Probabilistic Seismic Damage Assessment for Urban Transportation Network

Mohammad. R. Zolfaghari
Associate Professor, KN Toosi University of Technology, Tehran, Iran

Meysam Mogheisi
MSc Student, KN Toosi University of Technology, Tehran, Iran

SUMMARY:
In this paper an analytical procedure is proposed for probabilistic assessment of seismic damages and consequence disruptions to urban transportation network following earthquakes. Seismic damage to urban transportation network and consequence road congestions are modeled based on falling debris from damaged building stocks as well as disruption caused by structural damages to bridges. Monte Carlo simulation process and logic tree algorithm are taken into account to model uncertainties associated with different factors controlling ground motion estimation, assessment of physical damages to building stocks and bridges and also estimation of falling structural debris. Synthetic earthquake catalogues representing long term seismicity and attenuation functions are used to model probabilistic strong ground motions levels impacting buildings and road networks. Each earthquake scenario results in probabilistic and spatial distributions of damages to building surrounding urban road networks and bridges. Volumes of falling debris are estimated for each group of buildings, based on building types and building damage stages.

Keywords: Lifeline System, Urban Road Network, Risk Assessment, Seismic Hazard

1. INTRODUCTION

During an earthquake, all components of urban building stocks, infrastructure and lifeline systems may be exposed to various types of seismic hazards. Damages and disruptions to urban lifeline systems are in particular important factors in post-disaster relief measures and crises management. Among the urban infrastructures and lifeline systems, performance of transportation network happens to be very crucial in effectiveness of post-disaster response measures. Experiences from past earthquakes show that failure of road structures and transport networks not only cause tremendous economic losses and daily life disruptions of inhabitants, it affects effectiveness of early responses measures and evacuation process (*e.g.* Change & Nojima 1999; Franchin *et al* 2006). Success and effectiveness of post-disaster response efforts relies on reliability of transportation network after big events. Recent disastrous seismic events have widely documented the crucial role of the transport network in the management of the emergency and in the facilitation of the response and recovery phases, including the restoration of other lifeline systems that is, clearly, very dependent upon people and equipment being able to move to the sites where damage has occurred (Pitilakis *et al* 2006; Stephanie & Nobuoto, 1999; Rossi *et al* 2010; World Bank 2008). On the other hand, performance and serviceability of roads and transport network after an earthquake are directly related to seismic vulnerability of road structures as well as performance of buildings and structures on the border of such networks. Public roads in densely populated urban areas are in particular vulnerable to falling debris and collapsed structures from marginal buildings on road sides.

Computer modelling of physical damages and economic losses caused by natural catastrophes, using multi-disciplinary expertise has paved its way through many scientific and commercial applications. These models aim at estimation of the likelihood of economic and humanitarian consequences of natural hazards based on pre-defined catastrophe scenarios or in a pure probabilistic term. Similar techniques have been used in recent years for modelling damages to lifeline systems following large earthquakes. Many of the earlier studies on the risk assessment of transportation network are based on deterministic scenarios. Werner *et al* (1997) modelled seismic damages to the transportation network for Shelby County, consisting of 286 bridges. In their study, they used four earthquake scenarios on the New Madrid seismic zone. In another study, Shinozuka *et al* (2000) introduced a scenario for 2225 bridges in Orange County, Los Angeles region. Kiremidjian *et al* (2006) carried out similar study for the same region but using a Monte Carlo simulation process. An area of concern with such methodologies is the lack of proper treatment of uncertainties associated with various components of such models. In a recent study by Kiremidjian *et al* (2007) for the San Francisco transportation network consisting of 2640 bridges, probabilistic seismic losses and road congestion and journey disruption were estimated using a GIS tool.

In this paper a GIS-based computer tool has been designed and developed which consists of modules for analytical and probabilistic analyses as well as GIS functionality for spatial analyses and data visualization. To test the model, urban road network and building stocks for a district in the city of Tehran is used and results in term of maps showing seismic induced road closure are presented at the end of this paper. The extent of debris spreading out on the roads are estimated based on damage pattern from previous earthquakes and where necessary expert judgments.

