Earthquake insurance in Iran: Solvency of local insurers in light of the current market practice

Mohsen GHAFORY-ASHTIANY[1] and Hooman MOTAMED[2]

Abstract:

Owing to its geographical positioning within one of the most seismically active zones globally, Iran has experienced numerous historically impactful earthquakes. To finance a part of these losses and reconstruction expenses, earthquake insurance has been offered as a rider of fire insurance policy by the Iranian insurers. This mechanism, if well operated, can substantially contribute to disaster risk management. On the other hand, if the pricing and management of catastrophe risk lack a sound, risk modeling-based practice, it might add to the problems and act to the detriment of disaster risk management. In this paper, we first compare the current earthquake insurance pricing and risk management in the Iranian insurance industry with a state-of-the-art insurance regulation in the European Union (Solvency II). Then, we examine the consequence of following each approach in terms of business profitability and viability by conducting a numerical analysis on a hypothetical portfolio of property risks in Iran. In so doing, a seismic risk model has been developed by adopting EMME hazard model and a peer-reviewed vulnerability model, and by developing an exposure model for residential dwellings in Iran. The results suggest that modeled earthquake premium rates are about 5 times larger than the rates currently used in the market. Furthermore, a comparison between solvency capitals calculated following the methods specified by the European Solvency II and the Iranian Directive 69 indicates a visible underestimation of the earthquake solvency capital by the Iranian insurers. It seems that maintaining the current insurance pricing and risk management practice in Iran will probably lead to a substantial accumulation of earthquake risk for domestic firms and eventually endanger the solvency of these companies in the event of large-scale earthquake losses in future.

Keywords: Iran earthquake risk, probabilistic event-based modeling, Insurance pricing, Insurance regulatory, Solvency

---

[1] Professor, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran. ashtiany@iiees.ac.ir (Corresponding author)

[2] Assistant Professor, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran. h.motamed@iiees.ac.ir

1 Introduction

Being positioned in one of the most seismically active regions in the world, Iran has witnessed many devastating earthquakes through history, such as the 1978 M7.4 Tabas (USD 11 mn), the 1990 M7.4 Manjil–Rudbar (USD 2.8 bn), the 2003 M6.6 Bam (USD 1.5 bn), and most recently the 2016 M7.3 Sar-e Pol-e Zahab (USD 5 bn) (Ibrion, et al., 2015; Maghsoudi & Moshtari, 2020). Although almost all these events occurred in rural areas or small-size cities with less than 100,000 of inhabitants, the resulting socio-economic consequences have been substantial. If a similar magnitude earthquake struck a major Iranian city with millions of populations, the volume of physical and human losses would be much higher.

To compensate a part of earthquake losses and facilitate the process of reconstructions, Iranian insurance firms offer earthquake insurance as a rider of fire insurance policy. However, despite the common practice in the global insurance market, almost none of the domestic insurers use catastrophe risk models to quantify seismic risk for pricing policies, purchasing reinsurance, and managing accumulated risks. Instead, old-fashion and seemingly underestimating pricing tables are still utilised nationally to determine earthquake insurance policies based on main construction materials and geographical location of insured buildings. This pricing approach is likely to result in insurance companies collecting insufficient premiums to cover future catastrophe losses. In a similar way, on the regulatory side, the solvency capital for catastrophe properties is not risk-based and is determined according to the amount of premium collected (which seem to be not commensurate to risk) and history of company's losses (which does not reflect long-return period events risks like earthquakes). To date, due to the low penetration rate of insurance in Iran, about 1.8% in 2022, catastrophe risks assumed by Iranian insurance companies are not significant, implying that even in the event of medium to large natural catastrophes, the insurance losses usually are reimbursable by the insurers. With the expected Iran Building Catastrophe Insurance Pool (IBCIP) starting to operate soon, all residential buildings will be covered under a national policy. As such, there will be likely considerable business opportunities for domestic insurers to extend their catastrophe property portfolio to provide supplementary coverage to the primary protection which IBCIP offers. These new business opportunities, although financially attractive, can dramatically expose Iranian insurance and reinsurance companies to natural hazards risk. In other words, in the event of major catastrophe events, such as earthquakes in urban cities or widespread flooding, which are likely in the Iranian geography, many local insurers can quickly become insolvent. These said, it is essential to examine the of sufficiency of the current insurance rates and the effectiveness of the solvency capital requirements mandated by Central Insurance of Iran (CII) to cover future catastrophe losses to happen in Iran.

In so doing, two parallel approaches have been followed. First, a probabilistic event-based earthquake risk model was developed which helps calculate risk-based pricing framework for earthquake insurance policies. The model entails components of a standard catastrophe risk model, namely exposure, hazard, and vulnerability which are separately adopted, tailored, or developed based on the state-of-the-art methodologies and up-to-date data. These components are convolved using GEM's OpenQuake as a probabilistic event-based risk assessment platform to generate risk output such as Average Annual Loss (AAL) and loss Exceedance Probability (EP). In addition, a similar risk-based methodology to what employed by the European insurance solvency regime, Solvency II, was adopted to create a standard formula for determining solvency capital for given earthquake risk portfolios. A hypothetical portfolio of earthquake risks was assumed to compare the factor-based solvency capital (as mandated by CII) with a risk modeling-based one (as determined following Solvency II methodology) to examine the sufficiency of the current earthquake rates and solvency capital. Further, the profitability of the underwriting and the likelihood of solvency is benchmarked using the values generated using the risk-based pricing method and the standard formula of solvency capital.

This paper comprises six sections. First, a background on insurance solvency with a focus on the European Solvency II and its proposed method for calculating risk-based solvency capital earthquake is provided in Section 2. Then, Section 3 describes the evolution of earthquake risk models in Iran. Section 3 provides information on the methodology and data adopted or developed to calculate risk parameters such as AAL and EP (99.5% percentile) and estimate risk-based solvency capital for a portfolio of risks with earthquake coverage. Numerical results of the proposed methodology are outlined in Section 4 where the solvency capital of a hypothetical portfolio of risks under earthquake policy is calculated using the current factor-based and the proposed risk-based methods. A discussion on the differences between the two methods and possible consequences on the viability of Iranian insurers is given in Section 5. And finally, Section 6 concludes the process and its findings. A reference list is also provided at the end of the article.

The initial ideas for this research topic emerged during meetings with managers from the Central Insurance of Iran, the country's insurance regulator. These discussions focused on the necessity of using catastrophe modeling in the industry. The research process then continued with presentations to insurance executives, sharing the challenges and potential solutions identified. This represents the final stage of this activity, with the aim of disseminating the findings at both the regional and international level.

2 Natural Catastrophe Insurance Regulations in the European Union (EU) and Iran

The significance of natural catastrophes and their impact on the viability of insurance firms has received increasing attention over time, and the occurrence of major catastrophic events such as Hurricane Andrew (1992), the Northridge Earthquake (1994), Hurricane Katrina (2005), the 2011 Great East Japan Earthquake and Tsunami has highlighted the issue. Catastrophe losses endanger the solvency of small and medium reinsurance firms and consume the accumulated provisions of well-capitalised reinsurers (Anderson, 2002). While, to many, the term catastrophe is closely associated with natural hazards (e.g., earthquake, flood and windstorm), it can also be used to address intensive damages from human-made events (Lawson, et al., 2001). Catastrophe risks have different characteristics compared to non-catastrophe losses. They are highly dependent and occur so rarely that historical claims data could not be efficiently utilised to predict future losses. As a result, the insurance industry has evolved to prepare for the consequences imposed by disasters by developing risk management rules and regulations. This section provides a brief history of the regulations regarding the insurance solvency capital as a risk management measure in the insurance industry, focusing on the European Solvency II regime and the solvency regulations set by the Central Insurance of Iran (CII) as the national insurance regulator. In addition, technical aspects of calculating the Solvency Capital Requirement (SCR) in the two abovementioned regulatory systems are described with brevity.

2.1 European Insurance Solvency Regulation

In 2004, Thorburn has provided a history of the difficult times that catastrophic losses created for the insurance industry and the countries’ response to these challenges in the form of developing insurance regulatory institutions and adopting solvency mandates as an effective measure to manage catastrophe risks to which insurers are exposed (Thorburn, 2004).

In general, insurance supervision aims to protect policyholders’ interests by ensuring a sound financial operation and proper management in the insurance business. Therefore, effective regulations must be established to evaluate insurers' liabilities adequately and determine provisions to cover these commitments. It is also necessary to consider an extra layer of protection in the form of capital margin to respond to unexpected financial shocks, e.g., catastrophic losses. That is why solvency supervision regulations were established and improved over time.

Catastrophic losses, both natural and man-made, have resulted in higher claims provisions, reduced capital power, reduced profitability, and in some cases, made insurance firms insolvent. Remarkable examples of such bankruptcies are the 1906 San Francisco earthquake with 12 insurance companies declared insolvent, the 1992 Hurricane Andrew with 9 firms being bankrupt, and the 2011 Christchurch earthquakes that resulted in the ruin of 2 insurance companies (Kelly & Stodolak, 2013).

The first steps in harmonising Europe-wide insurance supervision were taken by the approval of the first [3]non-life and life insurance Directives in the 1970s (First Council Directive, 1973; First Council Directive, 1979). These directives required the European Member States to comply with harmonised solvency capital requirements. The Directives were later revised by adding second and third amendments in 1982 and 1992 (Second Council Directive, 1988; Council Directive, 1990; Directive, 1992; Council Directive, 1992). The entirety of these regulations, which were later named Solvency 0 by (Sandström, 2019), underwent a comparative examination in the 1990s, showing that they were not sufficiently taking into account the full spectrum of risks that insurance companies were exposed to. As such, new directives (known as Solvency I) were again introduced to both life and non-life insurance in 2002 to fortify the stance of insurers in the event of catastrophic losses (Directive, 2002; Directive, 2002a). Both Solvency 0 and Solvency I regulations followed a similar approach in determining the Solvency Capital Margin, which was mainly based on factoring gross earned premium and gross incurred claims (Sandström, 2019). However, this was only a transitional remedy to incorporate a risk-based approach in the insurance solvency capital requirement regulations, as Solvency I was still inefficient in terms of asset and liability valuation and capital allocation (Rae, et al., 2018). A drastic reform to solvency regulation was introduced about one decade later as the Solvency II Framework.

Influenced by the then-new risk-based banking regulation, Basel-II (Basel Committee on Banking Supervision, 2004), Solvency II, the latest European insurance supervising regime, replaced Solvency I in 2016. This new regime provides a more comprehensive risk-based approach for determining solvency requirements for insurance undertakings. The new regulation also includes a market-based valuation system for assessing companies' assets and liabilities (Directive, 2009). With a higher degree of confidence, this could potentially reduce the risk of insurance firms being insolvent. In addition, the Directives contribute to the harmonisation of insurance supervision in the European market. Solvency II encompasses three pillars, namely Pillar I, Pillar II, and Pillar III. The first pillar focuses on the quantitative aspects of solvency capital that insurers must hold to cover their risks adequately. The second pillar addresses the qualitative aspects of solvency regulation, emphasizing risk management and governance, and Pillar III aims to enhance market discipline by promoting transparency and accountability. Two types of capital requirements are represented in Pillar I: the Minimum Capital Requirement (MCR) which is the least authorised capital of insurance companies, and SCR which enables an insurance institution to absorb significant financial shocks, giving reasonable assurance to policyholders and beneficiaries. Under the underwriting risk category, the institution can use either a Standard Formula or an Internal Model, each having its pros and cons regarding the level of sophistication and SCR size. Despite all the promising features and improvements of Solvency II, it has been subject to much research since its introduction (Rae, et al., 2018; Linder & Ronkainen, 2004; Kousky & Cooke, 2012; Gurenko & Itigin, 2013; Clarke, et al., 2014; Baione, et al., 2018; Deligiannakis, et al., 2021). These researches mainly focused on the areas such as economic justification of the then-new solvency regime, different results obtained using the

---

[3] Life insurance provides coverage for an individual's life and offers fixed health benefits for critical illnesses such as cancer, heart ailments, and more. On the other hand, general insurance encompasses non-life assets, including houses, vehicles, health, events, travel, and other aspects.

Standard Formula of Solvency II and Internal Models, comparison between the implications of Solvency II and Solvency I, and possible improvements to the new directive.

