Seismic Risk Analysis of Metropolitan Tehran: A Link Between Hazard Analysis, Vulnerability Assessment and Loss Estimation Studies

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ABSTRACT

Metropolitan Tehran, as the capital, the economic and political center, and the most populated city in Iran, has a special position in earthquake preparation, mitigation and response. Tehran is vulnerable to earthquakes and is expecting a destructive earthquake with a magnitude greater than 7. In the present paper, the items of hazard analysis, vulnerability assessment, and loss estimation in respect of Tehran are introduced, and the relevant research concerning the category of physical and structural damage is investigated. The results from vulnerability assessment indicate the vulnerability of a major part of the buildings in Tehran. The results from the loss estimation indicate a high percentage of damage in the event of an earthquake in Tehran. Furthermore, based on the loss estimation results, the likely amount of debris generated and possibilities for positioning of the temporary housing are provided. The results emphasize the necessity of short-term, average-term and long-term policies for damage reduction and seismic reinforcement.

Keywords:
Earthquake; Tehran; Risk analysis; Loss estimation; Vulnerability assessment; Debris; Temporary shelter

1. Introduction

The estimation of earthquake risk is essentially dependent on the quantitative evaluation of ground shaking and the consequent reaction of structures. The gradual improvement in construction techniques and appropriate countermeasures are based on such works. Peak ground acceleration (*PGA*) and macro-seismic intensity have been the traditional base for seismic risk and loss assessment in this growing research field.

Although several different software programs utilize the recently developed risk assessment methodologies [1-3]; unfortunately, it is impossible to verify the estimated seismic scenario, the selected methodology and the defined assumptions, other than through a full-scale devastating earthquake. However, such programs enable us to calibrate our models and input parameters against such a catastrophe, and the results of different risk estimation methods can be compared. Generally, most risk and loss assessment studies, define individual scenario earthquakes as the main basis for planning [4-13].

Estimated intensities or ground motion acceleration information in maps of the mentioned studies are derived from the available information of regional geology and seismic activity. In addition to other types of input data (e.g., building stock, population density), they can be used to estimate the extent of damage to structures and lifelines as well as the impact on population. Such scenarios can be used to reduce the degree of damage from a possible future event and to prepare for it accordingly. Therefore, it seems that the usual loss study has concentrated on a single event that is applied in the long-term pre-event period, and is employed mainly by those concerned with seismic safety planning and disaster management.

In addition to the necessity to enhance life safety in respect of the structural behavior during earthquakes, it is also vital to evaluate the potential ability of emergency response agencies to respond to such seismic disasters. Emergency response services depend heavily upon the operability of urban lifelines, thereby giving rise to the importance of identifying more critical locations in which damage can impede the standard emergency response activities. Thus, such loss estimation tools should be localized.

The seminal paper on hazard by Cornell in 1968 [14] marked the departure of earthquake risk and loss estimation. Following the 1971 San Fernando earthquake, the prediction of human loss (number of casualties and injured used to estimate the needs in terms of health care and shelters in the immediate aftermath of a strong event) received strong emphasis. However, the disruption of the serviceability of roads, telecommunications and other important lifeline systems came to be the subject of later investigations [2-3].

Subsequently, the Federal Emergency Management Agency [15] began a study on seismic risk estimation for all regions of the United States using the national loss estimation tools *HAZUS*-99 and *HAZUS-MH*. Their main objective was to analyze and compare the seismic risk across regions in the *US* with different levels of hazard, arising from different population densities or physical structural vulnerability.

Japan and Taiwan, as described by Yamazaki [16] and Yeh et al [17], respectively, have currently replaced the rapid loss estimation systems. Their available options are greater than most regions of this area, due to the relatively denser network of seismic instrumentation and the high level of automatic system monitoring that currently exists. Nevertheless, the situation that exists, and methodologies that are currently employed in these countries, should help the selection of a loss estimation framework that is capable of incorporating at least the level of sophistication, in terms of seismic monitoring, that is currently observed in these countries.

As can be seen, there is a real need for a seismic risk analysis system for the cities in Iran, especially Tehran the capital. In the following sections, after introducing the available earthquake loss estimation software, the Hazard Analysis, Vulnerability Assessment and Loss Estimation in a seismic risk analysis framework for Metropolitan Tehran, in respect of physical and structural damage, are investigated and the results are discussed.

2. Earthquake Loss Estimation Software (ELE)

This section reviews Earthquake Loss Estimation (*ELE*) software tools that have been developed worldwide in recent years. Fifteen software packages are identified and summarized in Table (1). In addition, descriptions of these seismic damage analysis software packages are provided in Table (2).

*HAZUS-MH MR*2, in its latest version, includes near-real-time analysis capabilities for rapid post-event response. Some secondary hazards (liquefaction, fault rupture, landslide) are also considered. Damage states for the general building stock are estimated, as well as for lifeline systems. Essential facilities and large-potential-loss facilities are also considered, which are calculated at the census tract level and include both social (casualties, homeless, disruption) and economic loss.

EPEDAT is a software package developed by *EQE* International, Inc. It has been developed to provide an "integrated real-time information system capable of providing a new level of decision support for emergency responders in the critical minutes and hours following a major damaging earthquake" [18].

INLET, as a web-based loss estimation tool, stores the data, model updates and results on a centralized system, which can be cascaded to users via online Internet Map Servers. Thus, the consistency of the information available to all users at any time is ensured. A simplified implementation of the *HAZUS* models provides the loss estimation methodology.

SES 2002 is for the evaluation of potential earthquake losses in Spanish cities. The loss estimations are based on intensity and limited to the general building stock. Losses are expressed in terms of social impact (number of fatalities, injured and homeless), as well as in terms of the number of dwellings with respect to each damage state. (L.M. Barranco, personal communication, 2006).

SELENA is based on the *HAZUS* methodology. It is a Matlab-based software package, which is currently under development at *NORSAR* [19]. The current version is validated for the Oslo area [20] and is calibrated to Norwegian conditions in terms of ground-motions, and uses the *HAZUS* capacity and vulnerability curves. In order to replace the conventional *ATC*-40 [21] the secant-stiffness method has

Table 1. Introduction and specifications of different damage evaluation software packages.

ELE Software	Owner or Developer	Applicability Region	Validation Regions	Complete Name	Commercial GIS Required	Other Software Required
HAZUS-MH	FEMA/NIBS	United States	Los Angeles region (Northridge data)		ArcView 9.1 SP1*	none
EPEDAT	EQE International, Inc. for California Governor's Office of Emergency Services	United States (California)	Los Angeles region (Northridge data)	EPEDAT (Early Post-Earthquake Damage Assessment Tool	MapInfo	none
REDARS	MCEER/FHWA	United States	Shelby County, Tennessee; Los Angeles region	Risks from Earthquake Damage to Roadway Systems	none	none
INLET	Image Cat, Inc. for RESCUE Project	United States (Southern California)	Los Angeles County; Orange County	INLET (Internet-based Loss Estimation Tool	none	none
SES 2002	Spanish Civil Protection	Europe (Spain)	Catalonia	Simulation de E scenarios Seismicos	Map Objects 2.1	none
SIGE/ ESPAS	Italian Civil Protection Department	Europe (Italy)	Region affected by the 31/10/2002 Molise-Puglia earthquake.		none	none
KOERILOSS	KOERI for LESSLOSS Project in Istanbul	Europe	Istanbul	by the Kandilli Observatory and Earthquake Research Institute (KOERI)	Version 1.0 runs under MapInfo; ArcView-compatible version under development	none
LNECLOSS	LNEC for LESSLOSS Project in Lisbon	Europe (Portugal)	Lisbon Metropolitan Area	developed by the Laboratorio National de Engenharia Civil (LNEC)	none	any data plotting software
SELENA	NORSAR Europe DBELA ROSE School/EU-Centre in Pavia	Europe	Oslo	Seismic Loss Estimations using a logic tree Approach	none	optional ArcView-compatible output Matlab
DBELA	ROSE School/EU-Centre	Europe	Marmara region, Turkey	A (Displacement-Based Earthquake Loss Assessment	none	any data plotting software
EQSIM	Karlsruhe University	Europe	Bucharest		information not available	information not available
RADIUS	OYO Corporation for United Nations ISDR Secretariat	World	9 urban centers (Addis Ababa, Ethiopia; Guayaquil, Ecuador; Tashkent, Uzbekistan; Tijuana, Mexico; Zigong, China; Antofagasta, Chile; Bandung, Indonesia; Izmir, Turkey; Skopje, TFYR Macedonia)	Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disasters	none; optional ArcView-compatible output	Excel 97
QUAKELOSS	ESRC/WAPMERR	World	Areas affected by 513 earthquakes (a-posteriori calculations) and 31 earthquakes (near-real-time calculations) that occurred worldwide between 1980 and 2003	developed at the Extreme Situations Research Centre (ESRC)	information not available	none
NHEMATIS	Canadian Civil Protection	World (Canada)	Vancouver, Edmonton, Ottawa-Carleton, Montreal and Fredericton municipalities; British Columbia region	Natural Hazards Electronic Map and Assessment Tools Information System	ArcView 3.1; not compatible with higher versions	none
EQRM	Geoscience Australia	World (Australia)	Newcastle; Perth	Earthquake Risk Management	none	Matlab

Table 2. Description of different seismic damage analysis software packages.