2. EARTHQUAKE INDUCED DAMAGES TO URBAN ROAD NETWORK

Road structures are vulnerable to ground shaking as well as ground failure caused by faulting and other geotechnical events such as landslide and liquefaction. Seismic hazards may result in various types of physical damages to urban road network which in turn result in vast economic and social consequences. In addition to the economic damages such hazards may cause, road closure and traffic disruption are the most important consequences which affects emergency and post disaster efforts. The main forms of such consequences are listed below and shown in Figure 1:

- Direct seismic damages to brides and other road structures which in turn result in road closure
- Instability of slopes resulting in road damages or road closure due to sliding materials
- Damages to buildings and other structures bordering roads, resulting in partial or total road closures
- Urban utility damages (gas, water, electricity and waste water network) with further consequences on road functionality
- Cars left on the roads by drivers attempting to reach their dependents following disruptions caused by earthquakes
- Disruption and damages to traffic lights, traffic controlling systems and cameras

Real examples of such effects are shown in Figures 2. Ground failures resulted from fault ruptures and geotechnical hazards may threat urban transport network crossing active faults or on young and mountainous geological materials. However, in most cities around the world, ground shaking is considered to be the main factors affecting urban road network and in this study only the effects of ground shaking on buildings and road structures are taken into account. One of the most important factors controlling the serviceability of urban road network following earthquakes, particularly in mega cities and densely populated areas, is the seismic performance of marginal buildings on the road sides. Experiences from pervious earthquakes show that falling debris from damaged buildings and structural collapses on urban roads result in significant road closure and disruptions in hours and days after earthquakes (Argyroudis *et al*, 2003; Goretti & Sarli 2007; Fırat & Kubat 2012; Cheng *et al* 2010). In this paper a probabilistic approach is proposed to estimate likelihood of road closure following earthquakes. Lighter shaded boxes in Figure 1 are the effects considered in this paper.

3. METHODOLOGY

In this paper attempt is made to model sources of uncertainties associated with seismic damages to buildings and road structures and consequence road congestions and journey disruptions. Collapsed buildings and falling debris from buildings bordering urban roads, particularly in cities and regions with high concentration of building stock, may result in partial or total road closure. Such effects are functions of building height, building structural types/materials, building distance to roads and road width. While falling structural debris might not be of an important concern for the serviceability of road network in less populated or rural and suburban areas in some countries, in the case of most mega cities, particularly in developing countries, this remains an important factor controlling the performance of road network after big earthquake. Main components and procedure to estimate road closure as the result of seismic damage to buildings are shown in a logic tree framework in Figure 3. The procedure involves probabilistic convolution of uncertainties associated with earthquake distributions in time and space, ground motion distribution and damage induced to buildings and road structures. The "OR" operators in this figure represent probabilities summation. This procedure results in the probabilistic distribution of extent of structural debris for each building on the road border. As shown in Figure 3 the shape of this distribution function could vary for each building based on ground motion level and building vulnerability.

To represent probabilistic seismic hazard in this model, regional seismogenic characteristics are used to synthetically simulate an earthquake catalogue, providing earthquake locations, magnitudes and recurrence time. Each earthquake in such catalogue stimulates a real earthquake which can potentially occur in the vicinity of the modelled area. Ground motions in terms of Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV) and MMI are estimated for each earthquake scenario using empirical attenuation functions. Aleatory and epistemic uncertainties associated with attenuation functions are taken into account using Monte Carlo simulation process. This process results in probabilistic distribution of ground motions for buildings and road structures.