2.2 Iranian Insurance Solvency Regulation

The Central Insurance of Iran (CII) is the regulator of the Iranian insurance market. As one of its principal duties, CII approves and enacts decrees and directives through the High Council of Insurance (HCI) to regulate different aspects of the insurance business in Iran (High Council of Insurance, 2019). Before the approval of the first Directive on the solvency capital adequacy, CII supervised the operation of Iranian insurance firms by examining monthly reports on companies' collected premiums and paid claims (Hashemi, et al., 2010). As the pricing system in the Iranian insurance market was no longer tariff-based then, new regulations needed to be developed and implemented by CII to monitor the financial solvency of insurance firms. Consequently, Directive 69 was approved and enacted by HCI in 2011, which required insurance firms to put aside a factor-based solvency capital for four categories of risks: insurance, market, credit, and liquidity. The Directive also recognized the market value (compared to book value) as the correct method of valuing own funds in the accounting system. This regulation, which is still in place, represents five classes of solvency. A company belongs to the first solvency capital level when it keeps a solvency capital equal to or greater than the Solvency Capital Margin (SCM). Should an insurance company fail to maintain a sufficient solvency margin, it enters levels 2 to 5 depending on the capital deficit. At level 5 of solvency, CII can officially cancel the business permission of the insolvent firm. For natural catastrophe policies (fire, engineering, automobile, and life), the SCM is the greatest of gross earned premium and gross incurred claims, each multiplied by a fixed risk factor (Similar to Solvency 0). These fixed factors were calculated based on an assessment carried out on the financial statements of Iranian insurance firms and the financial time series of the Iranian real estate and stock market. The computed solvency capitals of the named risks are ultimately combined assuming zero correlation between risks to form the company’s SCM. Directive No. 69 was reviewed by (Shahriar, et al., 2016) and a number of improvements regarding changing the risk metric to Value at Risk (VaR), using a 99% confidence level for calculation SCM, and consideration of linear correlation for different risks was suggested.

3 Methodology and Data

This section describes the theoretical framework of the quantitative comparison between the methods for calculating earthquake risk solvency in the Solvency II Directive and Directive 69 of the Iranian insurance regulation. In so doing, mathematical formulations are detailed in both methodologies, encompassing the selection of risk metrics, risk factors, and implementation of the risk diversification effect. Then, as a pre-requisite for calculating the solvency capital, components of a stochastic earthquake risk model for Iran are outlined, covering seismic hazard, vulnerability, exposure, and financial calculation models. The introduced earthquake risk model estimates the 99.5 loss percentile and Average Annual Loss (AAL) of earthquakes in Iran as input to Solvency II formulas. To feed Directive 69, the conventional earthquake risk pricing table of the industry is utilised.

A hypothetical portfolio of 1500 residential dwellings evenly distributed between three main construction types of steel, reinforced concrete, and masonry, and across five provincial capital cities of Tehran, Esfahan, Tabriz, Ahvaz, and Kerman has been considered to compare the earthquake risk solvency charge calculated by each methodology. The reason for selecting these capital cities is that they are located in various and seismicity zones and contain different composition of construction types. This allows us to consider the effect of diversification in the comparison process.

3.1 Calculation of earthquake solvency capital

3.1.1 Directive 69

High Council of Insurance (2011) requires insurance and reinsurance institutions to hold eligible own funds as the solvency capital using the fixed factors determined for different types of risks, namely underwriting, market, credit, and liquidity risks. The Directive provides risk factors for miscellaneous lines of business, including catastrophe fire insurance (non-life) without any distinction between various natural catastrophes in terms of fixed risk factors and assumes zero correlation between risks in different lines of business and geographies (meaning that losses are deemed fully independent). According to this directive, to calculate the solvency charge of a property catastrophe portfolio, first, the products of gross earned premiums and gross incurred claims with their corresponding risk factors (0.580 and 0.841, respectively) are computed, and then the greatest of these values is considered as the solvency capital. Since no reliable information on the gross incurred earthquake loss claims were available to us at the time of writing this paper, we only use the term determined by gross earned premiums. In so doing, average values of earthquake premium rates of five Iranian insurance firms, which were extracted from a popular Iranian insurance quotes aggregator website[4] are employed to calculate the premium-based part of the formula for the portfolio. These rates are still based on a study conducted in 1991 by (Ghafory-Ashtiany, 1991) who determined the relative riskiness of different construction types in various seismic zones in Iran (please see the original table at Table A1). Table 1 presents average market earthquake insurance premiums for masonry, concrete, and steel buildings of 10 years of age in five provincial capital cities. It seems the rates provided do not accurately reflect the building class vulnerabilities and seismic risk profiles of the cities mentioned. An appropriate approach is to leverage catastrophe risk modeling exercise to determine more reasonable premium rates which is addressed in the following sections of the paper.

It should be noted that we have selected these cities as representatives of different seismic zones in Iran; Tehran and Tabriz in highly seismic Alborz zone in Northern Iran, Esfahan in low seismicity central areas, Khuzestan in low seismicity southwestern Iran, and Kerman to medium-high seismic zone of Zagros.

Table 1: Market earthquake premium rates (in 1000) for different building types in various province capital cities in Iran

Province	County[5]	Capital city	Construction type		
			Masonry	Steel	Concrete
Tehran	Tehran	Tehran	1.1	0.50	0.50
East Azarbayjan	Tabriz	Tabriz	1.1	0.50	0.49
Esfahan	Esfahan	Esfahan	0.78	0.33	0.32
Kerman	Kerman	Kerman	1.1	0.37	0.36
Khuzestan	Ahvaz	Ahvaz	0.78	0.33	0.32

---

[4] Azki.com

[5] County or Shahrestan is second-order administrative division of Iran.

3.1.2 Solvency II

As outlined in Annex IV of Directive 2009/138/EC (2009) and CEIOPS (2010) on the application of the natural catastrophe Standardised Scenarios (standard formula), to calculate earthquake charge, the Weighted Total Value Insured (WTIV) should be computed at CRESTA[6] level using the Total Insured Value[7] (TIV) for each line of business. Eq.1 presents the mathematical formulation of this stage (Directive, 2009; Committee of European Insurance and Occupational Pensions Supervisors (CEIOPS), 2010).

$$WTIV_{ZONE} = F_{ZONE} \times TIV_{ZONE} \qquad \text{Equation 1}$$

Since the 99.5% VaR, as the risk factor, are provided at the country level in CEIOPS (2010), a relativity factor (F_{ZONE}) takes the role of adjusting the national risk factor at subnational (CRESTA) level in the Standardised Scenario. The catastrophe capital charge ($CAT_{peril-ctry}$) is then calculated by applying the effect of geographical aggregation of WTIVs of different CRESTA zone within the country of interest multiplied by Q_{CTRY} (1-in-200-year risk factor of earthquake at country level). Eq.2 illustrates the calculation of solvency capital required for earthquake risk at the country level.

$$CAT_{PERIL-ZONE} = Q_{CTRY} \times \sqrt{[WTIV_{ZONE}]^T[AggMat][WTIV_{ZONE}]} \qquad \text{Equation 2}$$

Where $[WTIV_{ZONE}]$ is the array presentation of WTIV within the country (of interest and $[WTIV_{ZONE}]^T$ is its transposed form. $[AggMat]$) is basically a correlation matrix determining how different CRESTA zones are correlated to each other in terms of experiencing simultaneous earthquake loss and it comprises elements of 1 (fully correlated), 0.5 (semi correlated), 0.25 (slightly correlated), and 0 (no correlation). CEIOPS (2010) provides sub-country correlation matrices for EEA countries in an excel spreadsheet.

To follow the procedure proposed by Solvency II to calculate the catastrophe charge for earthquake risks in Iran, we use the output of a stochastic earthquake risk model developed in this study, separately presented in section 3.2. This catastrophe model can produce risk results (e.g., AAL or 1-in-200-year loss) at finer administrative levels than CRESTA. In accordance with local underwriting and risk management practice in Iran, we use the county-level resolution to calculate the solvency capital. Therefore, there is no need to use a relativity factor for TIV at the county level since we already have the Q factor for each county. That said, we can rewrite Eq.1 to Eq.3:

$$CAT_{EQ-County} = Q_{County} \times TIV_{County} \qquad \text{Equation 3}$$

Here, we can directly calculate each county's catastrophe charge for earthquake risk. Following that, we aggregate these charges at a province and then country level to determine the total solvency capital for a given portfolio of earthquake risks. Eq.4 and Eq.5 exhibit the mathematical form of these calculations.

$$CAT_{PERIL-ZONE} = \sqrt{[WTIV_{ZONE}]^T[AggMat_{Province}][WTIV_{ZONE}]} \qquad \text{Equation 4}$$

---

[6] CRESTA zones are a system used in the insurance industry to evaluate and manage catastrophe risks. CRESTA stands for "Catastrophe Risk Evaluation and Standardizing Target Accumulations." These zones are geographic areas that are defined based on various factors, including seismic activity, weather patterns, and other natural perils.

[7] Total Insured Value (TIV) refers to the total amount of insurance coverage that an individual, organization, or entity has on its assets, properties, or liabilities

$$CAT_{PERIL-ZONE} = \sqrt{[WTIV_{ZONE}]^T\left[AggMat_{Country}\right][WTIV_{ZONE}]} \quad \text{Equation 5}$$

The symmetric aggregation matrices for province and country levels are constructed using either 1 (fully correlated), 0.5 (semi-correlated), 0.25 (slightly correlated), and 0 (non-correlated) members. It is assumed, mainly considering distance factor, that each county is fully correlated with itself and semi correlated with its neighbouring counties. In the case of provinces, due to the larger size, the neighbouring provinces are assumed to be slightly correlated.

3.2 Modeling the Earthquake Risk in Iran

As a requisite for using a risk-based methodology in calculating the earthquake risk capital charge, for example, the described method by Solvency II, it is necessary to have a stochastic catastrophe model for quantifying the required percentile of confidence of seismic losses (here, 99.5%) at different locations and for various construction types. This subsection explains how we developed an earthquake risk model for Iran utilizing the most reliable methodologies and the highest quality of data. The subsection describes the risk model components: the calculation platform (OpenQuake), seismic hazard model, residential building exposure model, and vulnerability functions. Because this paper's main objective is to compare solvency capital calculation methods, efforts were made to keep the risk model development description as brief as possible.

The common practice for quantifying natural catastrophe risks in the insurance industry is (event-based) stochastic catastrophe modeling. The process incorporates three main components of hazard, exposure, and vulnerability using a Monte Carlo simulation method to generate loss results. Loss results are then post-processed to calculate risk parameters such as Average Annual Loss (AAL) and loss Exceedance Probability (EP) for specific level of confidence which are employed for various underwriting and risk management decisions in the business. The practice of modeling seismic risk in Iran is rather in its early stage and a few studies have been conducted on catastrophe modeling over the last decade, e.g., (Ghafory-Ashtiany & Nasserasadi, 2012), (Pakdel-Lahiji, et al., 2019), (Motamed, et al., 2019), (Shahbazi, et al., 2020), and (Bastami, et al., 2022). In this study, the open-source OpenQuake platform developed by the Global Earthquake Model (GEM) foundation was utilised to do the seismic risk modeling, due to its recognition in the insurance market and its flexibility in terms of input data and generation of required risk parameters.

3.2.1 Seismic hazard model

After reviewing several available studies on the seismic hazard of Iran (Motamed, et al., 2019; Mirzaei, et al., 1997; Tavakoli & Ghafory-Ashtiany, 1999; Yazdani & Kowsari, 2013; Şeşetyan, et al., 2018; Lotfi, et al., 2022; Pagani, et al., 2020), the Earthquake Model of Middle East (EMME) (Şeşetyan, et al., 2018) was selected due to the availability of its OpenQuake-ready input data and credibility of the study in the earthquake engineering society. The EMME seismic model comprises two models for line and area sources, prepared with collaboration of seismologists from Iran, Middle East region, and Europe. In this study, only seismogenic sources within Iran and a 300 km beyond its borders have been considered. Figure 1 illustrates the delineation of seismogenic zones and active faults used in the input seismicity model.