Forecasting Models Considered in Available ELE Packages		
Deterministic-Predicted	User-Specified Earthquake	All of ELE Except of SES 2002
	User-Specified Ground Motions	HAZUS-MH, REDARS, LNECLOSS and SELENA
Deterministic-Observed	Historical Ground Motions	HAZUS-MH, REDARS, INLET and QUAKELOSS
	Automated Ground Motions	HAZUS-MH, EPEDAT, REDARS and INLET
Probabilistic	Poisson Model	HAZUS-MH, REDARS, SES 2002, KOERILOSS, SELENA, DBELA and EQRM
	Time-Dependent	None
Earthquake-Related Hazards Considered in Available ELE Packages		
Ground Shaking	All of ELE	
Liquefaction	HAZUS-MH, EPEDAT, REDARS, DBELA and NHEMATIS	
Fault Rupture	HAZUS-MH and REDARS	
Landslide	Only HAZUS-MH	
Tsunami/Seiche	Only HAZUS-MH	
Inventory Elements for Which Direct Physical Damage is Calculated in Available ELE Packages		
General Building Stock	All of ELE Except of REDARS	
Essential Facilities	Only HAZUS-MH	
Large Loss Potential Facilities	None	
Transportation Lifelines	HAZUS-MH, EPEDAT, REDARS, INLET, KOERILOSS and RADIUS	
Utility Lifelines	HAZUS-MH, EPEDAT, KOERILOSS and RADIUS	
Social Losses Computed		
Fatalities	All of ELE Except of REDARS, SELENA and DBELA	
Injured	All of ELE Except of REDARS, SELENA, DBELA and INLET	
Homeless	HAZUS-MH, EPEDAT, INLET, SES 2002, KOERILOSS, LNECLOSS and NHEMATIS	

been implemented. An innovation with respect to the *HAZUS* methodology consists of the inclusion of the epistemic uncertainty on the ground-motion model through the specification of user-defined weights for the *GMPE* considered. At this stage, other epistemic uncertainties are excluded.

DBELA is currently being developed at the *ROSE* School/*EU*-Centre in Pavia [1]. As an advanced loss estimation tool, its procedure uses mechanically derived formulae to describe the displacement capacity of classes of buildings (grouped by structural type and failure mechanism) at three different limit states. This enables a direct comparison of displacement demand and capacity at any period. Its comprehensive consideration of the uncertainties involved in the estimation of both demand and capacity is another innovation of *DBELA*.

QUAKELOSS aims to rapidly determine human losses in developing countries, in order to assess the necessity of rescue operations. It provides near-real-time estimates (within two hours) of building damage and casualties (fatalities and injuries) for a database of about 2 million settlements for which population data and a typical building fragility profile are available or can be inferred from the available data.

GEM will build a global-owned model for the assessment of seismic risk on a global scale by 2013. There is a need for seismic risk information to become accessible to a wide spectrum of organizations and individuals around the globe. In response to this need, the Global Earthquake Model (*GEM*) initiative aims to establish uniform open standards to calculate and communicate earthquake risk worldwide, by developing a global, state-of-the-art and dynamic earthquake risk model together with the community, and ensuring it has understandable interfaces and tools for *GEM's* multitude of stakeholders. Three scientific modules form the underlying basis of *GEM's* Global Earthquake Risk Model -Seismic Hazard, Seismic Risk and Socio-Economic Impact- to allow for integral risk modeling and assessment [22].

EQRM [23], as an adaptation of *HAZUS* [15] methodology, includes a number of modifications to adapt to Australian conditions and is similar to *SELENA* [20]. It does not require any *GIS* software, as it has been written in Matlab.

3. Hazard Analysis

Tehran, with a population of more than eight million [24], is located at the foot of the Alborz Mountains, which form part of the Alpine-Himalayan Orogenic Belt. Tehran consists of 22 districts, 144 areas, and approximately 1,500 neighborhoods.

It is geographically located in a position with active faults with different seismic powers, including the Mosha-Fasham Fault, North Tehran Fault, Niavaran Fault, Telo Paeen Fault, Mahmoudieh Fault, Shian and Kosar Fault, North Rey Fault, South Rey Fault, Kahrizak Fault, Garmsar Fault, Pishva Fault and Parchin Fault, see Figure (1). There are also secondary faults in this area including the Narmak Fault, Shadabad Fault, Davoudieh Fault, Abbas Abad Fault, and Bagh-e-Feyz Fault.

Although Tehran has not experienced severe seismic damage in the last 150 years, it has had several major earthquakes in its history, see Table (3). The latest earthquake in Tehran with a moment magnitude of more than 7 occurred in 1830 [26]. Therefore, considering the large number of faults in Tehran and the history of their activities, it is entirely probable that it will experience another earthquake in the foreseeable future.

As the most politically and economically important city in the country [26], Tehran has experienced rapid urban development and increasing population density in recent decades; however, appropriate

Table 3. Specification of past earthquakes in the vicinity of Tehran with epicenter less than 200km [25].

Year	Month	Day	M_W	Latitude (Degrees)	Longitude (Degrees)	Epicentral Distance (Km)
743			7.1	35.30	52.20	81
855			7.0	35.60	51.50	12
856	12	22	7.9	36.20	54.30	263
864	1		5.4	35.70	51.00	41
958	2	23	7.7	36.00	51.10	46
1119	12	10	6.4	35.70	49.90	140
1177	5		7.1	35.70	50.70	68
1301			6.6	36.10	53.20	164
1485	8	15	7.1	36.70	50.50	140
1608	4	20	7.6	36.40	50.50	116
1665			6.4	35.70	52.10	59
1687			6.4	36.30	52.60	123
1809			6.4	36.30	52.50	116
1825			6.6	36.10	52.60	113
1830	3	27	7.0	35.80	51.70	25
1868	8	1	6.3	34.90	52.50	130
1930	10	2	5.4	35.78	52.02	52
1957	7	2	6.7	36.20	52.60	118
1962	9	1	7.1	35.54	49.39	187
1983	3	26	5.3	36.12	52.21	83
1990	6	20	7.4	36.96	49.39	232
1994	11	21	4.5	35.90	51.88	45

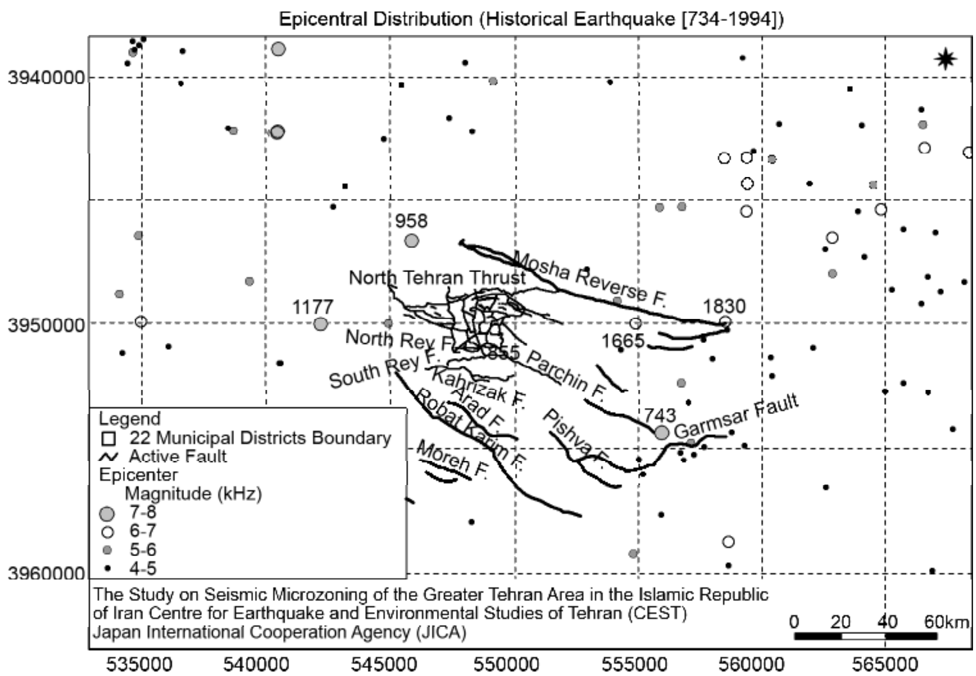

Figure 1. Map of Tehran faults [25].

earthquake mitigation measures have not been given high priority [25].

