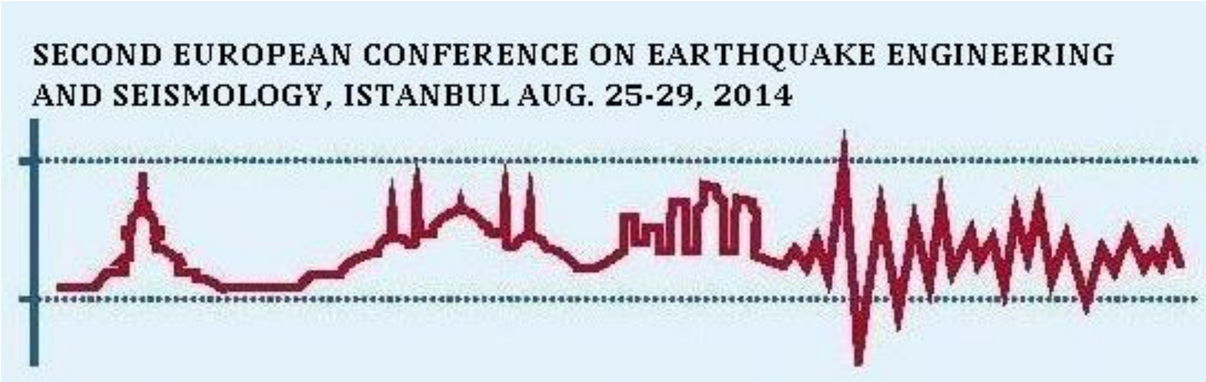


ASSESSING THE RISK OF EARTHQUAKE IN URBAN AREAS (CASE STUDY: TEHRAN CITY)

Meghdad HAJIBABAEE[1], Kambod AMINI-HOSSEINI[2] and Mohammad Reza GHAYAMGHAMIAN[3]

ABSTRACT

It is necessary to make a comprehensive assessment of vulnerability and seismic hazards in different parts of the urban area to effectively reduce the risk of earthquake. This could provide essential information for decision makers for better understanding the priorities of risk mitigation activities. However, in most cities, the absolute estimation of potential consequences of earthquake is not possible due to lack of required data. Therefore, in this paper, a comprehensive methodology is introduced to estimate the relative seismic risk among urban zones instead of absolute measurement. This method needs less data and information through definition of new evaluation approaches. For this purpose, parameters with significant contribution to seismic risk are selected and classified into physical, human life and socio-economic categories. The risk associated to each category is estimated by combining the vulnerability indicators by relevant hazard factors. The post- earthquake capacity of response is also considered by using indicators of planning, resources, accessibility and evacuation capacity. The total relative seismic risk index (RSRi) is then defined through integration of the risk and response capacity indicators. Finally, the model is implemented to assess the seismic risk of Tehran city. The results show that district 15 and 17 of the city have the highest rank of seismic risk. Also the comparison of the results with JICA (2000) study for Tehran, demonstrates the important contribution of response capacity as well as other indicators in overall risk assessment.

INTRODUCTION

The comprehensive assessment of seismic risk can provide significant information for city managers to understand the mitigation priorities. The absolute estimation of earthquake losses and casualties in urban fabrics is also the major part of cost-benefit analysis for retrofitting and improvements. However, in most of countries, due to absence or shortages of required data, the absolute measurements cannot be performed. In such regions, methodologies based on indicators can be adopted to estimate the distribution and extent of the risk in various urban divisions (or zones). Examples of risk assessment methodologies developed based on the risk indicators can be found in literatures (Cardona et al., 2007; Duzgan et at., 2011; Frolova, 2011; Hajibabaee et al., 2013, 2014). Among such methods, Earthquake Disaster Risk Index (*EDRI*) presented by Davidson and Shah (1997) considered several aspects of seismic risk and vulnerability. However, since it was developed for city scale, it is not applicable for assessing the risk at urban divisions.