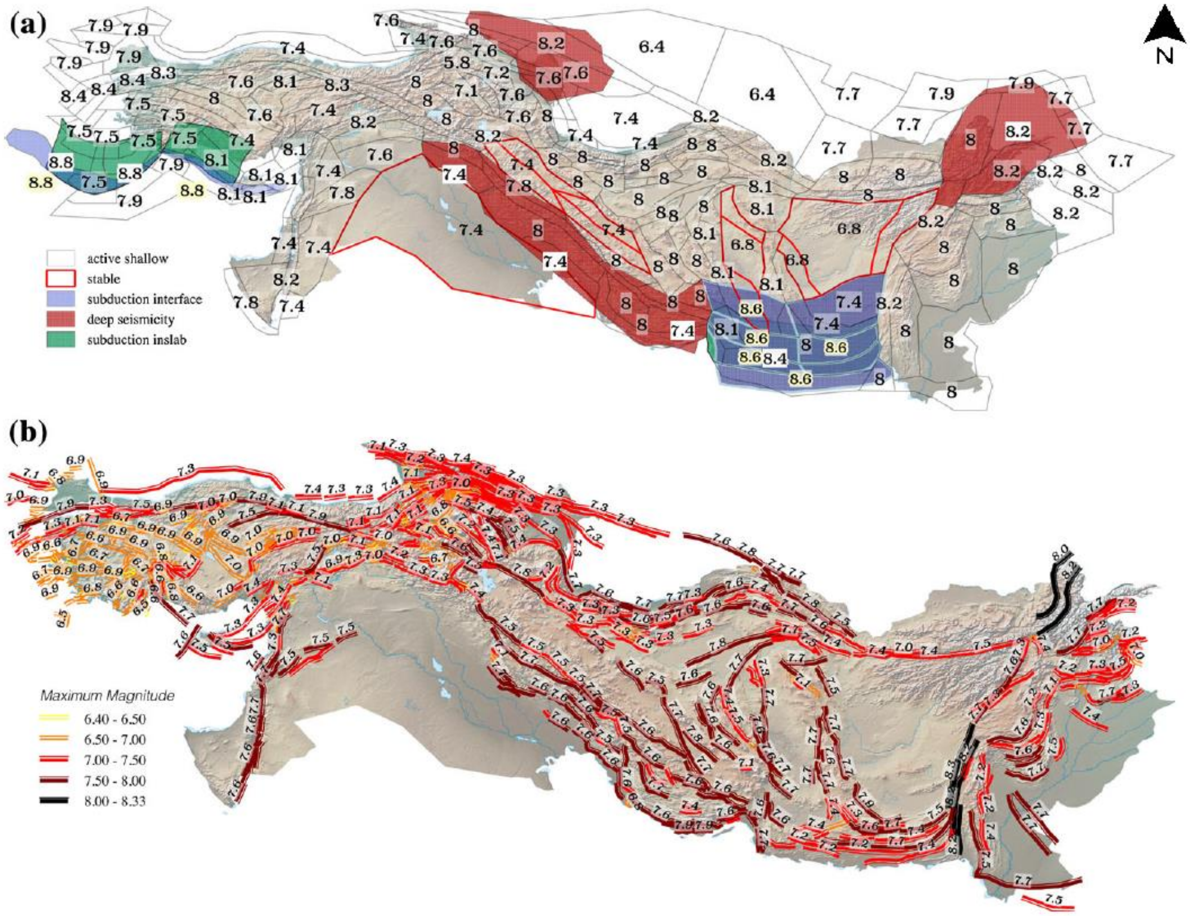


Figure 1: Seismogenic sources of EMME project used in the seismicity model: Area sources (a) and fault sources (b) Original maps from (Danciu, et al., 2018)

In addition, a set of Ground Motion Prediction Model Equations (GMPE) for different seismotectonic characteristics in Iran (including active shallow crustal, stable shallow crustal, subduction, and deep seismicity sources), and two logic trees for treating epistemic seismic hazard uncertainty were utilized to calculate the ground motion intensity parameter (PGA) at exposure locations. Figure 2 exhibits the structure of the GMPE logic tree and the attenuation relationships that were employed in the hazard model. The minimum magnitude of 5 was used in the analysis due to its impact on building damage and optimizing the computation demand. These are the same settings suggested in EMME project, however; we used a more recent version of GMPEs whenever possible.

Table 2: GMPEs used in the hazard model and their corresponding weights

Seismotectonic type	GMPE	Weight
Active shallow crust	(Akkar & Cagnan, 2010)	0.20
	(Akkar, et al., 2014)	0.35

	(Chiou & Youngs, 2008)	0.35
	(Zhao, et al., 2006)	0.10
Stable shallow crust	(Atkinson & Boore, 2006)	0.40
	(Toro, 2002)	0.25
	(Campbell, 2003)	0.35
Subduction interface	(Atkinson & Boore, 2003)	0.20
	(Lin & Lee, 2008)	0.20
	(Youngs, et al., 1997)	0.20
	(Zhao, et al., 2006)	0.40
Subduction in-slab	(Atkinson & Boore, 2003)	0.20
	(Lin & Lee, 2008)	0.20
	(Youngs, et al., 1997)	0.20
	(Zhao, et al., 2006)	0.40
Deep seismicity	(Lin & Lee, 2008)	0.50
	(Youngs, et al., 1997)	0.50

To convert bed rock ground motion intensity to ground-level PGA, a soil model (shear velocity distribution) based on methodology suggested by Allen and Wald (Allen & Wald, 2009) was used. Using the components adopted, an event-based probabilistic seismic hazard analysis was carried out using GEM[8]’s OpenQuake engine and 20,000 years of seismicity were simulated. Figure 2 illustrates the Peak Ground Acceleration (PGA) distribution on the bedrock with an equivalent return period of 475 years in Iran, based on averaging several realizations of PGAs.

---

[8] Global Earthquake Model

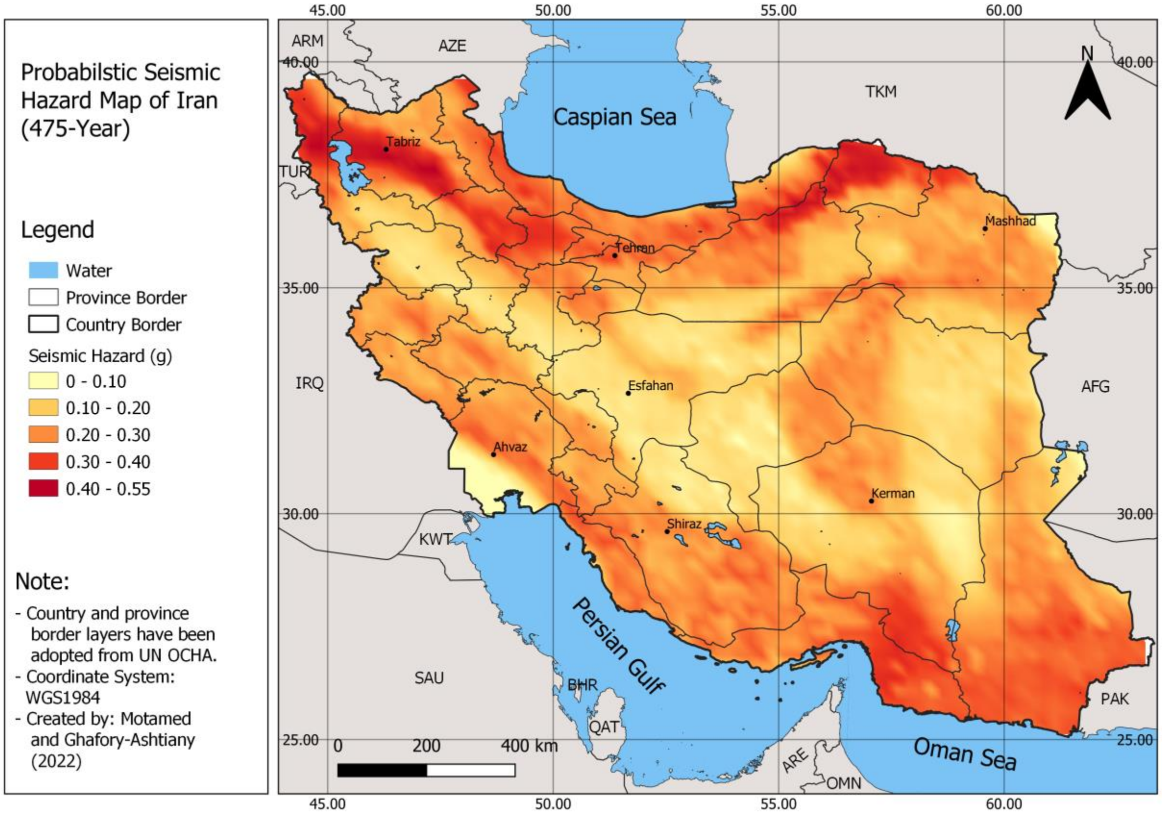


Figure 2: Spatial distribution of hazard parameter (PGA) of 475-year return period

As seen in Figure 2, the northern part of the country (Alborz and Koppe-Dagh seismotectonic zones), including the cities of Tabriz and Tehran, and south-eastern regions (central Iran and Makran zones) containing the city of Kerman show the highest levels of seismic hazard. In the Zagros zone in western-southwestern Iran, the PGA level is lower than northern and southeastern parts, but still high. On the flip side, the province of Esfahan in central Iran and southwestern parts of Khuzestan in south-western Iran contain zones with the lowest PGA levels. The sharp contrast in PGA values in Khuzestan is due to the lack of seismic events and active faults in this region which has been smoothed in the Inverse Distance Weighted (IDW) method. Other regions fall between these upper and lower seismicity limits.

Attention should be paid that this study has been carried out at the national level; therefore, the resolution is coarser than more accurate local studies and both distribution and intensity of PGAs might be different to such works. To validate the results of the hazard model, we compared our results with some recent seismic hazard analysis studies conducted at national or regional levels for Iran over the recent years, including (Lotfi, et al., 2022), (Lloyd's and CAT Risk Solutions, 2017), and (Şeşetyan, et al., 2018). Table 3 summarizes the results of seismic hazard analysis (10% probability of exceedance in 50 years equal to 475-year) for these studies and the present work.

Table 3: Comparison of the seismic hazard analysis results in this research with other studies

Study	Min PGA (g) on bedrock	Max PGA (g) on bedrock	Geographic zones with highest PGA

Lotfi et al (2022)	0.1	0.55	N and SE (very high), W-SW (high)
Şeşetyan, et al. (2018)	0.1	0.5	N and SE (very high), W-SW (high)
Lloyd's and Cat Risk Solutions (2017)	0.05	>0.40	N and W-SW (very high), SE (high)
Present study	0.05	0.55	N and SE (very high), W-SW (high)

As seen, there is an acceptable similarity between the range of 475-year PGAs and spatial distribution of it at the national level.

3.2.2 Vulnerability model

To estimate the damage ratio of exposed assets under a given earthquake scenario with known intensity parameters (in this study PGA), it is necessary to use vulnerability functions. These are typically functions or curves that relate various levels of hazard intensity to damage ratio or percentage for specified types of groups of assets (vulnerability classes). In this study, the vulnerability curves developed by Mansouri and Amini-Hosseini (2013) as one of the components of the project Earthquake Model of the Middle East (EMME) (Şeşetyan, et al., 2018) were used due to the credibility of the methodology used (RISK-UE), consistency with building attributes publicly available for Iranian buildings (please look at the exposure model section), and compatibility with past earthquake losses in Iran). In this study, 10 building vulnerability classes were defined based on construction material, height of building, and construction vintage as a proxy for the ductility of the structure to earthquake loads. Table 4 summarizes the vulnerability classification of Iranian buildings based on their physical attributes.

Table 4: Classification of Iranian building vulnerability based on physical attributes (Mansouri & Amini-Hosseini, 2013)

Vulnerability class	Material type	Height category	Construction date	Short description
Adobe	Adobe	Low-rise	All time periods	High vulnerability
M1	Reinforced masonry	Low-rise	1996-2006	Low vulnerability
M2	Unreinforced masonry	Low-rise	1996-2006	High vulnerability
M3	Unreinforced masonry	Low-rise	Before 1976	High vulnerability
RC3	Concrete frame	Mid-rise	Before 1976	High vulnerability
RC2	Concrete frame	Mid-rise	1976-1996	Moderate vulnerability
RC1	Concrete frame	Mid-rise	1996-2006	Low vulnerability
S3	Steel frame	Mid-rise	Before 1976	High vulnerability
S2	Steel frame	Mid-rise	1976-1996	Moderate vulnerability
S1	Steel frame	Mid-rise	1996-2006	Low vulnerability

Since the newest vintage of buildings at the time conducting this study was 2016, we shifted the original vulnerability (Table 4) by 10 years to pre-1986, 1986 to 2006, and post-2006. This is a valid modification because buildings had become 10 years older after the publication of the original paper and since then a new version of the Iranian Standard for Seismic design of buildings had come into force in 2014. These classes and their corresponding vulnerability curves represent seismic vulnerability of ten building classes of adobe (one class), masonry (three classes), steel (three classes), and reinforced concrete (three classes). Figure 3 exhibits examples of these curves for different types of building with medium-quality construction. am, mm, rcm, sm in this figure stand for medium-quality adobe, masonry, reinforced concrete, and steel buildings.