One of the most important reasons for damage to the buildings in Tehran is the high probability of soil liquefaction in certain urban areas (southern parts), road construction in steep slopes (northern Tehran areas) and sudden sinking (in weak grounds like Yousef-Abad and southern Tehran). The results of liquefaction hazard analysis show that part of south Tehran has the potential for liquefaction. Figure (2) shows the value of liquefaction potential in Tehran [27]. In addition, the high density of population, old city texture and narrow passages, intensify the impact of earthquakes. The most obvious problems after the earthquake are chaos and lack of safety, lack of relief and rescue teams, disconnection of water and power lines, as well as fires caused by explosions in gas pipes. Thus, in order to analyze an earthquake in Tehran, three fields should be investigated - seismicity, vulnerability and damage evaluation [25].

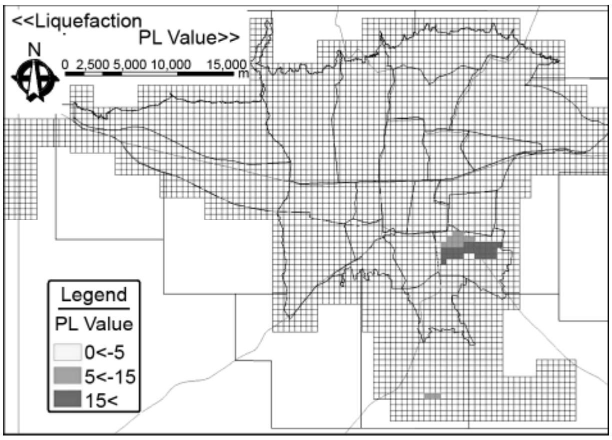

Figure 2. The value of liquefaction potential in the Tehran area [32].

The following studies have been conducted on the seismic analysis of Tehran:

- Zare et al [28], Zare et al [29], Zare et al [30] and Zare [31] suggested the empirical attenuation equation for different strong motion parameters *PGA*, *PGV* and *PGD*, both horizontal and vertical. Hypocentral distance, moment magnitude and site conditions are the independent variables. The dataset included 468 three-component accelerograms recorded from 1975 to 1997 from central Iran, the Alborz region and the Zagros belt of events with a magnitude range of M_W 2.7 to M_W 7.4 and hypocentral distances from 4 to 224*km*. The data set has events with focal mechanisms corresponding to pure strike-slip events, strike-slip with reverse faulting, pure reverse and pure vertical plane faulting [30-31].

Magnitudes greater than $M_W = 7.0$ and distances less than 20*km*, and for magnitudes greater than M_W 6.0 and distances less than 10*km* have been noted by this author. The ground motion may not be predicted accurately by the relationship [30-31]. This correlation shows that M_W is considered to be equal to M_s for magnitudes greater than 6 and equal to m_b and M_L for magnitudes less than 6. Regression coefficients for spectral acceleration corresponding to 146 frequencies and 5% damping, between 0.1*Hz* and 50*Hz* are available. Figure (3) shows the attenuation of horizontal for Peak Ground Acceleration

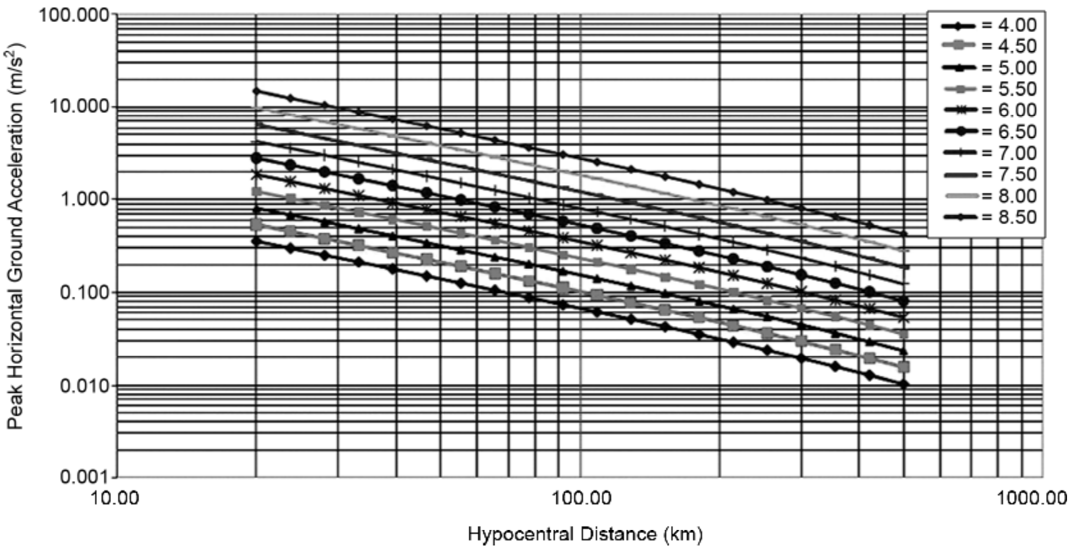

Figure 3. Attenuation of horizontal for peak ground acceleration with hypocentral distance (Mean +1σ) - Strong motion attenuation relationship for Iran - [30-31].

with hypocentral distance.

Zare et al [30] studied the Iranian strong motions database to obtain the attenuation of Iranian strong motions. This database contains more than 6,000 recorded three-component data (analog and digital) for which the teleseismic source parameters were available or calculated from the records. Here, in order to develop the attenuation model, the one-step regression method is used. As for deriving the empirical attenuation laws for different response spectral ordinates at different site conditions, the spectral values of the recorded strong motions in Iran are used. The empirical relationships are established for the spectral acceleration as the function of moment magnitude, hypocentral distances, and constant parameter representing the site conditions. The data set consists of 87 three-component accelerograms, all recorded in 1975-2003. Zare et al [30] proposed that the attenuation coefficients are in general accordance with the previous attenuation coefficients established for Iran. The spectral values gained here are, however, greater in comparison than those obtained by the previous studies (1999 and 2006). Selecting greater motions, recorded in closer proximity to the seismic source might be the reason for this difference [30].

The method proposed by Joyner and Boore [33], and Fukushima and Tanaka [34] was employed to establish the attenuation relationships for Iran. A one-step regression is used to fit a model to multiple independent variables (magnitude, distance, site parameters, etc.). In the two-stage methods, the parameters controlling distance dependence and a set of amplitude factors, one for each earthquake, are determined in the first stage by maximizing the likelihood of the set of observations. The parameters controlling magnitude dependence are then determined in the second stage by maximizing the likelihood of the set of amplitude factors [35]. In the one-step method, all parameters are gained simultaneously by maximizing the likelihood of observations. This approach yielding results similar to the two-step method for the spectral ordinates [36] is used by Joyner and Boore [33] and Brillinger and Pristler [37].

- Khademi et al [38] have prepared attenuation of peak and spectral accelerations in the Persian Plateau based on 160 horizontal records in the magnitude range 3.4-7.4 in the distance range from 0-180*km*. The Khademi relation is based on data from a presumably compression regime (not specified regions in Iran); however, unexpected low attenuation is observed. The predicted accelerations from this relation are extremely high for all magnitudes and distances, indicating also a low scaling with increasing magnitude, giving rise to caution [38]. The attenuation of horizontal peak ground acceleration with rupture distance is presented in Figure (4).
- Zafarani et al [39] generated six random horizontal components of motion based on a 5*km* grid of stations within a 110*km*x95*km* rectangular region, which covers the Tehran area, for generic rock condition based on the finite source stochastic method [40] for all the hypothetical scenarios (7x6=42, a total of 42 simulated records for each station). Path

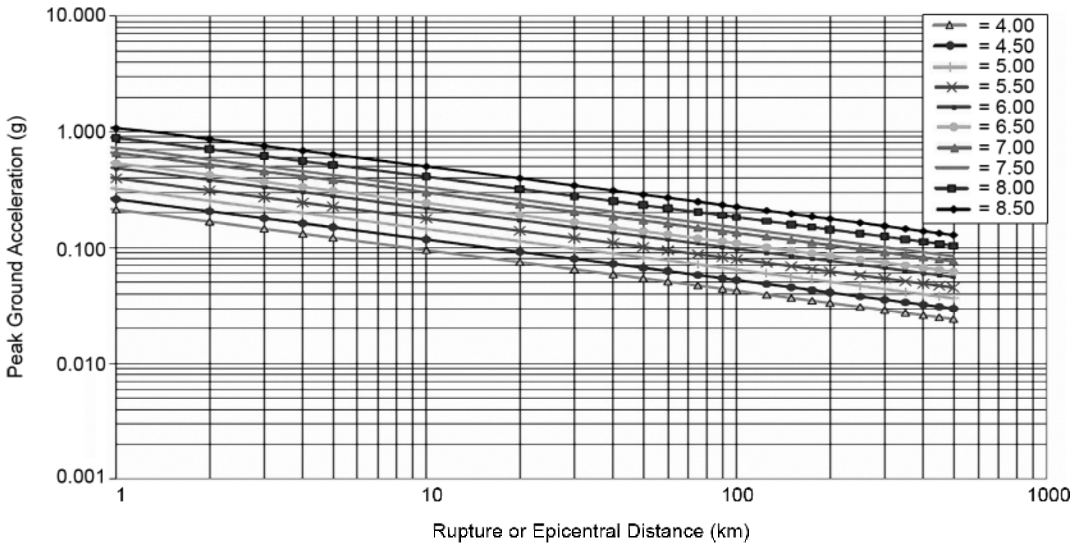

Figure 4. Attenuation of horizontal peak ground acceleration with rupture distance (mean values) for the Persian plateau [38].