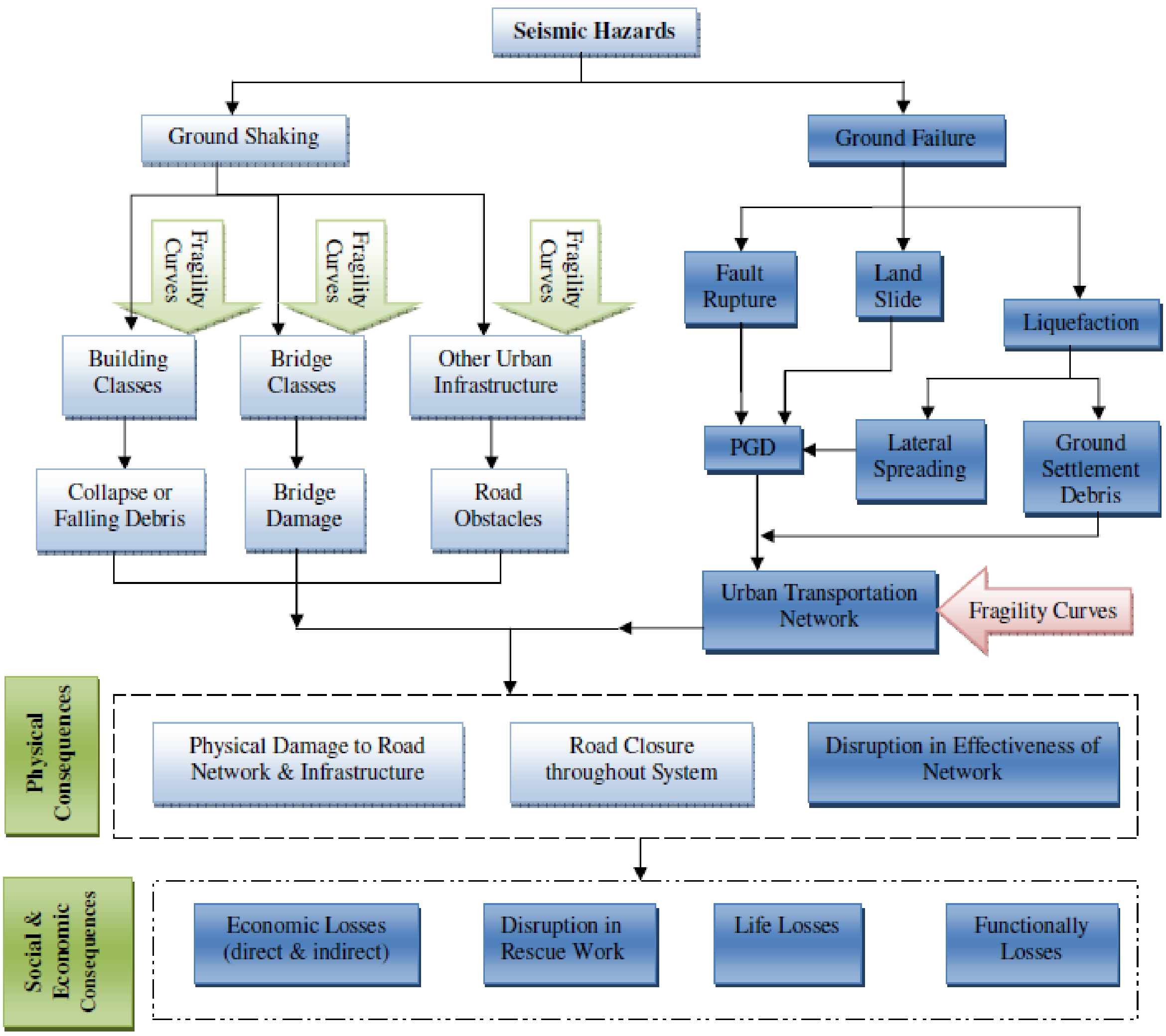

Figure 1. Seismic hazards and consequent types of physical, social and economic consequences to road network