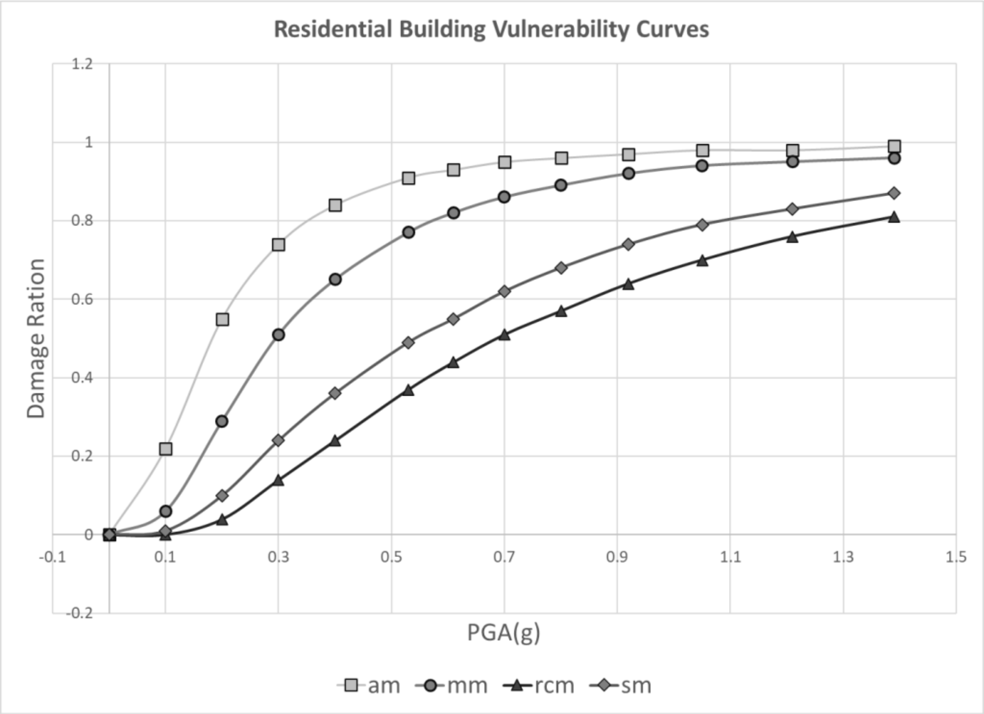


Figure 3 Vulnerability curves for medium-quality adobe (am), masonry (mm), reinforced concrete (rcm), and steel (sm) buildings (Mansouri & Amini-Hosseini, 2013)

As shown in this diagram, adobe is the most vulnerable class of building to earthquakes, while reinforced concrete and steel buildings offer the highest resistance to seismic loads. Masonry buildings fall between these two ranges. Also, buildings with older date of construction are considered more vulnerable to seismic forces.

3.2.3 Residential building exposure model

The exposure model provides attributes of the buildings at risk, such as physical attributes (material type, year built, height of the building), their monetary value, and their geographic locations in terms of, for example, geographic coordinates. The Iranian census data classifies the building materials into three main classes of steel, reinforced concrete, and masonry. The masonry class is furthered split to Brick & Steel or Stone & Steel, Brick & Wood or Stone & Wood, Cement Block (all kind of Roofs), All Brick or Brick & Stone, and All Wood. In this study, we only consider residential building because their attributes are collected on a regular basis in the national population and housing census and reported by the Statistical Centre of Iran (SCI) every 5 years. The date of constructions is expressed in 10-year, 5-year, and 1-year bins depending on the vintage of buildings since 1966. The census data is freely available at SCI website at county granularity. Due to the fact that the census data has not been updated since 2016, we have used 2016 datasets to develop the exposure model. Figure 4 illustrates common types of Iranian residential buildings in the city of Tehran.

(a) *(b)*

(c) *(d)*

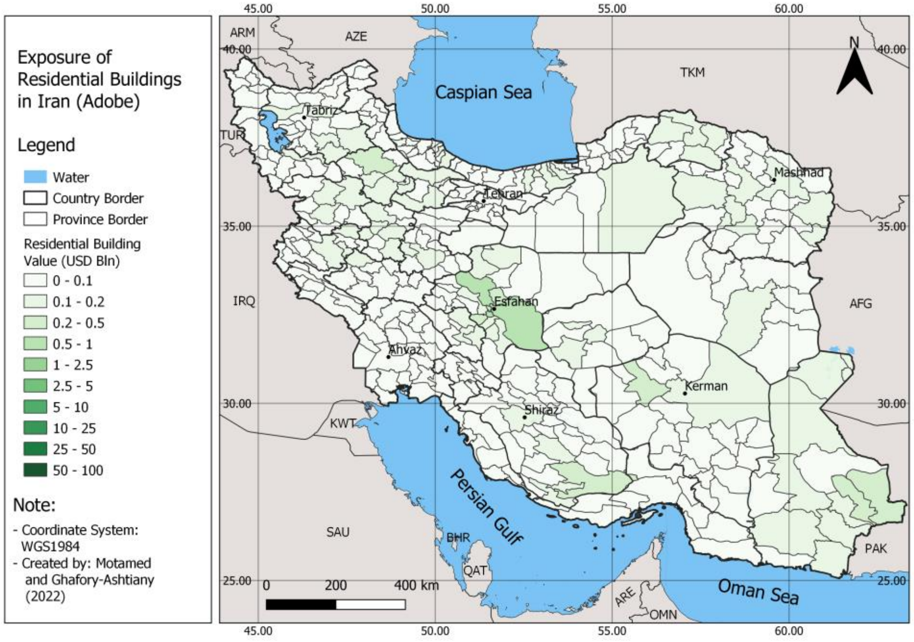
Figure 4: Examples of common residential buildings in Tehran: adobe (a), steel (b), reinforced concrete (c), masonry (d)

Photos by Ms. Niloofar Kazemi Asl

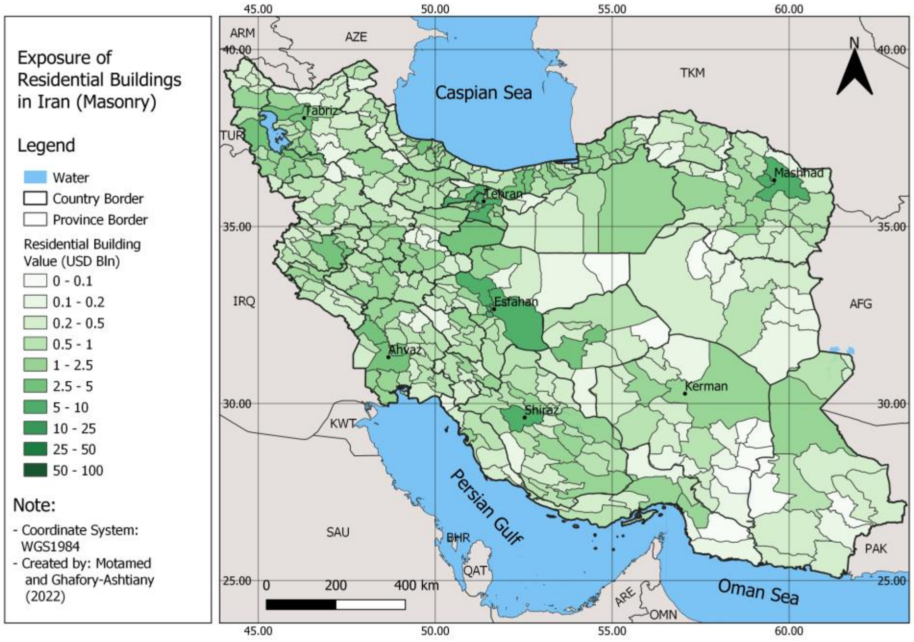
Until 2011, SCI reported four sets of building attributes, namely building material, construction date, and number and build area of dwellings split by building types and year built. We used the same vulnerability classes introduced by (Mansouri & Amini-Hosseini, 2013) as exhibited in Table 3 so that they are consistent with adopted vulnerability curves. Because census data of 2016 lacked the attribute of building vintage, we used the previous census data (2011) vintage attribute and updated it by making an assumption that if the number of dwellings has decreased between 2011 and 2016 census in a given county, the reduction would be due to destruction of buildings belonging to the oldest vintage bin, and if the number increased, that would be because of newly built buildings, thereby affiliating to the newest vintage bin. This assumption is compatible to the reconstruction trend of buildings and settlement development in Iran.

No national dataset on the number of stories or height of the buildings is available in Iran. As a results, we assumed a low-rise height class for adobe and masonry buildings and mid-rise class for steel and reinforced concrete buildings in Iran based on an engineering judgement. An estimate of construction cost of residential buildings can be enquired from builders in different provinces. The value of existing buildings can also be estimated by depreciating the value of the newly constructed buildings based on the date of construction or building vintage bins in the vulnerability model. Based on the research conducted, the average cost of construction per sqm in Iran in 2016 was USD 300. Using the data on build area and number of dwellings, we estimated the average building surface area of about 100 sqm for Iranian dwellings.

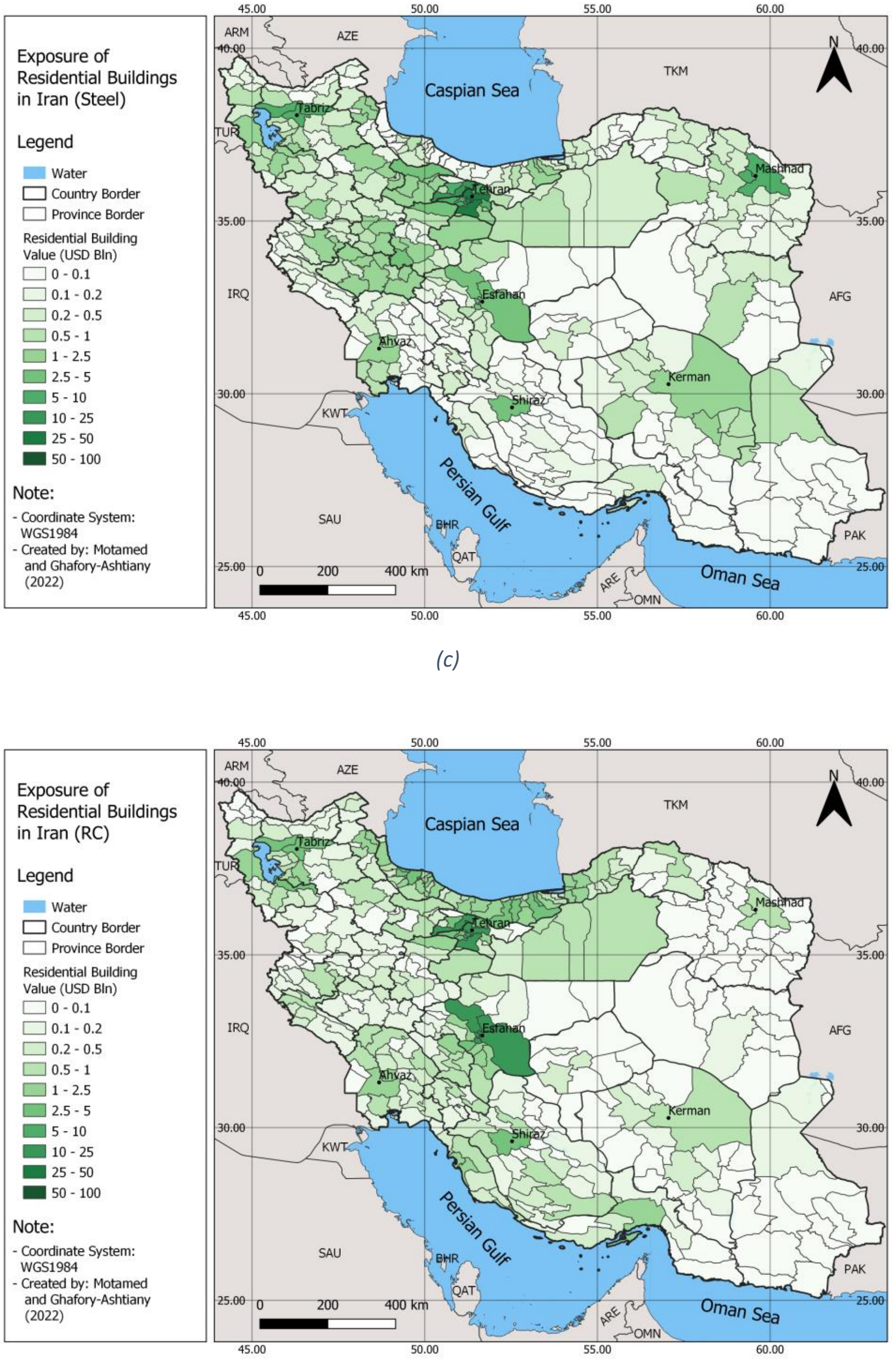
After creating the datasets for 10 building types at the county level, we used population data of Landscan (Bright, et al., 2017) with a 30-arc-second resolution to downscale the county-level building exposure data to a finer resolution for the loss calculation purpose. To accomplish this, we divide the number of dwellings of each building type by the total number of populations of the county to compute the number of dwellings per person, then we multiply the results to the number of populations in each cell to come up with number of dwellings in that cell. The process is repeated for all types of building for each county. Figure 5 presents the spatial distribution and monetary value of different building types of residential dwellings in Iran at the county level. Please note that numbers are absolute value of each building type at the county level.