[1] Ph.D. Student, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran, m.haji@iiees.ac.ir
[2] Associate Professor, IIEES, Tehran, Iran, kamini@iiees.ac.ir
[3] Associate Professor, IIEES, Tehran, Iran, mrgh@iiees.ac.ir

Cardona et al. (2007) is also developed a model for the seismic risk analysis of urban areas from a holistic view. This model takes into account physical risk, exposure and socio-economic characteristics of the different units of the city as well as disaster coping capacity or degree of resilience. However, they did not properly include many important parameters such as vulnerability of lifelines, lifeline’s interaction and socio-economic vulnerabilities. Later on, Khazai et al. (2008) proposed methodology based on the approach of Cardona et al. (2007) to estimate the risk of earthquake in Istanbul city. They defined the social vulnerability (*SV*) and disaster risk management (*DRM*) indicators for considering the effects of social fragility, lack of resilience and capacity of different operational and organizational policies at different districts of Istanbul. However, evaluation of some presented indicators need questionnaire data collection, which is not simple to carry out and be updated in most cities.
In case of Iran, which most of its cities are exposed to high risk of earthquake (Fig.1), many studies have been carried out to estimate the seismic risk of urban fabrics and recognize the priorities of mitigation activities (e.g. Bahreini, 1998; Zolfaghari, 2003; JICA, 2000, 2004; Zebardast, 2007; Ghadiri, 2008; Ahadnejad-Reveshty, 2009; Amini-Hosseini et al., 2009; Frughi, 2010; Mansouri, 2010; Ghayamghamian et al., 2011). Among the recent studies, Motamed et al. (2012) proposed a new methodology by taking into account a set of physical, and response capacity indicators. They implemented the model for Tehran and performed a cost-benefit analysis to find the optimized allocation of resources for improvement of a part of district 17 of the city. However, since they did not include all the significant parameters, their results cannot correctly reflect the existing condition of the risk among different urban zones.

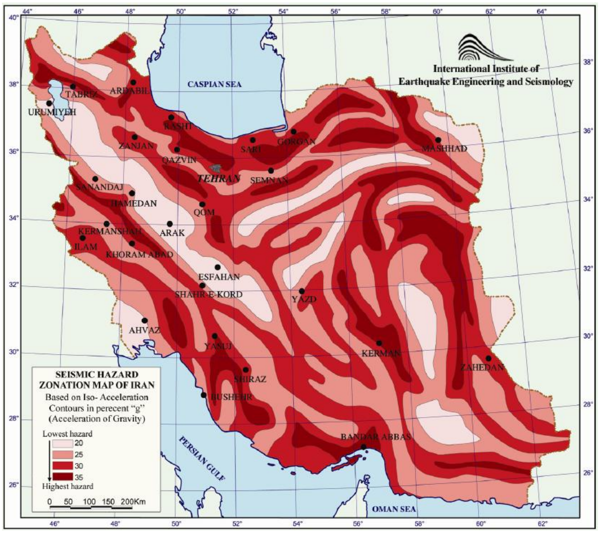


Figure 1. Seismic Hazard Zonation Map of Iran (Tavakoli and Ghafory-Ashtiany 2012)

Moreover, most of the other introduced methods are also not comprehensive for estimation of seismic risk in urban areas. Because they didn’t take into account all aspects of the risk (physical, socio-economic) and response capacity. Therefore, the results of such methods may not be authorized to be used by city managers for allocation of resources. However, some other studies, which proposed comprehensive methods (e.g. HAZUS, Syner-G), were designed for special countries with their specific conditions or need data and information that usually are not available in most countries.
In this paper, a new method is presented to assess the seismic risk by including a comprehensive set of indicators. Also, simplified approaches are presented to evaluate the indicators in urban areas where the sufficient data is not available. In this method, important vulnerability parameters of urban areas are studied and classified into physical, human life and socio-economic groups. Then, the earthquake associated hazard factors are suggested to evaluate the risk indicators through combination of hazard and vulnerability. The pre- and post- earthquake capacity of response activities are also considered in the model by defining the planning, resource, accessibility and evacuation capacity indicators. The total Relative Seismic Risk index (*RSRi*) is then defined as a weighted integration of the mentioned risk and response capacity indicators. This relative index represents the state of the risk in each zone

in comparison with other zones of the city. Finally, the proposed method is applied for assessing the earthquake risk in Tehran city. The outcomes have a good agreement with the expected state of risk in different districts of Tehran. Furthermore, the comparison of the results with JICA (2000), which is one of the most reliable studies carried out for assessing the risk of earthquake in Tehran, is performed to illustrate the effectiveness and applicability of the model. This comparison clarified the significance of considering a comprehensive set of indicators as well as employing appropriate methods for quantification of them. It also demonstrated the major contribution of response capacity term in measuring the risk in urban areas.