[41] and site effects [40] in these simulations are derived from using synthetic *PHA* values for generic rock conditions, as shown in Figure (5), with a contour interval of 50 and 100*cm/s/s*, as well as the location of the three fault planes employed to model the source of the scenario earthquakes. The largest ground motion in Tehran results from rupture along the North Tehran fault. In this case, for *M* 7.2, the calculations predict *PHAs* at rock sites in Tehran between 80 and 700*gal* [39].

All districts will experience damaging ground motions of 0.2*g* and greater; however, if the worst-case scenarios for each site take place, the area of the highest seismic hazard is the one confined between the North Tehran and Ray faults. The closer the regions are to the fault trace, the stronger the shaking experienced. If the worst-case scenario for each site takes place, potentially damaging ground motions of 0.1*g* and greater will extend along the west and south of the city at distances of 10-35*km* from the city border. This data can be quite helpful in deeper microzonation studies [39].

- Ghodrati et al [42] used *SEISRISK III* [43] for probabilistic seismic hazard assessment and calculated *PGA* of Tehran. Because of the incompleteness and low accuracy of the recorded data (due to the lack of a dense seismography network), and as it is based on the existing data and previous research related to the studied region, the *SEISRISK III* software is appropriate for this assessment. Figure (6) shows the final seismic zoning map (*PGA* over bedrock) of Tehran and its environs using logic tree for a return period of 475 and 950 years [42].

4. Vulnerability Assessment of Tehran Buildings

Building vulnerability is the measurement of the damage a building is likely to experience when it is subjected to ground shaking of a specified intensity.

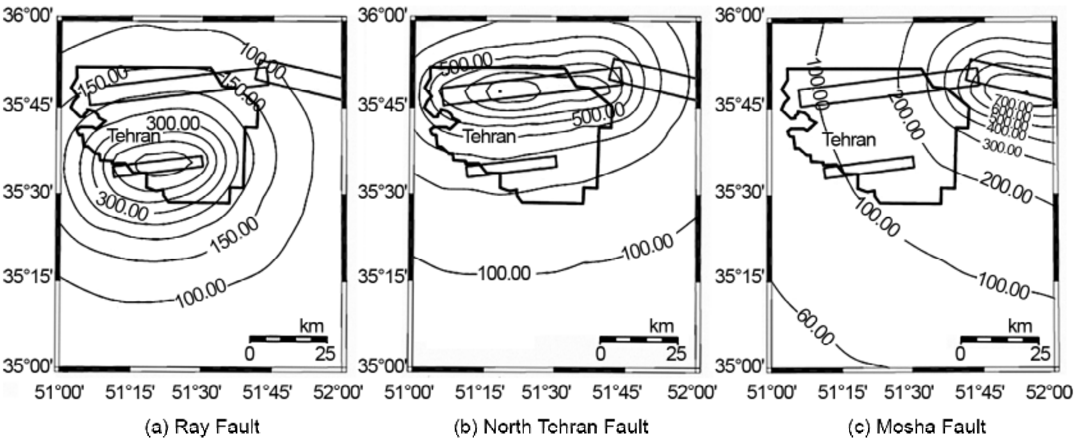

Figure 5. Synthetic PHA (100cm/s/s interval contours) map at rock for the assumed scenario earthquake along. The projection of the the three fault models is also shown. PHA values correspond to rock conditions [39].

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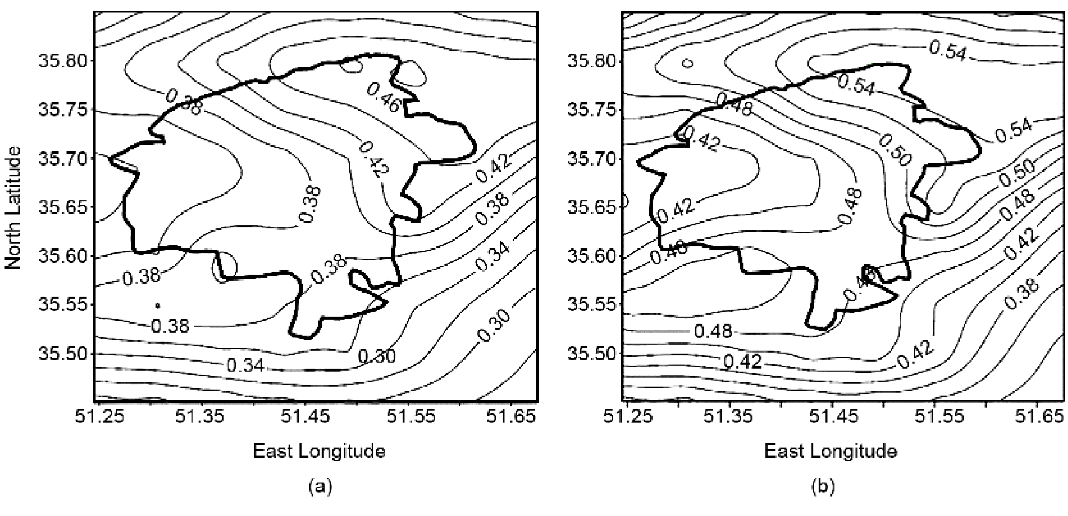


Figure 6. Two-dimensional zoning map showing accelerations in g for (a: 475; b: 950) year return period [42].

Vulnerability evaluation may employ qualitative or quantitative methods. The vulnerability of the buildings can be evaluated based on different approaches, including damage observation, expert judgment and analytical models. The way a structure dynamically responds to an earthquake depends on a number of interrelated parameters that are often very difficult, if not impossible, to precisely predict, thus, making it very complex. These include the exact character of the ground shaking the building will experience; the extent to which the structure will be excited by and respond to the ground shaking; the strength of the materials in the structure; the quality of construction, the condition of individual structural elements as well as the whole structure; the interaction between structural and non-structural elements; and the live load present in the building at the time of the earthquake. Although most of these factors can be estimated, they are never known exactly. Thus, the vulnerability curves have to be developed within levels of confidence.

Kircher et al [44] noted that: "Fragility curves predict the probability of reaching or exceeding specific damage states for a given level of peak earthquake response. The probability of being in a particular state of damage, the input used to predict building-related losses, is calculated as the difference between fragility curves". The distribution of these curves, or more appropriately their probabilistic nature, is also highlighted by Akkar et al [45]: "Generically, fragility curves are conditional cumulative distribution functions that define the exceeding probability of a damage state for a given ground motion intensity level, see Table (4). The probability distribution function is the standard lognormal distribution in most cases, and the curves represent median fragility values".

The seismic vulnerability for a built system is defined as its susceptibility to suffer a certain level of damage if subjected to an earthquake. It is possible to build the fragility curves using three methods in consideration of how and based on what knowledge the methods have been derived [47]:

- Analytical methods based on the mechanical calculation of the structural response of the building.
- Expert judgment based methods.
- Observed vulnerability methods (also referred to as the empirical approach or statistical method) based on statistical observations of recorded damage data of past events as a function of the intensity felt.

Several studies have been conducted on the vulnerability assessment of Tehran, such as Japan's International Cooperation Agency (*JICA*) [25], Jalalian fragility curves for masonry structures [48], Omidvar and Derakhshan fragility curves using observational methods [49-50] and fragility curves based on expert judgment method [51-52], which are provided for different residential buildings.

Generally, a building is destroyed when the seismic demand exceeds its seismic capacity. The fragility curves can be obtained given the specifications of seismic force, such as effective surface acceleration or earthquake intensity on *MMI* scale. The *JICA* project [25] classifies the residential buildings into nine groups according to their type of structure and age. Then, through collecting the records of catastrophic earthquakes (studying the Tavakoli and Tavakoli equation [26] regarding the relation between *PGA* and damage to villages in the 1990 Manjil earthquake) and extraction of local experience damage function, the relationship between the seismic force and the amount of damage is

Table 4. Comparison of various schemes to define damage states within loss estimation methodologies [46].