Exposure of Residential Buildings in Iran (Adobe)
Legend
Water
Country Border
Province Border
Residential Building Value (USD Bln)
0 - 0.1
0.1 - 0.2
0.2 - 0.5
0.5 - 1
1 - 2.5
2.5 - 5
5 - 10
10 - 25
25 - 50
50 - 100
Note:
- Coordinate System: WGS1984
- Created by: Motamed and Ghafory-Ashtiany (2022)
45.00
50.00
55.00
60.00
40.00
35.00
30.00
25.00
ARM
AZE
TKM
TUR
IRQ
AFG
KWT
SAU
BHR
QAT
ARE
OMN
PAK
Caspian Sea
Persian Gulf
Oman Sea
Tabriz
Tehran
Mashhad
Esfahan
Ahvaz
Kerman
Shiraz
N
0
200
400 km

(a)


Exposure of Residential Buildings in Iran (Masonry)
Legend
Water
Country Border
Province Border
Residential Building Value (USD Bln)
0 - 0.1
0.1 - 0.2
0.2 - 0.5
0.5 - 1
1 - 2.5
2.5 - 5
5 - 10
10 - 25
25 - 50
50 - 100
Note:
- Coordinate System: WGS1984
- Created by: Motamed and Ghafory-Ashtiany (2022)
45.00
50.00
55.00
60.00
40.00
35.00
30.00
25.00
ARM
AZE
TKM
TUR
IRQ
AFG
KWT
SAU
BHR
QAT
ARE
OMN
PAK
Caspian Sea
Persian Gulf
Oman Sea
Tabriz
Tehran
Mashhad
Esfahan
Ahvaz
Kerman
Shiraz
N
0
200
400 km

(b)



(c)

(d)

Figure 5: Exposure of residential buildings in Iran, adobe (a), masonry (b), steel (c), and concrete (d)

From a holistic point of view, most residential buildings are concentrated around the highly-populated capital cities of Tehran, Tabriz, Esfahan, Mashhad and Shiraz which is consistent with results of 2016 housing and population census which ranked provinces of Tehran, Esfahan, Razavi Khorasan (including Mashhad city), Fars (including Shiraz), Markazi (containing Arak), Khuzestan (including Ahvaz), and East Azarbayjan (including Tabriz) with largest residential built area As observed in map (a), the highest value of county-wise adobe buildings as the most vulnerable type is Esfahan (center of Iran), Fars (south), Kerman (east) and Sistan and Baluchestan (southeast). Also, masonry buildings, as the second most vulnerable building type, are almost common across the country with a more visible presence around the capital cities of Tabriz, Tehran and Mashhad in the north, Esfahan in the center, Shiraz in the south, and Ahvaz in southeast (See map 'b'). The two more earthquake resistant building types, namely steel and reinforced concrete are more frequent around capital cities of Tehran, Tabriz, followed by Esfahan, Mashhad, and Shiraz. According to statistical analyses on the exposure data, about 55% of residential dwellings in 2016 were made of modern construction materials such as steel and reinforced concrete, while the remaining 45% belonged to other types including masonry and adobe.

4 Numerical Results

After preparing the components of the risk model, an event-based probabilistic approach has been used to assess seismic risk of the Iranian residential dwellings. To achieve that, GEM's OpenQuake hazard and risk calculation engine was adopted due to its credibility within the earthquake engineering society, its transparency in terms of technical documentations, and flexibility in using different approaches in modeling risk. Figure 6 illustrates the schema of OpenQuake's probabilistic event-based engine and its input/output structure.

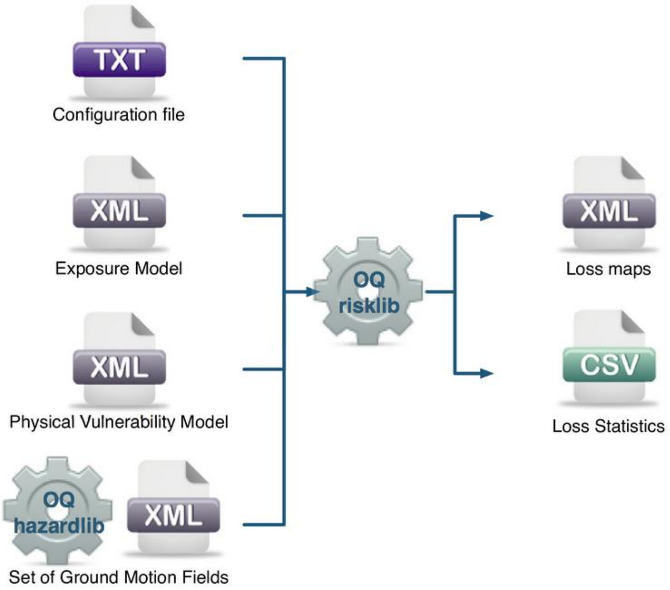


Figure 6: GEM's OpenQuake schema and its input and output components (OpenQuake website[9])

As described, the exposure, vulnerability, and hazard models need to be converted to required format before being incorporated in the engine. In addition to that, a configuration file that introduces the input data and other analysis parameters such as type of analysis (here: probabilistic event-based), number of simulated years (here: 20,000 years), and types of output, is required to set up the risk analysis. The risk assessment process starts with OpenQuake

---

[9] https://docs.openquake.org/oq-engine/manual/latest/risk.html accessed in 10 December 2023

hazard engine generating sampled earthquake events using the hazard model provided. For each seismic event generated, ground motion field (distribution of PGA on top soil) is calculated using GMPE models and the soil shear velocity information for all the locations existing in the exposure model within a defined radius around the sampled epicenter (here 150 km). Then, based on the typology of buildings at each location (a cell of 30-second arc dimension), relevant vulnerability curves are used to convert PGA value to damage percentage. Further, the damage percentage is multiplied with replacement value of that type of building to calculate loss. These OpenQuake output is then post-processed to calculate aggregate loss at different levels, namely county, province, and country. These values should be normalized to their corresponding exposure values for each building type to compute AAL rates. The same process is done, this time using EP 99.5% to calculate 1-in-200 EP loss for each building type at aforementioned aggregate levels which are adopted as solvency capital required according to Solvency II regime.

4.1 Earthquake Risk Assessment Results

Figure 7 shows the spatial distribution of seismic AAL for all residential building types in Iran, aggregated at the county level. Few studies exist on seismic risk topic for Iran at a national level e.g., (Ghafory-Ashtiany & Nasserasadi, 2012), and (Motamed, et al., 2019) which were previously done by authors of this study and are thus considered biased to be used to validate the risk results. Therefore, a risk component validation method is followed to control the sensibility of the results, in which it is tried to validate the risk distribution and intensity based on the values in the exposure, hazard, and vulnerability models used. As observed, almost all parts of the country are exposed to medium and high levels of seismic risk, except for sparsely populated areas of central deserts and the northern coasts of the Oman Sea. There are also visible high-risk counties, especially around major cities of Tehran and Tabriz in northern and north-western Iran, as well as in other populated areas proximate to Mashhad (northeastern Iran), Esfahan (central Iran), and Ahvaz, Shiraz, and Kerman in southern parts of the country. This pattern seems to be in accordance with the distribution of different classes of buildings and their exposure to the seismic hazard (please see figures 2 and 5 and comparative vulnerability of main building types in Table 4); in areas with a concentration of buildings and very high level of earthquake hazard (such as in Tehran and Tabriz cities) the seismic risk is the highest. Similarly, we can witness a high potential of loss in the populated southern cities of Ahvaz, Shiraz, and Kerman, that are subject to medium to high seismicity. The city of Esfahan, despite being located in a low seismicity zone, also shows high seismic risk, most probably due to its very high building exposure (the second-highest exposure value after Tehran) and the prevalence of more vulnerable building classes of masonry and adobe (look at map ‘a’ and ‘b’ in Figure 5). In south-eastern Iran, where the province of Sistan and Baluchestan exists, a medium to rather high level of risk can be distinguished, mainly because of the high level of seismicity in southern parts of province, existence of extremely vulnerable types of buildings (e.g., adobe).

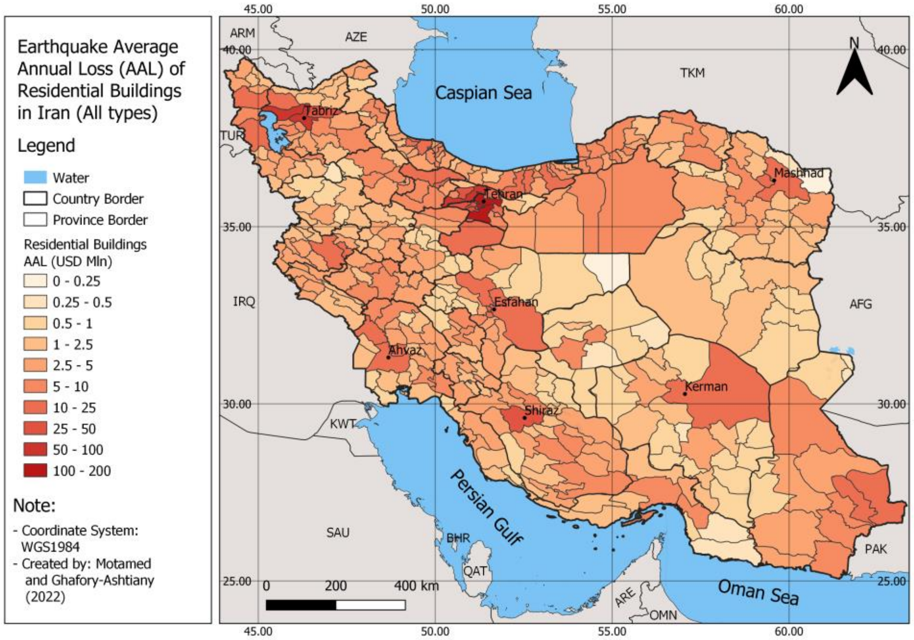
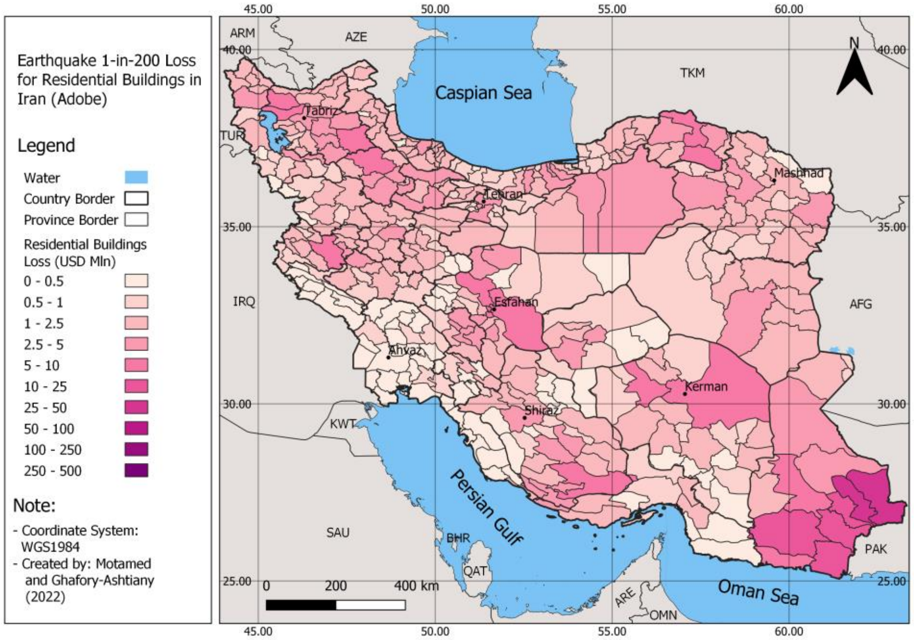
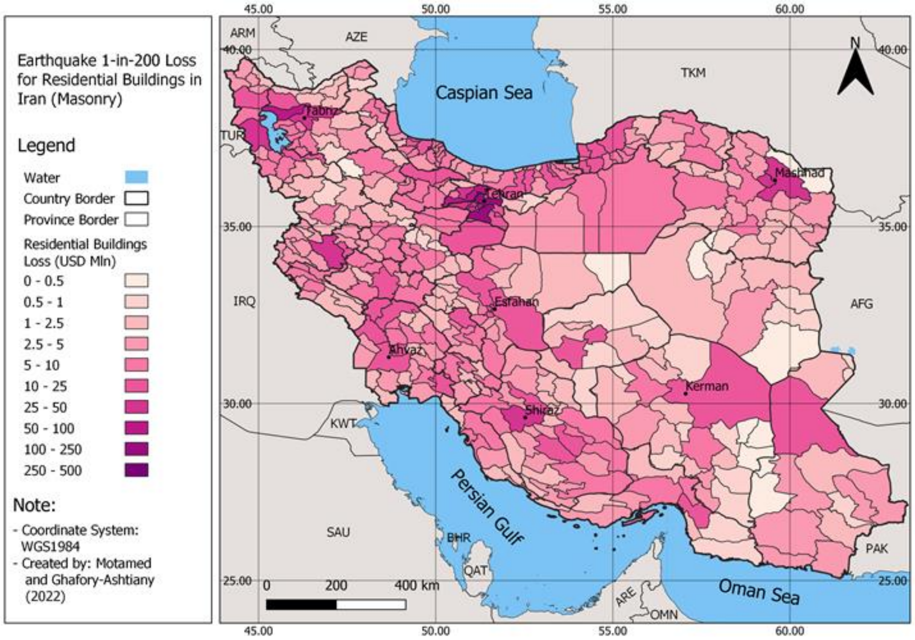