METHODOLOGY

The flowchart of the proposed model for estimating the seismic risk by means of vulnerability, hazard and response capacity terms is shown in Fig.2. As illustrated, in the first step by using the existing data and information, hazard factors (*H1-H4*), which represent the state of ground motion and secondary hazards, are evaluated. Then, the risk indices would be estimated by a combination of vulnerability indicators and their directly-related hazard factors. The response capacity index is also measured by the weighted combination of its components. Then, the total relative seismic risk index (*RSRi*) is estimated through integration of the mentioned risk and response capacity indices. From Fig.2, once the *RSRi* is measured in different urban zones, the disaggregated values can inform the managers and decision makers about the contribution of each parameter in overall risk. This can help them to understand the priorities of mitigation activities. Also, after taking some mitigation strategies, the risk and response capacity indices as well as *RSRi* can be reassessed in order to verify the effectiveness of employed activities and programs.

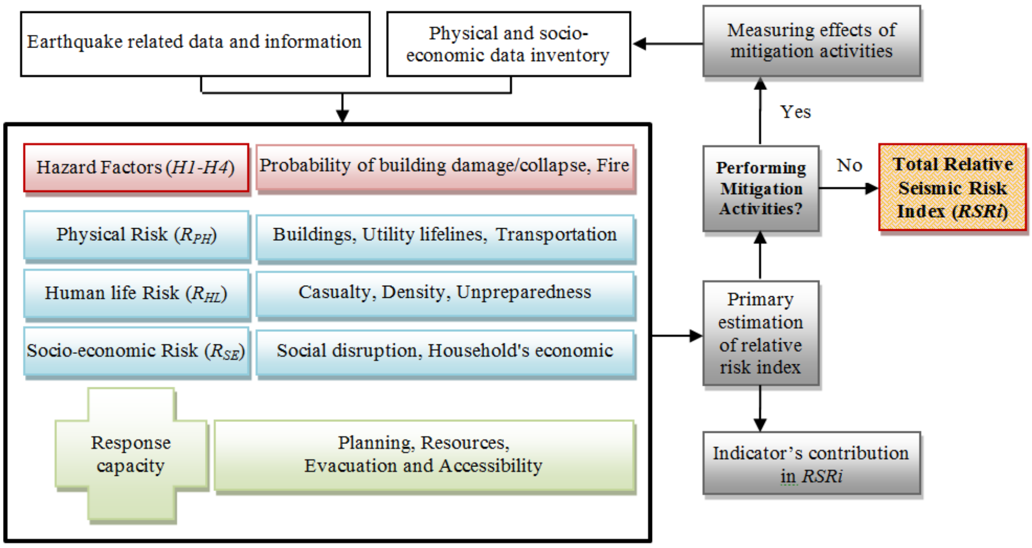


Figure 2. Flowchart of the proposed seismic risk assessment model (Hajibabaee et al. 2014)

In the presented method, a set of comprehensive but simple and measurable indicators are selected to evaluate each of the main risk and response capacity indices. For this purpose, the vulnerability of an urban area is divided to three main categories of physical, human life and socio-economic disruptions. These categories, their sub-components and the relevant weight values are shown in Table 1. Furthermore, the earthquake related hazards are considered by means of four hazard factors (*H1-H4*). *H1* and *H2*, respectively corresponds to the ground motion (*PGA* and *PGV*) and ground failure (*PGD*) parameters. These parameters would be used through fragility curves to estimate the risk indicators associated to physical vulnerabilities and casualty potentials. Factor *H3* indicates the average state of building damages and would be quantified between 0 and 1. In fact, *H3* is the main cause and direct threat for human casualties and social disruptions. Therefore, it is considered as a new separate hazard factor. Similarly, *H4* is defined as an individual factor to measure the secondary hazards (here only

fire initiation). The hazard of fire initiation is estimated based on the gas and electricity network damages by considering the number of hazardous facilities (e.g. gas stations) inside the urban zone.
The weight values for each indicator and its sub-components in the proposed approach are determined by applying AHP (Analytical Hierarchy Process) method and in some cases by engineering judgments. Furthermore, the obtained values of all indices and their relevant indicators would be normalized by means of a scaling technique to make a better explanation of the results. More details about the hazard factors, indicators evaluation methods and normalization technique were described in Hajibabaee et al. (2013).