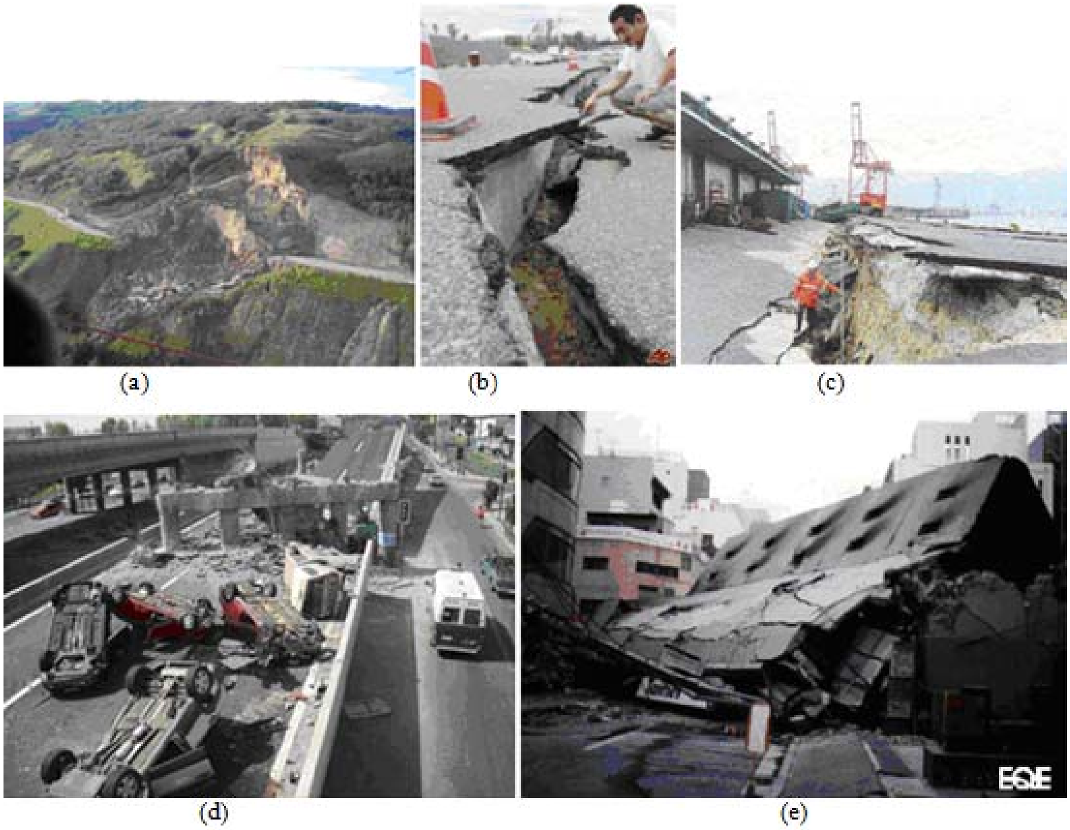

Figure 2. Various types of seismic hazards affecting roads serviceability: a) Landslide, b) Faulting, c) Liquefaction, d) Damaged bridges and e) Collapsed buildings

Data inventory of elements composing urban road network such as main bridges and buildings are modelled spatially using GIS vector data layers. To estimate the degree of damage induced by seismic hazards to each network element, fragility curves are used. In this study and in the absence of fragility curves for bridges in Tehran, the fragility curves proposed by HAZUS [9] are used in which likelihood of structural damage is presented as functions of seismic ground motion, in this case PGA. The curves are proposed for each type of building specifically and provide damage ratios.

The probability that extended debris gets value ED_i can be represented by the following total conditional probability definition:

$$P(ED = ED_i) = \sum_{k=1}^{n_{IM}} \sum_{j=1}^{n_{DS}} \sum_{i=1}^{n_{ED}} P(ED = ED_i \mid Ds_j) P(Ds = Ds_j \mid IM_k) P(IM_k) \quad (3.1)$$

In which n_{IM}, n_{DS} and n_{ED} represent number of ground motion stages, number of building damage stages and number of extended debris stages respectively. Following this procedures for all buildings in a given region, probabilistic distribution of extended debris for all buildings as a result of a given earthquake scenario are estimated. In order to present the state of road closure from each building, these distributions are sliced into four closure states based on road width and dimension of extended debris as shown in Figures 4-a and 4-b. A give road may experience one of these closure states if at least one of the buildings on its border provides necessary debris for such closure (Figure 4-c). This could be formulized probabilistically in the following form:

$$PC\textit{(At least one moderate closure no a given road section)} = 1 - \left[\coprod_{i=1}^{n} (1 - P_i(MC) \right] \quad (3.2)$$

In which $P_i(MC)$ represents the probability that building i generates enough debris to put road section in moderate closure state j in this case MC. Similarly, the probability of road closure in other stages can be calculated following the same procedure. In reality there is correlation between damage levels on buildings on close proximity, however, in this study the degree of seismic damage to buildings on a road are assumed to be independent. Also the cumulative extend of debris from more than one building are ignored in this study. The partitions between different road closure stages are based on personal judgment using ratio between building height to road widths.