Figure 7 Earthquake Average Annual Loss (AAL) of residential buildings in Iran (million USD)

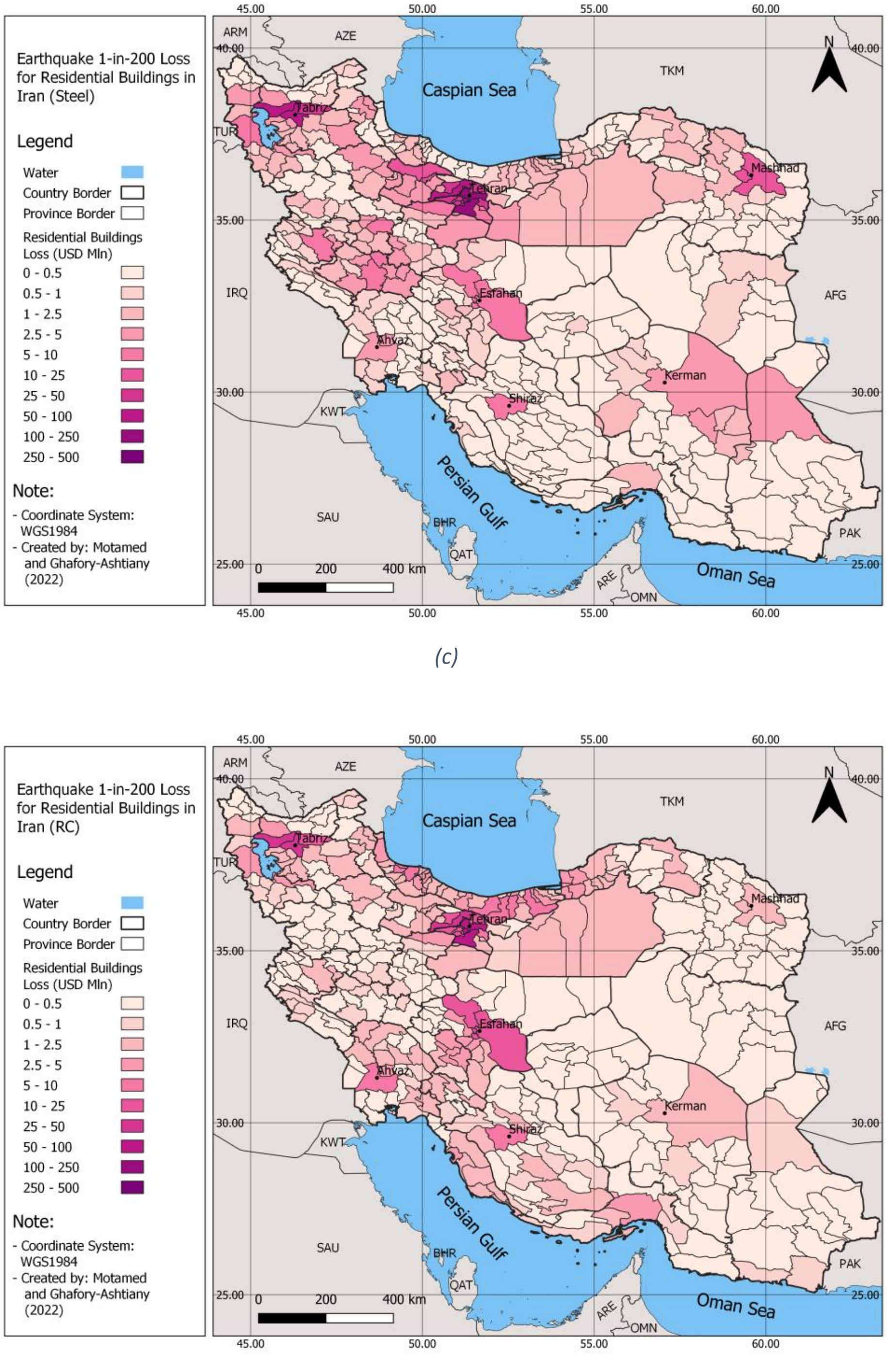
From what Figure 8 presented as the spatial pattern of 1-in-200-year losses of earthquakes in Iran, one could acquire an idea of the level of earthquake insurance capital required by the Solvency II regime for different types of buildings at the county level in Iran. Assuming a 100% insurance coverage for residential homes in Iran, the SCR or 1-in-200 loss for steel and reinforced concrete buildings would be the highest in Tehran, Tabriz, and to a lower extent in Esfahan (and their surrounding counties). The situation is more homogenous for masonry structure (because of its high prevalence and rather even distribution across the country), where significant seismic losses with 99.5% confidence could be distinguished in almost all major cities in the country, namely Tehran, Tabriz, Mashhad, Esfahan, Kermanshah, and Kerman. For adobe construction, again, a medium-to-high degree of losses could be expected in many counties except for areas located in Khuzestan and Fars provinces in the southwest. The only observable anomaly for 1-in-200 earthquake losses in adobe buildings is found in the country's most south-eastern counties in Sistan and Baluchestan province, particularly along the border with Pakistan. This pattern could be first due to the weighty number of absolutely vulnerable buildings made of adobe in these areas compared to other parts of the country. The second reason would be the eminent seismicity of this region, which is influenced by both shallow crustal and subduction seismic zones of Makran.


Earthquake 1-in-200 Loss for Residential Buildings in Iran (Adobe)
Legend
Water
Country Border
Province Border
Residential Buildings Loss (USD Mln)
0 - 0.5
0.5 - 1
1 - 2.5
2.5 - 5
5 - 10
10 - 25
25 - 50
50 - 100
100 - 250
250 - 500
Note:
- Coordinate System: WGS1984
- Created by: Motamed and Ghafory-Ashtiany (2022)
45.00
50.00
55.00
60.00
40.00
35.00
30.00
25.00
ARM
AZE
TKM
TUR
IRQ
AFG
KWT
SAU
BHR
QAT
ARE
OMN
PAK
Caspian Sea
Persian Gulf
Oman Sea
Tabriz
Tehran
Mashhad
Esfahan
Ahvaz
Kerman
Shiraz
N
0
200
400 km

(a)


Earthquake 1-in-200 Loss for Residential Buildings in Iran (Masonry)
Legend
Water
Country Border
Province Border
Residential Buildings Loss (USD Mln)
0 - 0.5
0.5 - 1
1 - 2.5
2.5 - 5
5 - 10
10 - 25
25 - 50
50 - 100
100 - 250
250 - 500
Note:
- Coordinate System: WGS1984
- Created by: Motamed and Ghafory-Ashtiany (2022)
45.00
50.00
55.00
60.00
40.00
35.00
30.00
25.00
ARM
AZE
TKM
TUR
IRQ
AFG
KWT
SAU
BHR
QAT
ARE
OMN
PAK
Caspian Sea
Persian Gulf
Oman Sea
Tabriz
Tehran
Mashhad
Esfahan
Ahvaz
Kerman
Shiraz
N
0
200
400 km

(b)



(c)

(d)

Figure 8: Earthquake 1-in-200 loss of residential buildings in Iran, adobe (a), masonry (b), steel (c), and concrete (d)

Table 5 presents the pure premium rate (AAL rate) calculated for the same cities previously selected in Table 1 of Section 3. If we draw a comparison between these rates and those used currently by the market for pricing earthquake insurance in Iran (Table 1), we notice a vast difference, implying a sizeable undervaluation of earthquake risk in the Iranian insurance industry, including the insurers and supervising bodies like CII. Here, we used county-level AAL rates as the representative of the modeled seismic risk of capital cities previously mentioned in Table 1. This is because the current market rates are only retrievable at the city level from the Iranian insurance quote aggregator websites.

This difference is more pronounced for cities with a higher level of seismicity, such as Tabriz where the modeled AAL rate (8.65) is about eight times larger than the current market premium rate (1.1) for masonry buildings. Considering that retrieved market premium rates are 'technical premium', the real discrepancy between risk-based and market rates are event higher. For seismically calmer cities like Esfahan, the discrepancy becomes milder, reaching a ratio factor of about 2 for reinforced concrete buildings.

Table 5: Risk-based (modeled) earthquake pure premium rates (x 0.001) for different types of selected cities in Iran

Province	County	Capital city	Risk-based earthquake pure premium rates		
			Masonry	Steel	Concrete
Tehran	Tehran	Tehran	7.15	2.01	1.65
East Azarbayjan	Tabriz	Tabriz	8.68	3.73	3.03
Esfahan	Esfahan	Esfahan	1.07	0.45	0.20
Kerman	Kerman	Kerman	3.35	0.90	1.04
Khuzestan	Ahvaz	Ahvaz	3.23	0.83	1.00

4.2 Calculation of Solvency Capital under Solvency II and Directive 69

In this section, we utilize the modeled solvency capital rates, specifically the 1-in-200 loss rates, and the current premium rates prevailing in the market (averaged across the market) to conduct a comparative analysis of the capital requirements for earthquake risk in Iran. The assessment is based on two distinct methodologies specified by the European Solvency II regime and the Iranian Directive 69. To highlight the difference between modeled (risk-based) solvency figures and those calculated based on the earned premium which are, per se, acquired by underwriting earthquake risks according to market premium rates, we use a hypothetical portfolio of risks in the five capital cities we selected previously in section 3.1. As mentioned before, these cities have been selected because they represent different seismic zones of Iran, namely Alborz (from northwest to north east including Tabriz and Tehran), Zagros (west, south, and southeast, including Ahvaz and Kerman), and Central Iran (Esfahan). These cities also lie within regions with different seismicity level, for example Tehran and Tabriz are highly seismic, Ahvaz and Kerman have medium-to-high seismicity and Esfahan is located in a seismically calm area.

To illustrate the influence of building types on solvency capital, we examined three primary construction classes: steel, reinforced concrete, and masonry. For all building classes, we assumed a replacement cost of USD 300 per sqm and an average built area of 100 sqm per housing unit, consistent with the parameters used in the exposure model. Additionally, we presumed an equal number of dwellings (100 dwellings for each construction type in each city) within the hypothetical portfolio. Using the city- and building type-specific solvency capital rates, we calculated the Solvency Capital Requirement (SCR) by multiplying the exposure values for each construction type by the corresponding SCR rates. Subsequently, the city-level SCRs needed to be aggregated to the portfolio level. In the Solvency II methodology, unlike Directive 69, which simply sums up city-level values to compute the portfolio-level

SCR, a geography-based correlation matrix is utilized to aggregate results. Therefore, we initially developed a correlation matrix for the selected five cities.

Following a methodology akin to that outlined in Annex IV of Directive (2009) and CEIOPS (2010), we established five province-level and one portfolio-level correlation matrices for the provinces hosting the pilot cities. The values within these correlation matrices were determined based on the proximity of administrative divisions, considering the relative positioning of counties within each province and the proximity of provinces. It was assumed that each county exhibits 100% correlation with itself. Similarly, each province is considered fully correlated with itself, reflected by a correlation value of 1.0. Furthermore, a 50% correlation was assumed between each county and its neighboring county. For provinces, a 25% correlation was assumed between proximate provinces, accounting for the larger dimensions of provinces compared to counties. As an illustrative example, Figure A1 and Table A2 in the Appendix depict the configuration of counties in Tehran province and its corresponding earthquake risk correlation matrix, providing a visual representation of the methodology applied.

Table 6 shows the results of solvency capital calculation based on the two solvency regimes at the county, province and portfolio levels for the hypothetical portfolio of risks.

Table 6: Earthquake risk solvency capital rates based on the methodologies suggested by the Iranian Directive 69 (D-69) and Solvency II (S-II)

		Exposure (USD million)			D-69 solvency capital rates (x 0.001)			S-II solvency capital rates (x 0.001)			D-69 solvency capital (USD)	S-II solvency capital (USD)
Level		M	S	RC	M	S	RC	M	S	RC		
Location	Tehran	30	30	30	0.64	0.29	0.29	17.00	4.76	3.89	36,540	769,500
	Tabriz	30	30	30	0.64	0.29	0.29	17.25	8.65	6.00	36,366	957,000
	Esfahan	30	30	30	0.45	0.19	0.19	3.49	1.91	1.02	24,882	192,600
	Kerman	30	30	30	0.64	0.21	0.21	7.44	2.74	2.42	31,842	378,000
	Ahvaz	30	30	30	0.45	0.19	0.19	6.02	2.15	2.67	24,882	325,200
Portfolio											154,512	1,339,296

As illustrated in the table, there's an approximately tenfold difference in the solvency capital requirement when calculated using the approach specified by Directive 69 compared to the European Solvency II for the same residential dwelling portfolio in the pilot cities. Two key factors contribute to this notable gap in required capital charges. Firstly, the variance in catastrophe capital rates between Directive 69 and the Solvency II system plays a significant role. The second contributing factor, albeit with a minor impact, is the dissimilarity in aggregation methods employed by each methodology. In the Iranian approach, where portfolio capital is determined by summing up county-level figures, the mitigating effect of geographical diversification is simply disregarded, leading to even higher results. According to the data presented in Table 5, the Solvency II risk-based rates are roughly twenty times greater than the Directive 69 capital rates. As mentioned, this disparity is somewhat mitigated when aggregating the solvency capital at the portfolio level. The ultimate catastrophe capitals at the portfolio level for the Iranian and European systems are reported as USD 154,512 and USD 1,339,296, respectively.