Table 1**.** Vulnerability classification (Hajibabaee et al. 2013)

Main category (Index)	Sub-components (Indicators)	Vulnerability characteristics
Physical Vulnerability (V_{PH}) (w_{PH}=0.30)	V1: Building vulnerability w=0.60	Building's structure and occupancy
	V2: Utility lifeline vulnerability w=0.30	Lifelines network type and material
	V3: Transportation vulnerability w=0.10	Type and width of roadways
Human life Vulnerability (V_{HL}) (w_{HL}=0.50)	V4: Casualty potential w=0.75	Population distribution in various structures and occupancies
	V5: Density w=0.15	Density of population and buildings
	V6: Unpreparedness (of people) w=0.10	Age distribution
Socio-Economic Vulnerability (V_{SE}) (w_{SE}=0.20)	V7: Social disruption potential w=0.50	Delinquency, social cohesion, education, socio-economic effect factor
	V8: Household's economic condition w=0.50	Income, employment, ownership, household dimension

Furthermore, the response capacity, which is a set of elements and activities that my affect emergency response and recovery, is characterized by indicators of Planning (Rc_P), Resources (Rc_R), Accessibility (Rc_A) and Evacuation capacity (Rc_E). The response capacity index (*Rc*) is then measured by weighted integration of these indicators. Also, the sharing of resources among adjacent urban zones is considered in the model by definition of coefficients based on the expert opinions. Accordingly, it is assumed that when an earthquake happens, each urban zone would be able to use 75% of its capacity and the rest part would be employed by its adjacent zones. Table (2) shows the response capacity indicators and the relevant sub-indicators. Also, the components of the resource indicator are presented in Table (3). In these tables, *w* is the weight value associated to each indicator or component. The evaluation methods of the response capacity indicators were presented in Hajibabaee et al. (2014).

Table 2. Response capacity indicators (Hajibabaee et al. 2014)

Index	Sub-components (Indicators)	Sub-indicators
Response Capacity (Rc)	C1:Planning Indicator (Rc_P) w=0.25	Adequacy level of plan(s) w=0.50
		Implementation level of plan(s) w=0.50
	C2:Resource Indicator (Rc_R) w=0.35	Available financial resources w=0.30
		Equipment and facilities w=0.35
		Trained manpower w=0.35
	C3:Accessibility Indicator (Rc_A) w=0.20	Road physical damage w=0.30
		Road blockage w=0.70
	C4:Evacuation Capacity Indicator (Rc_E) w=0.20	Regional evacuation capacity w=0.50
		Community evacuation capacity w=0.50

The post- earthquake reduction in the capacity of each urban zone is estimated by means of reduction factors. These factors are multiplied by the pre- earthquake values associated to components of the resource indicator to reflect the effect of damages and casualties in this field. In Table (3), the

Reduction Factors (*RF*) associated to the components of equipment and facilities is defined as a function of *H3*, which infers the average amount of physical damages in each urban zone. The reduction in capacity of trained manpower is assumed to be a function of human casualty factor (*cf*), which represents the average state of human casualties, and quantified by scaling the casualty risk indicator (Table 1) with its maximum value. Factors *dw* and *de* are the probabilities of complete/extensive damage state of water reservoirs and electricity sub-stations, respectively, which are estimated by using fragility curves provided by HAZUS (2003).

Table 3**.** Components of Resource indicator (Hajibabaee et al. 2014)

Sub-indicators	Components	Representative parameter	Reduction Factor (*RF*)
Financial Resources (w=0.3)	Funds available for response and recovery w=1.0	Rs1: GDP value	RF1=1.0
Equipment and facilities (w=0.35)	Health care (Hospitals and clinics), w=0.30	Rs2: Number of beds	RF2=1.0-(*H3*)/2
	Police and traffic control bases, w=0.20	Rs3: Number of bases	RF3=1.0- (*H3*)/2
	Firefighting stations, w=0.30	Rs4: Number of stations	RF4=1.0- (*H3*)/2
	Other relevant infrastructures, w=0.20	Rs5: Water (m3) in reservoirs	RF5=1.0-*dw*
		Rs6: Number of Electricity sub-stations	RF6=1.0-*de*
Trained Manpower (w=0.35)	Medical staffs in hospitals and clinics,w=0.25	Rs7: Number of medical staffs	RF7=1.0-(*cf*)/2
	Police & traffic control personnel, w=0.20	Rs8: Number of policemen	RF8=1.0-(*cf*)/2
	Fire and rescue teams, w=0.30	Rs9: Number of fire&rescue teams	RF9=1.0-(*cf*)/2
	Triage services staffs, w=0.25	Rs10: Number of triage staffs and ambulance services	RF10=1.0-(*H3*)/2 -(*cf*)/2

