizing the retrofitting of vulnerable older buildings. Establishing a transparent building performance assessment system and incentivizing owners through financial mechanisms such as tax reductions are critical. Additionally, enhancing public awareness, strengthening emergency preparedness systems, and developing updated seismic hazard maps for urban planning and site selection are necessary steps to improve resilience and mitigate future losses.
- To enhance the accuracy and transferability of results, future studies should incorporate post-earthquake damage data from Qom for validation of fragility curves and hazard assessments. Additionally, integrating more advanced modeling approaches (e.g., nonlinear dynamic analysis) and considering spatial and socio-economic factors (e.g., construction quality, building age, population distribution) can improve risk quantification. Furthermore, developing fragility curves for modern building systems would support risk assessment in rapidly urbanizing areas.

Statements & Declarations

Author contributions

Mahdi Moradi: Conceptualization, Methodology, Data collection, Investigation, Writing - Original Draft, Supervision.

Mohammad Sadegh Torkaman: Data organization, Writing - Original Draft, Writing - Review & Editing.

Mohammad Reza Hasani: Writing - Review & Editing.

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Data availability

Data available on request due to project restrictions: The data presented in this study are available on request from the corresponding author. The data are not publicly available because the project was conducted as a research plan supported by the Municipality of Qom.

Declarations

The authors declare no conflict of interest.

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