5 Discussion

The findings from the analysis indicate that the constant-factor approach utilized by the Central Insurance of Iran (CII) for calculating solvency capital related to earthquake risks significantly underestimates the risk compared to the methodology recommended by the Solvency II regime. This discrepancy raises concerns about the capacity of Iranian insurers and reinsurers to withstand catastrophic shocks stemming from medium to significant earthquake events in major cities across Iran. It is worth noting that, despite the low insurance penetration rate in Iran and the absence of medium to large events in main cities, there have been no recorded instances of catastrophe-related insolvency in the country. However, persisting with the current approach may jeopardize the stability of the insurance market in Iran, potentially giving rise to financial and social challenges in the event of future disasters.

Moreover, following the establishment of the Iran Building Catastrophe Insurance Pool (IBCIP), which provides primary insurance coverage for all residential buildings in the country, a substantial business opportunity arises for local insurance companies to address the gap between the partial coverage offered by IBCIP and the total insurable sum. However, if these insurance firms persist in utilizing the existing premium rates in this scenario, a significant accumulation of risk may occur over time due to the disparity between the actual risk and the written premium. This poses a considerable challenge, as the solvency capital held by these entities might be inadequate to cover losses resulting from medium-to-large seismic events in urban settlements, potentially leading to the insolvency of Iranian insurers. Additionally, given that a majority of domestic insurance firms are reinsured internally due to financial sanctions on Iran, the solvency issues of insurers could potentially have repercussions on other financial institutions. To break this cycle of catastrophe risk accumulation, it is advisable for the Iranian insurance regulator to transition from the current catastrophe pricing practice to a risk-based pricing system, incorporating scientifically-approved catastrophe modeling techniques.

Another consideration which is relevant to the topic of insurance solvency is the public-private collaboration for adopting and implementing new measures like the risk-based catastrophe solvency requirement. As the first step, governmental bodies and insurers can initiate educational programs to raise awareness about catastrophe modeling's significance in assessing natural hazards risk. Forming alliances between international institutions and local insurers is beneficial for knowledge exchange, especially amid current financial sanctions. Moreover, the government can incentivize insurers to integrate catastrophe modeling into risk assessments before enforcing capital mandates. This involves offering tax benefits or reduced regulatory burdens, prompting insurers to embrace advanced risk evaluation tools. These proactive steps aim to fortify the Iranian insurance market, preventing undervaluation, and enhancing resilience through modern practices.

It is important to note that due to the lack of frequent seismic losses, validation of an earthquake risk model is challenging because the average of past losses is not a correct representative of seismic risk in a given area. Depending on the utilized resolution, hazard model, vulnerability curves, exposure data, and loss calculation method, different risk results can be generated by various models. This is something accepted in the insurance market. When comparing the results to other studies, special attention should be given to possible differences in input data and assumptions. For example, when we compare the ratio of AAL in (Kohrangi , et al., 2021) which presents the results of a seismic risk assessment for the city of Esfahan with ours, we should notice the difference in the vulnerability curves, vintage of exposure data, and the most importantly the resolutions of the analysis (county-level in our study versus city-level in theirs). That said, our AAL ratio of 0.55 per thousand for the county of Esfahan (which includes other cities with lower seismicity level in addition to the city of Esfahan) can be comparable with AAL ration of 1.9 calculated for the city of Esfahan in that study. Undoubtedly, an enhancement in the quality of input data and assumptions will enable a more precise assessment of the seismic risk associated with Iranian buildings. This, in turn, would contribute to a more accurate evaluation of the prevailing insurance underwriting and pricing practices.

6 Conclusion

A numerical analysis was carried out in this paper to compare the earthquake catastrophe capital required by the European Solvency II and Directive 69 of the Central Insurance of Iran. Based on the literature reviewed, in the Iranian system, a constant factor is used to compute catastrophe charges based on each policy's earned premium and incurred losses. These earned earthquake insurance premiums are the result of an underwriting practice that uses a market-agreed rating schemes which seems to be not a proper representative of the existing seismic risk in the country. On the other hand, the Solvency II Directive requires a risk modeling-based capital calculation approach to compute the necessary catastrophe charge. In addition to the difference in the calculation of solvency capital rates, there is also a discrepancy between the two methodologies in risk aggregation: while the Iranian directive simply sums up the required capital charges at the city-level to calculate the portfolio-level figure, the European regime considers the diversification impact by making use of correlation matrices. To be able to implement Solvency II approach in calculating the risk-based solvency capital, a seismic risk model has been developed by adopting Earthquake Model of Middle East (EMME) seismicity model (Şeşetyan, et al., 2018), creating an exposure model for Iranian residential buildings based on the newest census data, using an earthquake vulnerability model for Iranian buildings (Mansouri & Amini-Hosseini, 2013), and combining in GEM's OpenQuake hazard and risk assessment engine. Average Annual Loss (AAL) and 1-in-200 EP values have been calculated for four main types of Iranian buildings at 30-second arc grid granularity.

The initial segment of the numerical findings was presented as the Average Annual Loss (AAL) and Exceedance Probability (EP) figures at the county level, achieved by aggregating the OpenQuake risk output tables for four distinct construction types. A comparison between these values and the AAL rates currently employed in the Iranian insurance market reveals a noticeable undervaluation of seismic risk, ranging from 1⁄2 to 1⁄8, depending on the risk location and construction type. Furthermore, to comprehend the implications of this dissonance between risk modeling-based and market-agreed rates, we computed the earthquake capital requirement for a hypothetical portfolio of residential dwellings in five Iranian cities situated in different seismotectonic zones. This calculation was conducted using the methodologies specified by Solvency II and the instructions provided by Directive 69 of the Iranian Central Insurance. The results demonstrate a significant 20-fold underestimation of earthquake solvency capital in the Iranian Directive 69 system compared to Solvency II. This undervaluation of earthquake risk poses a substantial risk of accumulating undue exposure for the Iranian insurance market. In the event of medium-to-large urban earthquakes, it could potentially lead to the insolvency of insurance undertakings due to the inadequacy of reserved catastrophe capital. We believe that this study is a unique and valuable in its kind for Iran and it could originate serious discussions and challenges for the bettering of the relevant sectors. It is worthwhile to mention that the earthquake solvency capital is a function of earthquake risk and risk appetite of the market. Here, we assumed a similar risk appetite between the Iranian insurance market and the European union. Although the average GDP per capita in the EU region is about 10 times Iran's, we are convinced that the earthquake capital requirement should follow the risk profile of the country and the sum insured. Given the significant impact of input data and models on the results of catastrophe modeling, it is crucial to acknowledge that a different risk perception may emerge if the same process is repeated using more recent exposure data or improved seismic hazard and vulnerability models, which may become available in the future.

In the end, the authors of this paper highly advocate for ongoing research focusing on various components of risk, specifically hazard, exposure, and vulnerability. Additionally, the introduction of more state-of-the-art earthquake models is encouraged to foster a more comprehensive and accurate seismic risk assessment for the Iranian insurance market. Moreover, although the subject of the paper is not directly related to parametric insurance, the seismic risk model developed can be used to design a parametric product for earthquake, perhaps something useful for the public natural hazard insurance fund in Iran.

7 Appendix

Table A1: Riskiness of different construction types in Iran (Ghafory-Ashtiany, 1991)

Type	Building Typology	Level of Earthquake Hazard				
		1	2	3	4	5
1	Adobe and Traditional	1.0	1.1	1.2	1.5	1.8
2	Confined Masonry	0.8	0.9	1.0	1.4	1.6
3	Pre-code Steel Structure	0.6	0.7	0.8	1.1	1.4
4	Pre-code Reinforced Concrete	0.4	0.5	0.6	0.8	1.0
5	Code Based Buildings Design and Construction (Post 1991)	0.2	0.3	0.4	0.6	0.8

Note: Hazard levels are based on zones defined in ‘Iranian Code of Practice for Seismic Resistant Design of Buildings - Code 2800’ as 1: no, 2: low (0.2g), 3: moderate (0.25g), 4: high (0.3g), 5: very high (0.35g).

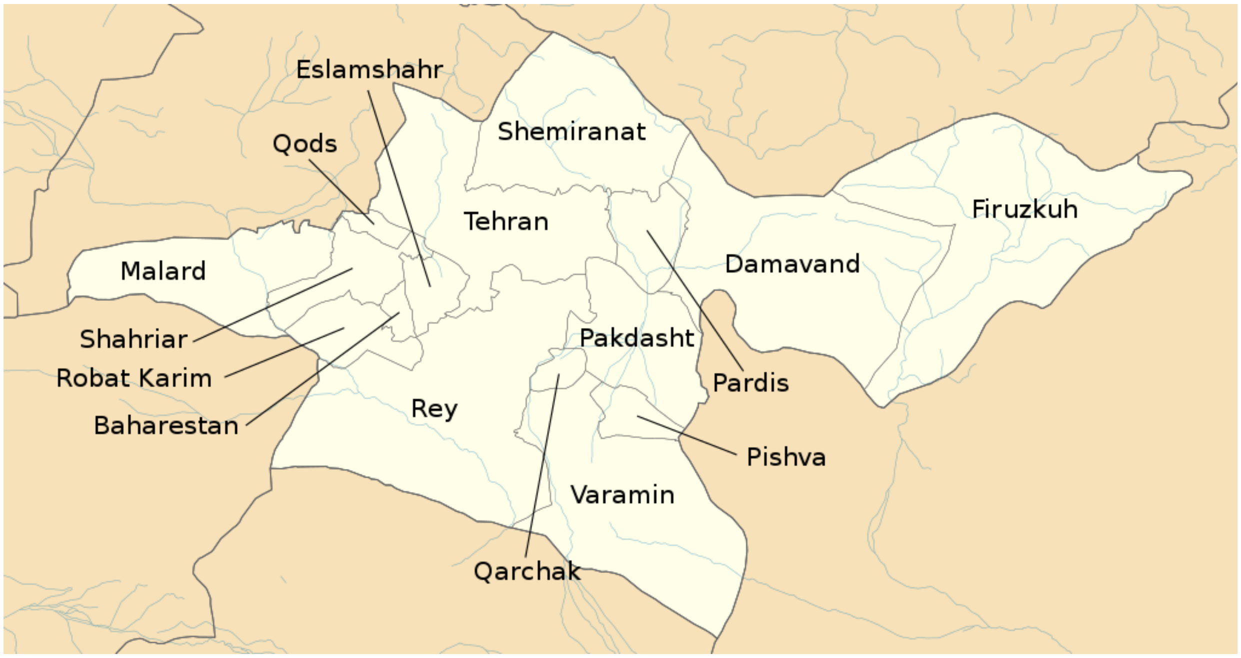


Figure A1: Tehran province and its counties

Table A2: Earthquake correlation matrix for Tehran province based on the methodology suggested by Solvency II

	Tehran	Shahriar	Eslamshahr	Baharestan	Malard	Pakdasht	Rey	Qods	Robat Karim	Varamin	Qarchak	Pardis	Damavand	Pishva	Shemiranat	Firuzkuh
Tehran	1															
Shahriar	0.5	1														
Eslamshahr	0.5	0.5	1													
Baharestan	0	0.5	0.5	1												
Malard	0	0.5	0	0	1											
Pakdasht	0.5	0	0	0	0	1										
Rey	0.5	0	0.5	0	0	0.5	1									
Qods	0.5	0.5	0.5	0	0.5	0	0	1								
Robat Karim	0	0.5	0.5	0.5	0.5	0	0	0	1							
Varamin	0	0	0	0	0	0.5	0.5	0	0	1						
Qarchak	0	0	0	0	0	0.5	0.5	0	0	0.5	1					
Pardis	0.5	0	0	0	0	0.5	0	0	0	0	0	1				
Damavand	0.5	0	0	0	0	0.5	0	0	0	0	0	0.5	1			
Pishva	0	0	0	0	0	0.5	0	0	0	0.5	0.5	0	0	1		
Shemiranat	0.5	0	0	0	0	0	0.5	0	0	0	0	0.5	0.5	0	1	
Firuzkuh	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	1

8 Data Availability

Data used in this research are the intellectual property of Iran National Science Foundation who funded the study and cannot shared by the authors.