ATC-13		**Vision 2000**		**HAZUS99**		**FEMA 273/356**	
(ATC 1985)		(SEAOC 1995)		(FEMA 1999)		(FEMA 2000)	
Damage State	%Loss	Damage State	%Loss	Damage State	%Loss	Damage State	%Loss
Non	0	Negligible	0-2	Non	0-2	Very Light	0-1
Slight	0-1	Light	2-10	Slight	2-10	Light	1-10
Light	1-10	Moderate	10-50	Moderate	10-50	Moderate	10-50
Moderate	10-30	Severe	50-100	Extensive	50-100	Severe	50-100
Heavy	30-60	Complete	100	Complete	100		
Major	60-100						
Destroyed	100						

calculated. The numerical relation between the kinetics of the earthquake and the damage was obtained from reference [26], as the only available reference for brick-steel structures in Iran. Therefore, it was selected as the basic equation for the determination of vulnerability of other structures, using the transfer method of "damage proportion" curves on the scale of earthquake intensity, in order to calculate the vulnerability function for brick-steel structures, see Figure (7).

The fragility curves provided by Jalalian for masonry structures, see Figure (8), and the fragility curves used in concrete structures are for damage levels of 0-30% and 60-100%. Due to the lack of information on steel structures, no information has been provided for these structures. In these curves, *PGA* is utilized as the earthquake force parameter [48].

Omidvar et al [49] and Derakhshan [50] suggested a model for evaluating the vulnerability of the Iranian buildings using an observational method following a brief review of the vulnerability assessment methods in Iran and other countries. This method enables the vulnerability assessment for numerous sets of buildings by defining the vulnerability curves for each building type based on the observation of damage for previous earthquakes. In order to define the vulnerability curves, a building typology classification is presented in this article, as a sample of Iranian building characteristics. The hazard is described in terms of the macroseismic intensity, and the *EMS*-98 damage grades have been considered for classifying the physical damage to the buildings. The resulting vulnerability and fragility curves, which would be useful for further loss estimation could be used in GIS-based programs.

The sample typology of the current building stock that prevails in the built environment in Iran, considered the following items:

- Developing vulnerability models to describe the relation between potential building damage and the adopted seismic hazard determinant;
- Developing fragility models to define the probability of exceeding, or being in a given damage state as a function of response spectral parameters, based on analytical studies and expert judgment;

The probabilistic distribution of different damage states for *RC* buildings produced by Omidvar et al is shown in Figure (9) [49].

Figure (10a) shows the comparison between the proposed Iranian vulnerability curves and the

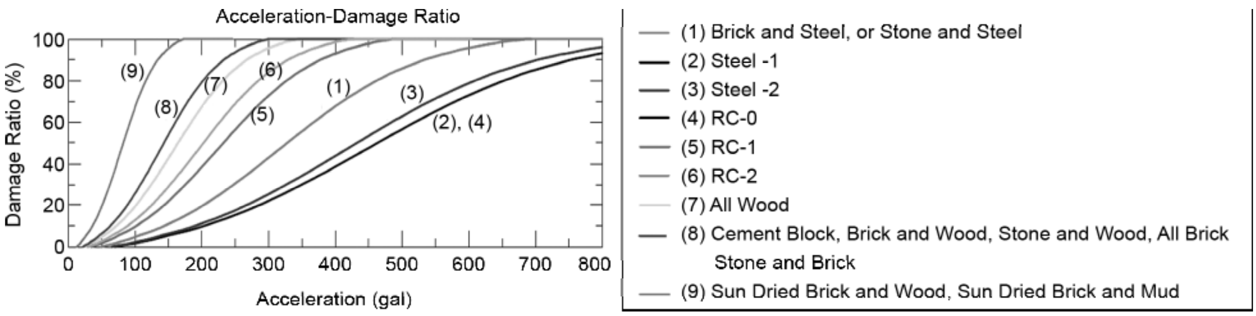


Figure 7. Vulnerability function of residential buildings applied in the study [26] .

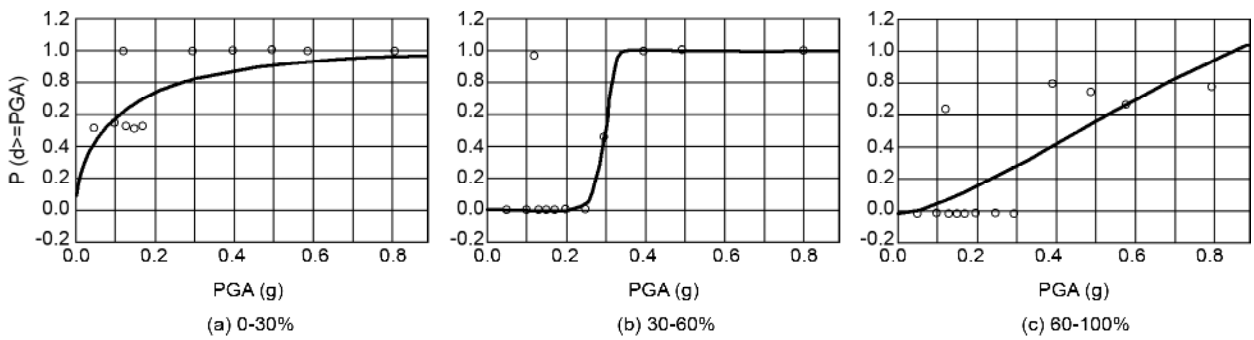


Figure 8. The fragility curves for masonry structures in damage levels of 0-30% and 60-100% [48] .

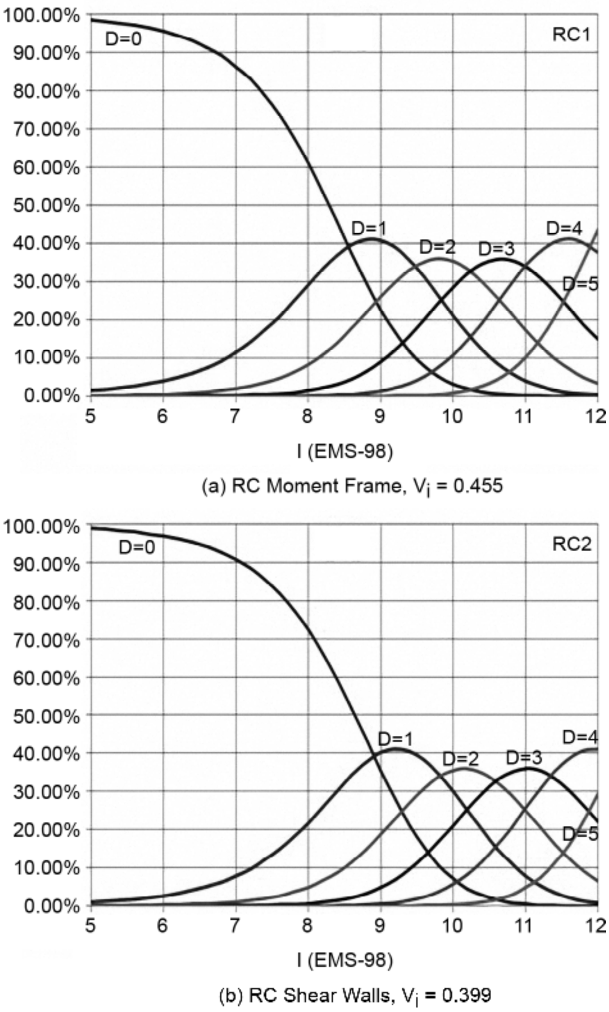


Figure 9. Probabilistic distribution of different damage grades for RC buildings [49]. Damage State: D0=None; D1=Slight; D2=Moderate; D3=Heavy; D4=Very heavy; D5=Destruction.

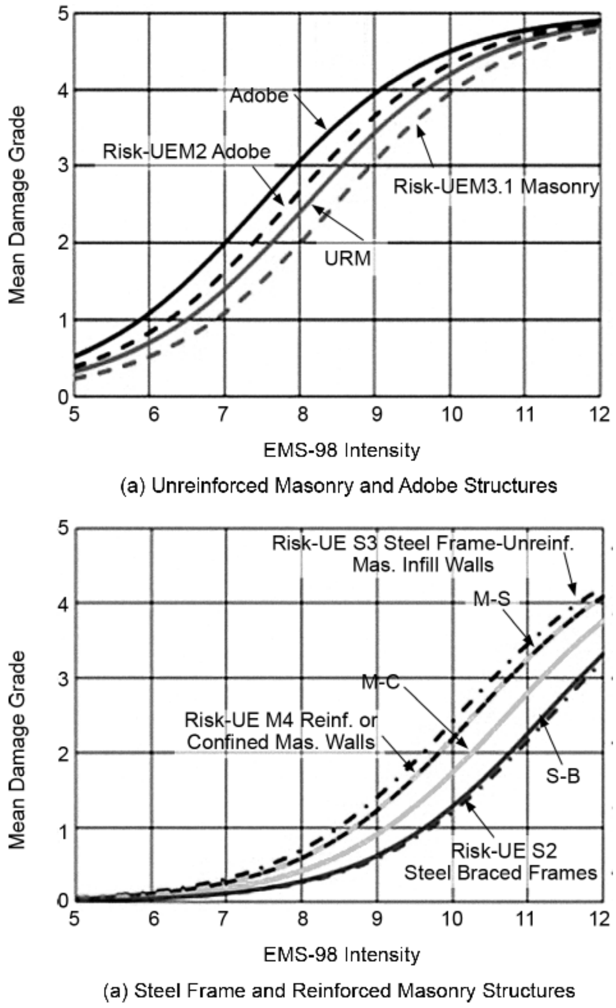


Figure 10. Comparison between the Iranian data and the Risk-UE vulnerability curves [51].