In order to evaluate the overall risk index (*RSRi*), the gross values of the risk and response capacity indices and their relevant indicators should be normalized to values that are similar in magnitude. For this, the standardization process is performed by using 'the mean minus two standard deviations' technique. In this method, by involving the mean and standard deviation of all samples, each gross value is normalized relative to all others. The normalized values are usually between 0 and 4.0.
It is assumed that, with the exception of 'lifelines risk', 'transportation risk' and 'response capacity' indicators, all other risk indicators can be quantified at normalized in neighborhood to whole city scales. These excepted indicators cannot be simply measured at small scales such as neighborhoods due to their wide network, interconnections and dependencies. However, they can be estimated in larger scales and the normalized values can be assigned to their relevant smaller divisions. Finally, when the risk and response capacity indicators are evaluated at each urban zone, the *RSRi* is measured by Eq. (1) to compare the overall risk among urban zones.

$$RSRi = (w_{PH} R_{PH} + w_{HL} R_{HL} + w_{SE} R_{SE}) / (1 + Ln(Rc)) \quad (1)$$

In this equation, R_{PH}, R_{HL} and R_{SE} are physical, human life and socio-economic risk indices, respectively. From this equation, the risk indices are added linearly according to their weight values (*w*), presented in Table (1). However, response capacity index (*Rc*) is included as a reductive term through a natural logarithmic function. In this logarithmic function, the slope of the curve decreases as *Rc* increases. This can represents the fact that an improvement of *Rc* has more effect in relative reduction of overall risk index (*RSRi*) in urban zones having less capacities of response activities.

IMPLEMENTATION FOR TEHRAN

In order to assess the capability of the presented model, it has been applied to estimate the seismic risk in 22 municipal districts of Tehran city, which as the capital of Iran is exposed to very high threat of earthquake. For this purpose, the Ray fault scenario, as the most destructive potential earthquake in Tehran (JICA, 2000) is selected, and the mean values of *PGA*, *PGV* and *PGD* are determined at each district (More detail introduced in JICA 2000 report). This fault is located in south of the city with a potential moment magnitude of 6.7 (Mw).The required data on population and buildings are gathered from the Statistical Center of Iran (CSI), according to the 1996 survey. Although this data is rather old, it allows the results to be compared with JICA (2000), which is one of the comprehensive and reliable studies of risk assessment carried out for Tehran based on 1996 census data. Fig.3 shows the distribution of *PGA* values associated to Ray fault scenario at different districts of the city. As seen, *PGA* in northern districts is considerably higher than northern ones.

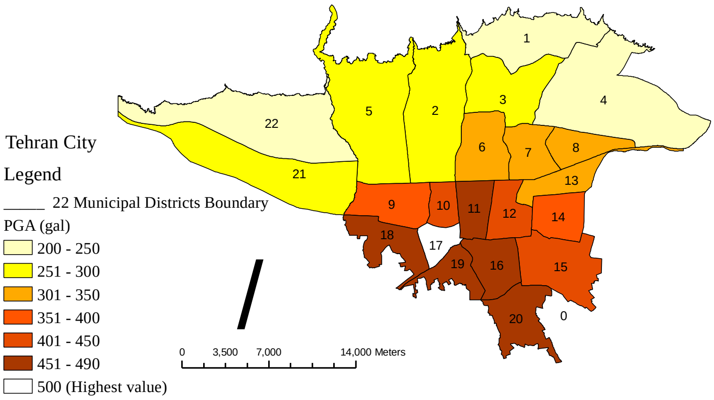
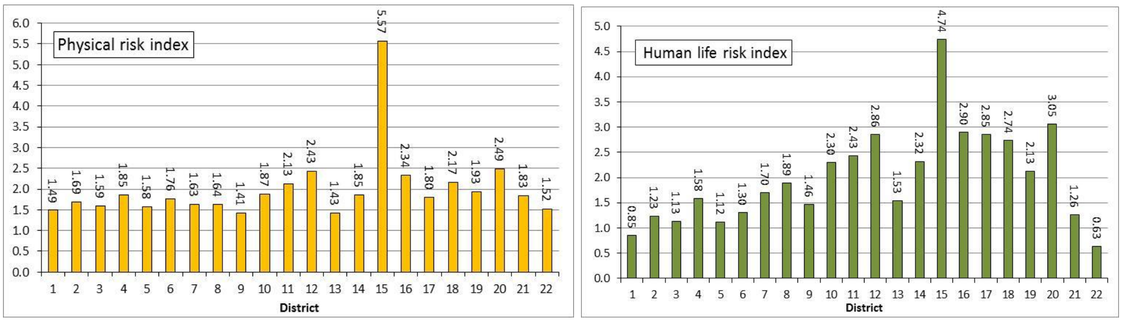