9 Authors Contribution

In the preparation of this report, Prof. Mohsen Ghafory-Ashtiany has planned the research project and contributed to the content of different chapters mainly in the earthquake hazard and risk assessment and modeling and review and validation of results. Dr. Hooman Motamed has been mainly responsible for authoring the insurance regulation content and numerical analysis. Both authors have equally edited the final manuscript.

10 Competing Interests

The contact author has declared that none of the authors has any competing interests.

11 Acknowledgement

The authors would like to express their gratitude to Iran National Science Foundation for the financial support they provided for conducting this research work under the research project number 94811162.

12 References

Akkar, S. & Cagnan, Z., 2010. A local ground-motion predictive model for Turkey, and its comparison with other regional and global ground-motion models. *Bulletin of the Seismological Society of America,* pp. 2978-2995.

Akkar, S., Sandıkkaya, M. A. & Bommer, J. J., 2014. Empirical ground-motion models for point-and extended-source crustal earthquake scenarios in Europe and the Middle East. *Bulletin of earthquake engineering,* pp. 359-387.

Allen, T. I. & Wald, D. J., 2009. On the use of high-resolution topographic data as a proxy for seismic site conditions (VS30). *Bulletin of the Seismological Society of America,* p. 935–943.

Anderson, T. J., 2002. *Innovative financial instruments for natural disaster risk management,* New York: Inter-American Development Bank.

Atkinson, G. M. & Boore, D. M., 2003. Empirical ground-motion relations for subduction-zone earthquakes and their application to Cascadia and other regions.. *Bulletin of the Seismological Society of America,* pp. Vol. 93, 1703-1729.

Atkinson, G. M. & Boore, D. M., 2006. Earthquake ground-motion prediction equations for eastern North America. *Bulletin of the Seismological Society of America,* pp. 2181-2205.

Baione, F., De Angelis, P. & Granito, I., 2018. *On a capital allocation principle coherent with the Solvency II satndard formula,* New York: Cornell University.

Basel Committee on Banking Supervision, 2004. *Basel II: International Convergence of Capital Measurement and Capital Standards: A revised Framework,* Basel: Bank for International Settlements (BIS).

Bastami, M. et al., 2022. Development of hybrid earthquake vulnerability functions for typical residential buildings in Iran. *International Journal of Disaster Risk Reduction, Vol. 77,* p. https://doi.org/10.1016/j.ijdrr.2022.103087.

Bright, E., Rose, A., Urban, M. & McKee, J., 2017. *LandScan Global 2016 ,* s.l.: Oak Ridge National Laboratory.

Campbell, K. W., 2003. Prediction of strong ground motion using the hybrid empirical method and its use in the development of ground-motion (attenuation) relations in eastern North America.. *Bulletin of the Seismological Society of America,* pp. 1012-1033.

Chiou, B. S. G. & Youngs, R. R., 2008. An NGA model for the average horizontal component of peak ground motion and response spectra. *Earthquake Spectra,* pp. Vol. 1, 173-215.

Clarke, S., Mitchell, S. & Phelan, E., 2014. *Capital Management in a Solvency II World.* [Online] Available at: https://www.milliman.com/en/insight/2014/capital-management-in-a-solvency-ii-world/

Committee of European Insurance and Occupational Pensions Supervisors (CEIOPS), 2010. *Catastrophe Task Force Report on the Standardised Scenarios for the Catastrophe Risk Module in the Standard Formula.* [Online] Available at: https://register.eiopa.europa.eu/CEIOPS-Archive/Documents/Reports/CEIOPS-DOC-79-10-CAT-TF-Report.pdf

Council Directive, 1990. Council Directive 90/619/EECof 8 November 1990 on the coordination of laws, regulations and administrative provisions relating to direct life assurance, laying down provisions to facilitate the effective exercise of freedom to provide services and amendi. *European Union Official Journal,* pp. 50-61.

Council Directive, 1992. Council Directive 92/96/EEC on the coordination of laws, regulations and administrative provisions relating to direct life assurance and amneding Directives 79/267/EEC and 90/619/EEC. *European Union Official Journal,* pp. 1-27.

Danciu, L. et al., 2018. The 2014 Earthquake Model of the Middle East: seismogenic sources. *Bulletin of Earthquake Engineering, Vol. 16,* p. 3465–3496.

Deligiannakis, G., Zimbidis, A. & Papanikolaou, I., 2021. Earthquake loss and Solvency Capital requirement calculation using a fault/specific catastrophe model. *Geneva Papers on Risk and Insurance,* pp. https://doi.org/10.1057/s41288-021-00259-x.

Directive, 1992. Directive 92/49/EEC on the coordination of laws, regulations and administrative provisions relating to direct insurance other than life assurance and amending Directives 73/239/EEC and 88/357/EEC. *European Union Official Journal,* pp. 1-23.

Directive, 2002a. Directive 2002/83/EC of the European Parliament and of the Council of November 2002 concerning life assurance. *European Union Official Journal, No. L345,* pp. 1-51.

Directive, 2002. Directive 2002/13/EC of the European Parliament and the Council of 5 March 2002 amending Council Durective 73/239/EEC as regards the solvency margin requirements for non-life insurance undertakings. *European Union Official Journal,* pp. 17-22.

Directive, 2009. Directive 2009/138/EC of the European Parliament and the Council of 25 November 2009 on the taking-up and pursuit of the business of insurance and reinsurance (Solvency II). *European Union Official Journal,* pp. 1-155.

First Council Directive, 1973. First Council Directive 73/239/EEC on the coordination of laws, regulations and administrative provisions relating to the taking-up and pursuit of the business of direct insurance other than life assurance. *European Union Official Journal,* pp. 3-19.

First Council Directive, 1979. First Council Directive 79/267/EEC of 5 March 1979 on the coordination of laws, regulations and administrative provisions relating to the taking-up and pursuit of the business of direct life assurance. *European Union Official Journal,* pp. 1-18.

Ghafory-Ashtiany, M., 1991. *Earthquake Insurance in Iran,* Tehran: International Institite of Earthquake Engineering and Seismology (IIEES).

Ghafory-Ashtiany, M. & Nasserasadi, K., 2012. *Primary Earthquake Insurance Premium Indices for Iranian Buildings,* Tehran: Insurance Research Center (in Persian).

Gurenko, E. N. & Itigin, A., 2013. *Reinsurance as Capital Optimization Tool under Solvency II - Policy Research Working Paper,* New York: the World Bank.

Hashemi, S. A., Safari, A. & Kamali-Dolatabadi, M., 2010. Assessment of Solvency Margin of Insurance Companies in Iran. *Journal of Insurance Industry, vol. 25(2),* pp. 79-120.

High Council of Insurance, 2019. *Directive 69: Methods of calculating and monitoring the financial solvency of insurance institutions,* Tehran: Central Insurance of Iran.

Ibrion, M., Mokhtari, M. & Nadim, F., 2015. Earthquake Disaster Risk Reduction in Iran: Lessons and “Lessons Learned” from Three Large Earthquake Disasters—Tabas 1978, Rudbar 1990, and Bam 2003. *International Journal Disaster Risk Science, Vol. 6,* p. 415–427.

Kelly, G. & Stodolak, P., 2013. *Why insurers fail - Natural Disasters and Catasrophes,* Toronto: Property and Casualty Insurance Compensation Corporation (PACICC).

Kinder, U. & Ronkainen, V., 2004. Solvency II: towards a new insurance supervisory system in the EU. *Scandinavian Actuarial Journal, Vol. 6,* pp. 462-474.

Kohrangi , M., Bazzurro , P. & Vamvatsikos, D., 2021. Seismic risk and loss estimation for the building stock in Isfahan: part II—hazard analysis and risk assessment. *Bulletin of Earthquake Engineering,* Volume 19, p. 1739–1763.

Kousky, C. & Cooke, R., 2012. Explaining the failure to insure catastrophic risks. *Geneva papers on Risk and Insurance, Vol. 37, No. 2,* pp. 206-227.

Lawson, R. C., Card, N. & Vass, G., 2001. *Insurance Industry Catastrophe Management Practices,* New York: American Academy of Acruaries.

Linder, U. & Ronkainen, V., 2004. Solvencz II / Towards a new insurance supervisorz szstem in the EU. *Scandinavian Actuarial Journal, Vol. 6,* p. 462/474.

Lin, P. S. & Lee, C. T., 2008. Ground-motion attenuation relationships for subduction-zone earthquakes in northeastern Taiwan. *Bulletin of the Seismological Society of America,* pp. Vol. 98, 220-240.

Lloyd's and CAT Risk Solutions, 2017. *Seismic Shock, A new earthquake model for the Middle East,* London: Lloyd's.

Lotfi, A., Zafarani, H. & Khodaverdian, A., 2022. A probabilistic deformation-based seismic hazard model for Iran. *Bulletin of Earthquake Engineering,* 20(13), pp. 7015-7046.

Lotfi, A., Zafarani, H. & Khodaverdian, A., 2022. A Probabilistic Deformation-based Seismic Hazard Model for Iran. *Bulletin of Earthquake Engineering,* pp. Vol. 20: 7015-7046.

Maghsoudi, A. & Moshtari, M., 2020. Challenges in disaster relief operations: evidence from the 2017 Kermanshah earthquake. *Journal of Humanitarian Logistics and Supply Chain Management, Vol. 11, No. 1,* pp. 107-134.

Mansouri, B. & Amini-Hosseini, K., 2013. *Global Earthquake Risk Model (GEM) - Earthquake Model of the Middle East Region (EMME) - WP4: Seismic Risk Assessment, Final Report,* Tehran: IIEES.

Mirzaei, N., Gao, M. T., Chen, Y. T. & Wang, J., 1997. A uniform catalog of earthquakes for seismic hazard assessment in Iran. *Acta Seismologica Sinica English Edition, Vol. 10, No. 6,* p. 713–726.

Motamed, H., Calderon, A., Silva, V. & Costa, C., 2019. Development of a probabilistic earthquake loss model for Iran. *Bulletin of Earthquake Engineering, Vol. 17, No. 4,* p. pages 1795–1823.

Pagani, M., Garcia-Pelaez, J., Gee, R. & al., e., 2020. The 2018 version of the Global Earthquake Model: Hazard component. *Earthquake Spectra,* pp. 226-251.

Pakdel-Lahiji, N., Hochrainer-Stigler, S., Ghafory-Ashtiany, M. & Sadeghi, M., 2019. Consequences of Financial Vulnerability and Insurance Loading for the Affordability of Earthquake Insurance Systems : Evidence from Iran Consequences of Financial Vulnerability and Insurance Loading for the Affordability of Earthquake Insurance Systems. *Geneva Papers on Risk and Insurance, Vol. 40,* p. 295–315.

Rae, R. A. et al., 2018. *A review of Solvency II: Has it met its objectives?,* Cambridge: Cambridge University Press.

Sandström, A., 2019. *Models, Assessment and Regulation.* London: Chapman & Hall .

Second Council Directive, 8., 1988. of 22 June 1988 on the coordination of laws, regulations and administrative provisions relating to direct insurance other than life assurance and laying down provisions to facilitate the effective exercise of freedom to provide services and amendi. *European Union Official Journal ,* pp. 1-2.

Şeşetyan, K. et al., 2018. The 2014 Earthquake Model of the Middle East: overview and results. *Bulletin of Earthquake Engineering, Vol. 16,* p. pages 3535–3566.

Shahbazi, P., Mansouri, B., Ghafory-Ashtiany, M. & Käser, M., 2020. Introducing loss transfer functions to model seismic financial loss: A case study of Iran. *International Journal of Disaster Risk Reduction, Vol. 51,* p. https://doi.org/10.1016/j.ijdrr.2020.101883.

Shahriar, B. et al., 2016. *Review of the Method for Calculating and Monitoring the Financial Solvency of Insurance Firms,* Tehran: Insurance Research Center, Research Report No. 58.

Taherian, A. R. & Kalantari, A., 2019. Risk-targeted seismic design maps for Iran. *Journal of Seismology,* pp. Vol. 23, 1299-1311.

Tavakoli, B. & Ghafory-Ashtiany, M., 1999. Seismic hazard assessment of Iran. *Annali di Geofisica, Vol. 42, No. 6,* p. 1013–1021.

Thorburn, C., 2004. *On the Measurement of Solvency of Insurance Companies,* New York: World Bank Policy Research Working Paper 3199.

Toro, G. R., 2002. Modification of the Toro et al.(1997) attenuation equations for large magnitudes and short distances. *Risk Engineering Technical Report,* p. Vol. 10.

Yazdani, A. & Kowsari, M., 2013. Bayesian estimation of seismic hazards in Iran. *Scientia Iranica, Vol. 20, No. 3,* p. 422–430.

Youngs, R., Chiou, S., Silva, W. & Humphrey, J., 1997. Strong ground motion attenuation relationships for subduction zone earthquakes. *Seismological research letters,* pp. 58-73.

Zhao, J. et al., 2006. Attenuation relations of strong ground motion in Japan using site classification based on predominant period.. *Bulletin of the Seismological Society of America,* pp. Vol. 96, 898-913.