Risk-UE [51] vulnerability curves for the unreinforced masonry and adobe structures. It can be seen that for the same type of building, the vulnerability level is higher for the Iranian construction for non-engineered buildings than the European buildings. The difference is less important and is not evident for engineered buildings, see Figure (10b).

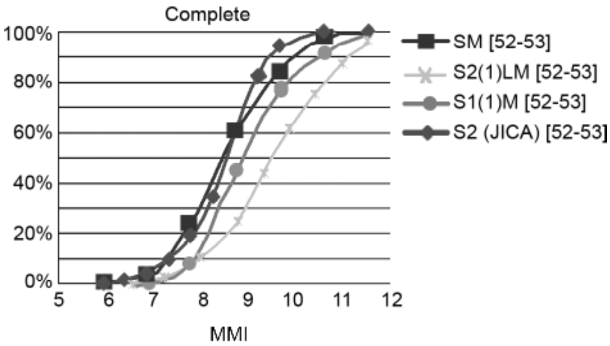
Omidvar and Shirazi [52], and Shirazi [53], in another method, used expert judgment for calculation of damage probability matrices for the vulnerability of Tehran buildings. In this method, buildings are categorized according to their construction material, their structure system and their height, into 45 categories and five destruction levels. According to the assumed damage, factor values and the damage probability matrices for each category are based on expert judgment.

The results obtained in this study are more conservative than the similar damage probability matrices in other countries, such as ATC13 [54] and other RISK-EU damage curves, and fairly optimistic in comparison with the JICA study and the damage curves from some of the most recent earthquakes in Iran, such as Qir (1972), Manjil (1990) and Ardekul (1997). The obtained fragility curves for different buildings can be seen in Figure (11) [52-53].

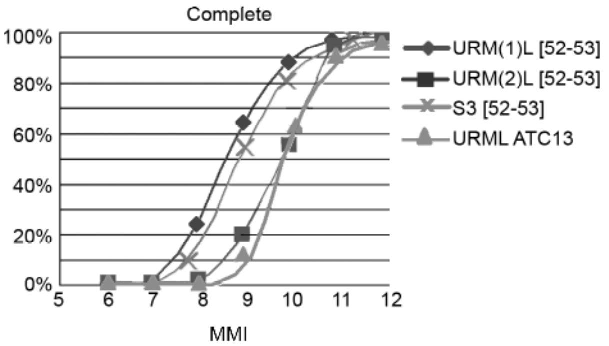
5. Loss Estimation

In order to manage a disaster, such as an earthquake, an estimation of the extent and level of destruction is important concerning two aspects. On the one hand, it is essential for initial decision-making and planning in response to an earthquake, and on the other hand, it has an important role in the preparation for earthquakes and allocation of resources. Therefore, developing a model for the estimation of damage to buildings after the earthquake is a must in disaster management.

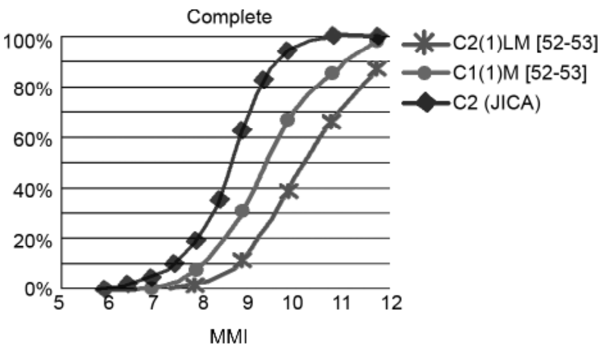
Loss assessment requires information from different fields, such as city texture, information concerning the structure of buildings, population density, and geographical position of faults. Considering that the major part of this information depends on the geographical position, utilizing the positional data and the science and techniques regarding Geographical Information Systems (*GIS*) provide a more practical and effective loss assessment.



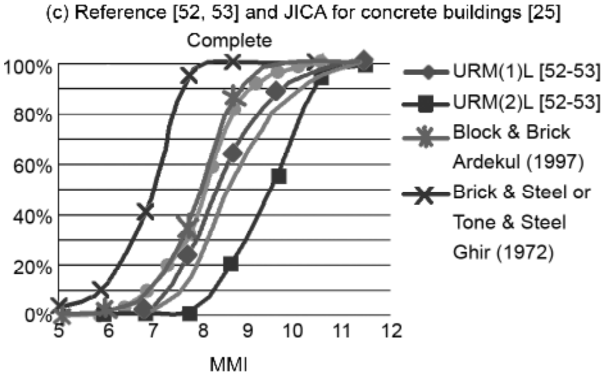
(a) Reference [52-53] and ATC 13 for Masonry Buildings [54]



(b) Reference [52-53] and JICA for Steel Buildings [25]



(c) Reference [52, 53] and JICA for concrete buildings [25]



(d) Reference [52-53] and Experimental Damage Curves of Qir-Ardekul for Masonry Buildings [26]

Figure 11. Comparison of fragility curves for complete damage level obtained from (a), (b), (c), and (d).

In this section, the results from the loss assessment of Tehran are presented, employing the information from *JICA* [25], Bazgard et al [55] and Bazgard [56], for the residential buildings of municipal district No. 1, Tehran; Saebi [57] and Omidvar et al [58] for debris estimation of the same district; and the work of Omidvar et al [59] and Baradaran-Shoraka [60] regarding temporary housing of the same area, based on damage analysis results and using the multi-attribute decision making method.

JICA studies were conducted on the basis of investigations and research on major faults of Tehran and the documentation of historical earthquakes affecting Tehran since 743 *AD*. *JICA* provided three scenarios concerning the activation of the three main faults and a scenario for the activation of hidden faults beneath the sedimentary layers of Tehran. Hence, there are four models for earthquake scenarios in Tehran, including the "Rey Fault" model, "North Tehran Fault" model, "Mosha Fault" model and Floating model [25].

In the *JICA* report, in order to assess the damage to buildings, the residential and commercial buildings, factories, public places, such as schools, hospitals and fire stations, are studied separately, and the damage resulting from all four scenarios is calculated individually. The investigation team, according to the 1996 census, has estimated a total of 900,000 buildings for Tehran of which 45% have a brick/steel structure, 40% have a metal structure, 10% have a reinforced concrete structure, and 5% have an adobe structure [25].

In the *JICA* Project [25], damage was estimated for various items. Damage to residential buildings and human casualties were estimated, as shown in Table (5).

Bazgard et al [55] and Bazgard [56] initiated the development of a model in a *GIS* environment for the residential buildings of district No.1, Tehran. After studying the fragility curves, they realized that comprehensive and appropriate fragility curves are not available for Tehran. Therefore, using the Pearson correlation test, *JICA* curves were compared

Table 5. Building Damage and Human Casualties [25].

Building Damage	Ray Fault Model	NTF Model	Mosha Fault Model	Floating Model	Current Condition
	483,000	313,000	113,000	446,000	Number of Buildings
Building Damage Ratio	55%	36%	13%	51%	876,000
Damage Cost (% of GDP) (Re-construction Cost of Residential Buildings)	22.7%	14.30%	5.16%	20.38%	Gross GDP 109 Billion US$(1998)
Number of Dead People	383,000	126,000	20,000	302,000	Population
Death Ratio	6%	2%	0.3%	5%	6,360,000

Note: Damage cost is calculated by using published GDP (1998) at price of US$50,000 per building (government official exchange rate 1US$=Rls.3000). Human casualties are for night time and no rescue operation case.

with that of *HAZUS*, and the code level was selected according to the buildings in Tehran. *HAZUS* fragility curves in the codes were employed for steel/reinforced concrete structures, while Jalalian fragility curves were employed for masonry structures in the developed model. Furthermore, the model uses three attenuation relations -Zare [30], Ambraseys [61], and the average. The results are obtained for each damage level (slight, moderate, extensive and complete) using these equations, and in two scenarios.