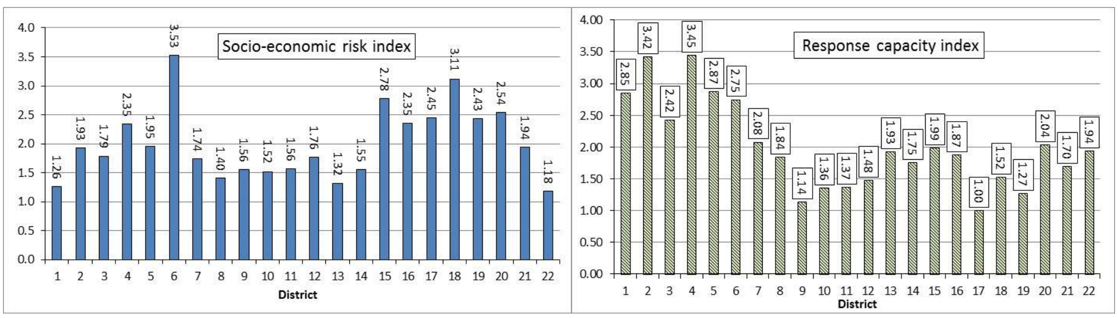
Figure 3. Distribution of *PGA* in different districts of Tehran, based on JICA (2000) study

The estimated and normalized values of physical, human life and socio-economic risk indices (Table 1) as well as response capacity index (Table 2) are presented in Figs.4 and 5. As shown, the physical and human life risk indices in district 15 of the city are significantly greater than the others. On the other hand, districts 6, 15 and 18 have the highest risk in socio-economic aspect. Also from Fig.5b, the capacity of response in northern districts especially districts 2 and 4 is considerably higher than northern ones. The estimated value of the total relative seismic risk index (*RSRi*) in different districts of the city is also displayed in Fig.6. As illustrated, districts 15 and 17 have relatively the highest overall risk, while the risk of northern districts (especially district 1) is not significant.



(a) (b)

Figure 4. Normalized values of (a) Physical risk index (R_{PH}), (b) Human life risk index (R_{HL}), in different districts of Tehran



(a) (b)

Figure 5. Normalized values of (a) Socio-economic risk index (R_{SE}), (b) Response capacity index (Rc), in different districts of Tehran

Furthermore, to clarify the contribution and impact of response capacity term, the results of *RSRi* based on the real values of *Rc* (estimated by the proposed model) are compared with those, which *Rc* is assumed to be same for all districts (*Rc*=1). The results show that the *RSRi* rank of some districts (such as 4, 9, and 20) may change significantly by including the real amounts of *Rc*. For instance, district 4 which was the 12th priority of risk mitigation among others drops to 17th, and the rank of district 20 is changed from 2nd to 7th (+5 step change of rank). On the contrary, in district 9, *RSRi* rank or the priority of risk mitigation is rise from 17th to 10th (-7 step change of rank) due to having low capacity of response.

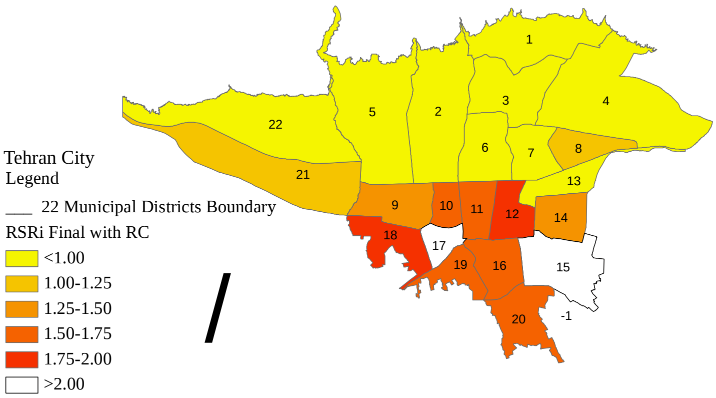


Figure 6. Normalized values of Relative Seismic Risk index (*RSRi*) in Tehran districts (Hajibabaee et al. 2014)