In the first scenario, an earthquake of magnitude 7 occurs in the North Fault, and in the second scenario, it is assumed that an earthquake of magnitude 7.5 takes place in the Mosha Fault near its center. The model includes four modules of input date preparation, earthquake scenario selection (hazard analysis), fragility curve selection (vulnerability assessment) and direct loss estimation. After employing the proposed model in reference [55-56] in a *GIS* development environment, the data were analyzed and processed. For the same purpose, the software was provided for the simulation of damage of buildings after the earthquake. A comparison of damage levels using the attenuation relations of Zare [30] and Ambraseys [61] and their average is shown in Table (6). Given the results of this model, the level of damage to buildings in the area is calculated. Figures (12) to (14) show the probability of exceeding the slight, moderate and extensive damage levels, respectively, using two attenuation relations of Zare and Ambraseys. It was also noted that most buildings are weak against earthquakes and need reinforcement, and that failure to do so will result in a catastrophe in the event of an earthquake in Tehran.

Considering the necessity of emergency operations planning and reconstruction stages, the amount of debris after a potential disaster in municipal district No.1, Tehran, has been evaluated to determine the necessary measures for debris management [57-58]. Debris is generally classified into small and large. Large debris includes constructional debris (concrete, steel, and fiberglass), furniture, home appliances, vehicles, and streetlights, while small debris includes trees, rock pieces, dust, bricks, electric wires, wastewater debris, flammable material, radioactive material, oil and petroleum.

Debris estimation is an experimental method based on observations and experiences from the past earthquakes. The debris resulting from damages to buildings depends on the weight of structural and non-structural elements, damage probability and surface area of each building, and debris generated from structural and non-structural elements in different damage levels [25].

Saebi [57] and Omidvar et al [58] concentrated on the development of an appropriate central model employing a geographical information system for earthquake debris estimation. Software in a *GIS*

Table 6. Building Damage and Human Casualties [25].

Relation \ Damage State	Slight	Moderate	Extensive	Complete
Zare Attenuation Relation	0.52	0.14	0.04	0.02
Ambraseys Attenuation Relation	0.64	0.22	0.08	0.04
The Average of Two Attenuation Relations	0.58	0.18	0.06	0.03

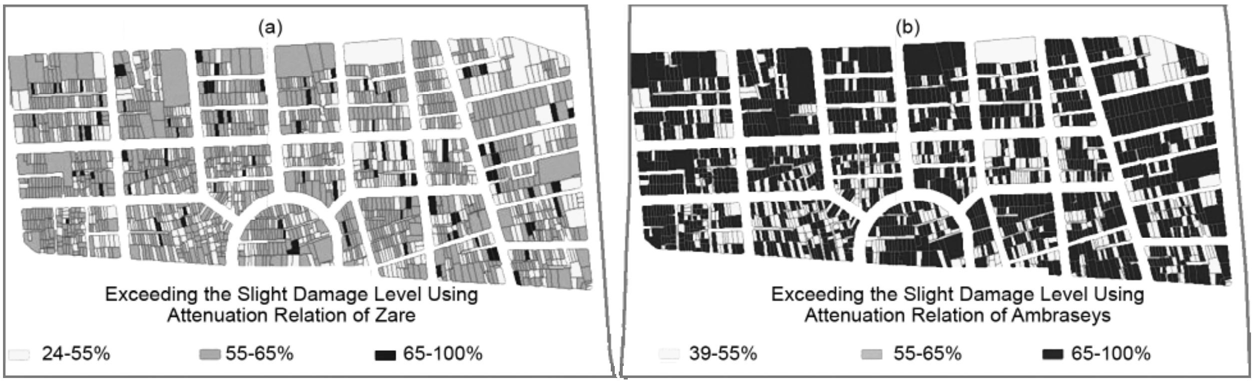


Figure 12. Exceeding probability of the slight damage level [56]. (a) using Zare attenuation relation, (b) using Ambraseys attenuation.

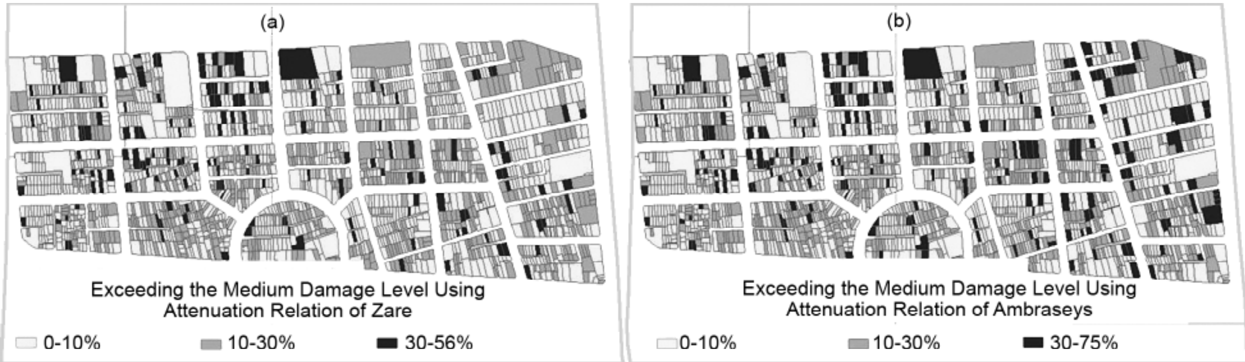


Figure 13. Exceeding probability of the moderate damage level [56]. (a) using Zare attenuation relation, (b) using Ambraseys attenuation.

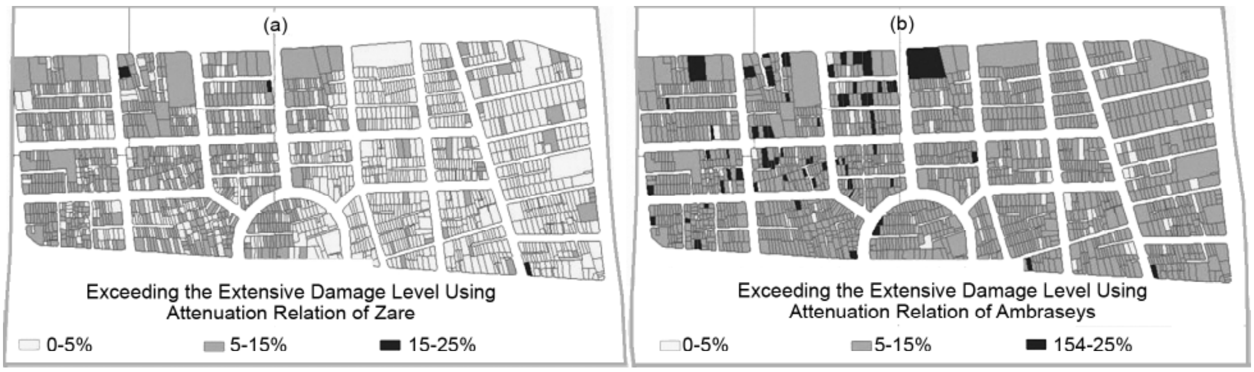


Figure 14. Exceeding probability of the extensive damage level [56]. (a) using Zare attenuation relation, (b) using Ambraseys attenuation.

environment was programmed to assess the damage and the amount of debris caused by an earthquake scenario in municipal district No.1, Tehran.

The measures necessary for debris management were also discussed. The debris caused by each typical structure is calculated, and the final weight of the entire debris is estimated for the study area, with regard to the experimental equations for debris estimation and the calculated probabilities for different damage states. Then, the equipment necessary for removing the debris is estimated. Eventually, the methods for reducing the size of debris and recycling are investigated, as well as the conditions of an appropriate site for storing the debris, suggesting a proper location for this purpose. Considering the attenuation relationship, Campbell-Bozorgnia and Khademi relations have been utilized. Two earthquake scenarios have been considered for damage analysis and debris estimation in district No.1 of Tehran:

- In the first scenario, according to the past earthquakes in Tehran, an earthquake of moment magnitude 5 is assumed to be caused by the North Tehran fault. This fault passes the northern parts of the district. The epicenter is considered in the middle length of the crossed part in the district.
- In the second scenario, an earthquake of Moment magnitude 7.5 is caused by the Mosha fault. The epicenter is considered in the nearest point of the fault to the center of district. The Mosha fault is located to the east of Tehran. A magnitude of 7.5 is selected because the largest known earthquake by this fault occurred with this magnitude in 956*A*.

Table (7) shows the results from *JICA* and Saebi Studies. Hence, these six results show that one number (the result of the Mosha fault model [25]) have more variance from the mean. Therefore, with the elimination of this result and averaging the remaining five results, 36% of the studied district will undergo extensive and complete damage.