Furthermore, the results are compared with JICA (2000) to show the benefits of the presented model. In JICA study, the overall seismic risk index was estimated by a linear combination of six indicators of Average seismic intensity, Residential building damage ratio, Death ratio, Population density, Open space per person, and Narrow road ratio. Based on JICA results, districts 17, 12, 10, 11 and 16 have respectively the rank of 1 to 5, and district 15 is the 8th in total risk score. According to the results of the presented model, the rank score of district 17 and 12 (2nd and 4th, respectively) are very similar to JICA results, but there is a big difference in rank of some others such as district 10, 11 and 15, which are 9th, 6th and 1st, respectively. The comparison of our results with JICA clarifies the effect of including all various aspects of the risk and response capacity for assessing the seismic risk that are not properly considered in JICA study. Moreover, we believe that indicator of “Average seismic intensity”, which is defined by JICA, should not be considered as a separate indicator, because the risk is conceptually defined as a combination of hazard and vulnerability. In addition, the ratio of damage and death (for assessing the indicators of Residential building damage ratio and Death ratio) cannot be considered as a reasonable parameter for determining the rank of overall risk over different urban zones. In the other words, to compare the risk among urban zones and understand the priorities and optimized allocation of mitigation resources, the overall losses or casualties should be estimated instead of the ratios. These remarks are among the main reasons of differences between JICA and our results.

CONCLUSION

In this paper, a new methodology was presented to simplify the comprehensive assessment of seismic risk in urban fabrics. For this purpose, a set of indicators including all important aspects of earthquake risk were defined to assess the overall risk through combination of them with formerly defined hazard factors. Furthermore, four indicators of planning, resource, accessibility and evacuation capacity are presented to measure the response capacity and aspects. This methodology makes an improvement in assessing the risk in urban areas where the required data for absolute assessment of losses and casualties are not available. The main features and improvements of the model can be summarized as follow;

- Presenting a comprehensive methodology: since all the physical, human life, socio economic and response capacity aspects were considered, the results can comprehensively show the seismic risk zoning of urban fabrics.
- Definition of hazard factors: according to the fact that each of earthquake related hazards (ground motion, ground failure and secondary hazards) has different effects on the consequence of an earthquake in an urban area, different hazard factors were defined for estimating each of risk indicators. It is assumed that, the combination of each vulnerability indicator with its directly-related hazard factor can conceptually make a better interpretation the risk and reduce the uncertainties in this field.
- Measuring the response capacity term: the capacity of response will change after the event due to damages, casualties and disruptions. Therefore, new reduction factors were defined to consider the post- earthquake condition for this term. Also sharing of the resources among adjacent urban zones was considered by definition of coefficients based on expert opinions.
- Evaluation of indicators based on relative scheme: since the model estimates the relative seismic risk instead of absolute evaluation of losses, simple approaches were defined for evaluation of the indicators. This makes the model more applicable for urban areas where the sufficient required data are not available.
- Native characteristics of the model: since at this stage the model was implemented for estimation of seismic risk in Iran cities, the parameters were quantified by employing the local studies. Moreover, opinions of Iranian experts were involved in selection of indicators and determination of their weight values by using AHP method. Furthermore, as a new research, the collapse rate of Iranian structures were surveyed using the database of 2003 Bam, Iran earthquake and a new relation was proposed for estimation of collapse probability in various buildings typology (Results of this study will be published in future).

Since there is no sufficient data associated to pre- and post- condition of past earthquakes in Iran, the verification of the model was not possible. However, the results were somehow compared with the most reliable risk assessment results produced by JICA (2000) for Tehran City based on 1996 database. Based on the results, southern districts (especially district 15) are exposed to higher risks in comparison with northern ones. This is in agreement with the expected condition of seismic risk in the city. Because, southern districts (old fabrics of Tehran), have relatively more amount of population and vulnerable buildings, in addition to having high earthquake hazards (*PGA*). Finally, the disaggregated values of *RSRi* can inform the decision makers about the contribution of each indicator in seismic risk of different urban zones. Such information can be employed for proper allocating the current resources for risk mitigation activities.

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