The debris generated in the scenarios is calculated with regard to four damage states. The final debris of the district No.1 of Tehran, based on the sum of debris by structural and non-structural members in different damage states, is estimated, see Table (8). In the worst case, the debris generated by the assumed 5 magnitude earthquake on North Tehran fault is estimated 28.6 million tons using Campbell-Bozorgnia attenuation relation [57-58].

In order to assess the necessary trucks for loading and transferring the debris in cleaning operation, the following assumptions are made:

1. Loading time is one hour.
2. Transportation time between the cleaning site and the temporary deposit locations is two hours.
3. It is assumed that trucks, with capacity of five tons, are used to transfer the debris and waste materials. Thus in 24 hours, each truck can travel eight times.
4. The cleaning process takes 60 days.

Considering the capacity of one truck, five tons, it can transfer 40 tons of debris in 24 hours. The number of trucks needed for the cleaning process is calculated and shown in Table (8).

Omidvar et al [59] and Baradaran-Shoraka [60], using multi-attribute decision making methods before an earthquake, proposed a systematic method for the site selection for temporary shelter. Initially, the attributes necessary for appropriate site selection for temporary shelter are introduced. Thirteen criteria, including earthquake damage assessment

Table 7. The results of damage assessment for municipal district No.1 of Tehran [25, 57].

Case No.	Model	Probability of Extensive and Complete Damage Based on Attenuation Relations of JICA	Probability of Extensive and Complete Damage Based on Attenuation Relations of Khademi [38]
1	Rey Fault Model [25]	Less than 30%	-
2	North of Tehran Fault Model [25]	About 50%	-
3	Mosha Fault Model [25]	About 10%	-
4	Model of Afloat [25]	Less than 30%	-
5	Model of First Scenario [57]	-	Less than 30%
6	Model of Second Scenario [57]	-	About 40%

Table 8. Estimation of the equipment necessary for removing the debris is estimated for two earthquake scenarios [57-58].

	Scenario Number One		Scenario Number Two	
	Earthquake Focal Point in the North Tehran Fault		Earthquake Focal Point in the Mosha Fault	
	The Attenuation Relationship of Campbell-Bozorgnia	The Attenuation Relationship of Khademi	The Attenuation Relationship of Campbell-Bozorgnia	The Attenuation Relationship of Khademi
The Final Weight of the Entire Debris (Million Tons)	28.6	22.6	20.75	16.2
Required Amount of Equipment Necessary (Trucks)	11900	9400	8846	6750

results are considered - accessibility, water supply, size of camp site (per capita), camp location, security and protection, topography and drainage, soil conditions, vegetation and fuel resources, culture and tradition, climate conditions, local health and other risks, public opinion, economical considerations and earthquake damage assessment criterion. Spatial specifications constitute most of the information. Therefore, initial site selection is done in the *GIS* environment based on spatial information analysis. For this purpose, the criteria are prepared in geographical information layers for municipality area No.1, Tehran, the capital of Iran. Municipal district No.1 occupies 210 square kilometers and contains a population of 379,962 [62]. The population distribution is assumed to be uniform in surface area of buildings. 36% of the residential buildings of the district will undergo extensive and complete damage, see Table (7) [57-58]. The estimated number of homeless people is equal to 136,786, with respect of the uniform distribution of the population and the assumed mean damage. Thus, considering a 30-45 square meters shelter for each person [63], the area for the required shelters will be 4.10-6.15 square kilometers .

Given this information, and the required shelter area, fourteen zones are initially suggested. *TOPSIS* and *ELECTRE*, as the methods for multi-attribute decision making, are used for the final selection of the site for temporary shelter. The two best results are combined based on the aggregation methods of Average Ranking, Borda and Copeland, and, finally, the mean of the aggregated ranking results is determined. Among the fourteen primary zones identified with a total area of 8.52 square kilometers, 10 zones with a total area of 6.78 square kilometers are selected as suitable zones for temporary shelter. Figure (15) shows the final selected zones for temporary shelter. In order to determine which method has the closest answer to the final ranking, the *RSS* (Residual Sum of Squares) method is used. The results are shown in Table (9). The method with the smallest *RSS* has the least relative error to the final ranking [59-60].

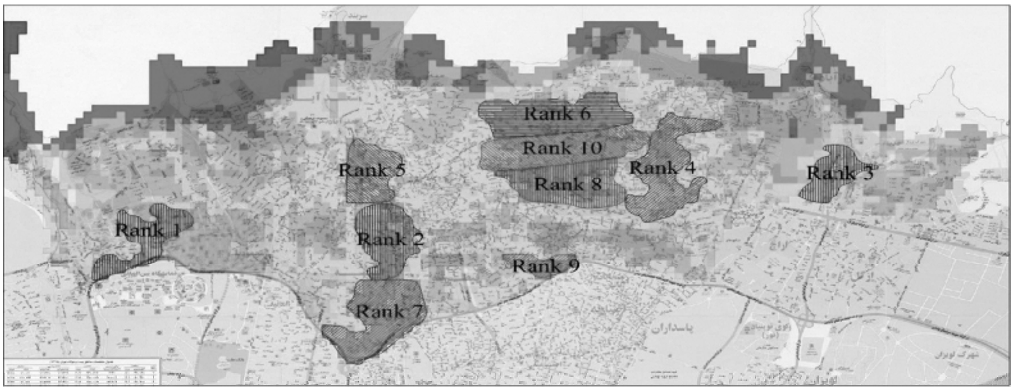


Figure 15. The final selected zones for temporary shelter [59-60].

Table 9. Comparing RSS of various methods of multi-attribute decision making with the final ranking.

Zone	Final Ranking	Topsis Ranking	Electre Ranking
1	2	2	2
2	6	6	6
3	14	14	5
4	13	13	13
5	5	5	7
6	9	7	9
7	7	9	11
8	11	11	14
9	12	12	12
10	10	10	10
11	8	8	8
12	3	3	1
13	1	4	3
14	4	1	4

	Rss Topsis	Rss Electre
	0	0
	0	0
	0	81
	0	0
	0	4
	4	0
	4	16
	0	9
	0	0
	0	0
	0	0
	0	4
	9	4
	9	0
RSS	26	118

6. Conclusion

The history and the existence of faults, indicates the seismicity of Tehran. Despite this potential danger, structures in Tehran will react poorly to such phenomenon, as this city was built and extended with no prediction for building safety. What intensifies its vulnerability is its population; the aged city texture; unreinforced construction materials; narrow passages, especially in south Tehran; the existence of facilities and dangerous applications; steep slopes and edges on the northern margins of the city; the existence of gas pipelines and high-voltage power lines, chemical factories with toxic materials, and urban military bases, which will lead to a high number of casualties. In such an event, the numerous fatalities and economic damage will mean that decades of development will have been in vain and the effect on the economic, political and social center of Iran will be catastrophic.

It is critical to prepare for such a disaster and take the necessary measures regarding the reconstruction of the old city texture and retrofitting of existing buildings. In order to estimate the seismic damage risk to Tehran, some research including seismic hazards analysis, earthquake vulnerability assessment, loss estimation, debris estimation and temporary housing site selection have been performed. The seismic risk analysis of the Metropolitan Tehran area is a link between Hazard Analysis, Vulnerability Assessment and Loss Estimation. It was shown that the results of research on hazard analysis could be used for seismic risk analysis of this city. Also the fragility curves of structures are provided for vulnerability assessment in a regional sense. The introduced curves are based on the expert judgment method and empirical approach.

Based on the results of hazard analysis and derived structural fragility curves, some loss estimation modeling was performed for municipality district No. 1, Tehran, as a sample. The studies included physical damage estimation, debris estimation and site selection for temporary shelter. It was shown that the average exceeding probability of moderate damage using Zare relation, Ambraseys relation and their average attenuation relation are 14, 22 and 18 percent, respectively. Furthermore, the corresponding values for extensive damage are 4, 8 and 6 percent.

It can be also observed that the average value of exceeding probability of extensive damage in the district based on *JICA* and Khademi attenuation relations is increased to 36 percent.

For illustrating a case of induced physical damage, an appropriate central model employing the geographical information system for earthquake debris estimation in the district was performed.

It was shown that the worst scenario resulted in 28.6 million tons of debris. The required number of trucks and equipment for removing that amount of debris is far beyond the available resources.

The site selection for temporary sheltering was investigated as an example of direct social/economic loss estimation. Among the fourteen primary candidate zones identified with a total area of 8.52 square kilometers, ten zones with a total area of 6.78 square kilometers were selected as suitable zones for temporary shelter. It should be noticed that the work was prepared based on the available data up to 2006. Furthermore, uncertainty analysis needs to be done in order to complete the study results, which is planned to be done by the authors for the future work.

The conducted research is only the beginning, and in order to have a safe city, further investigations and plans need to be conducted, mainly on the extent of damage received not only to residential buildings, but also to lifelines of the city and important buildings. Thus, the disaster administration can make quicker decisions in damage reduction, preparation and response phases.

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