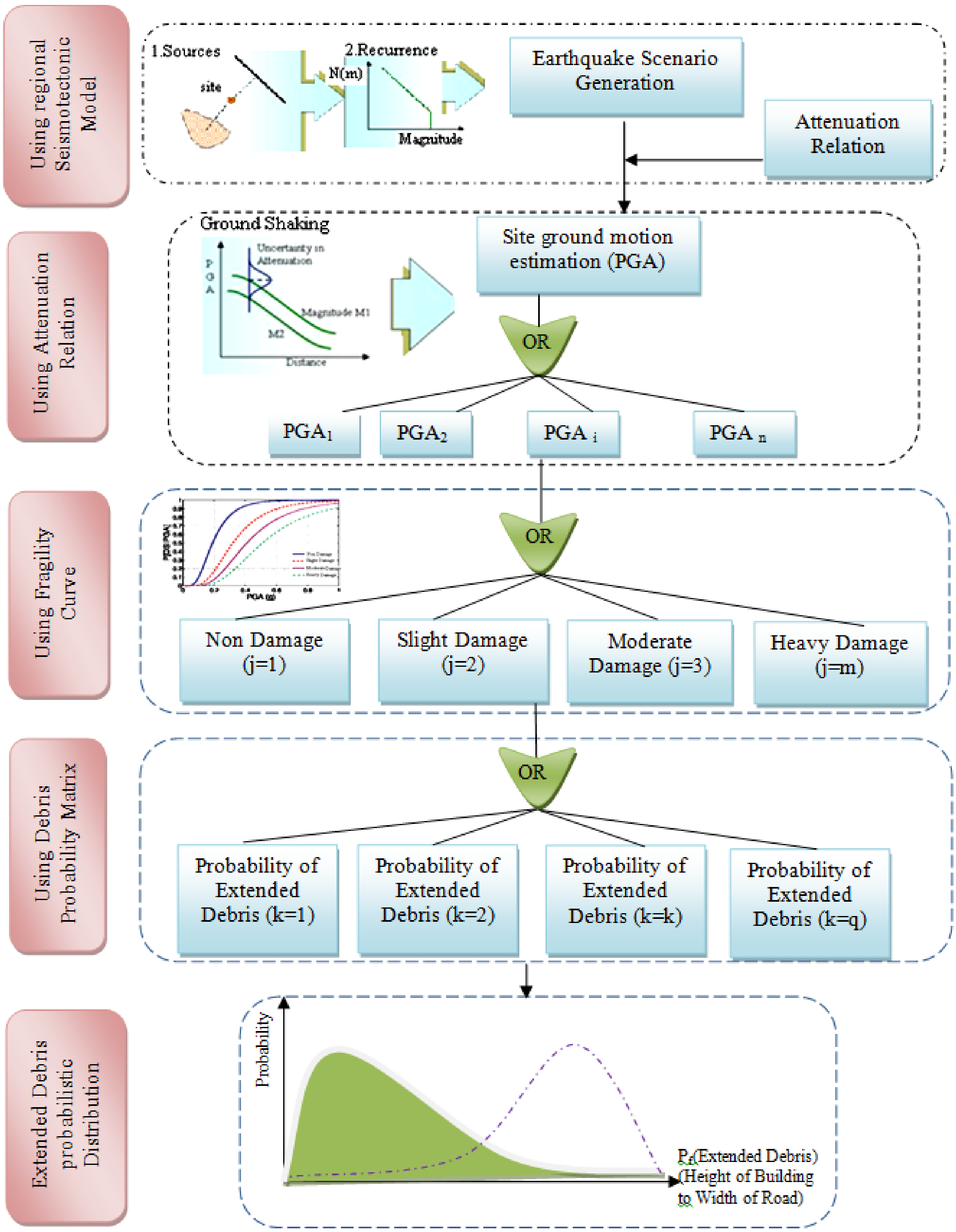

Figure 3. Logic tree algorithm to estimate probabilistic distribution of extended debris on urban roads caused by building damage. In this framework an earthquake may results in *n* levels of PGA at a site, each resulting in *m* stages of structural damages on a building, each damage level resulting in *q* stages of road closures.

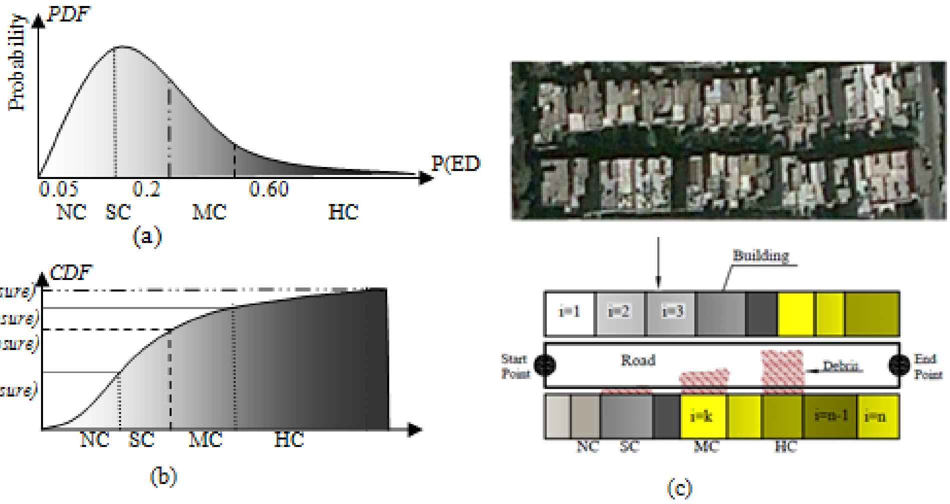

Figure 4. Probability distribution of extended debris for each building bordering a road section

Functionality and serviceability of urban road network are also dependent on the seismic behaviour of bridges and other road structures. In many of similar studies for urban transportation network, especial attention is paid to bridges as the most important factor controlling network functionality. Using fragility carves for bridges; it is possible to estimate the likelihood of different damage stages for each bridge. Serviceability of bridges following an earthquake requires visual inspection and estimate of suffered damage. A bridge with slight damage may cause partial or total closures to one or both roads crossing a given junction. For more destructive damage stages, the possibility of road closures increases and therefore, such damage stage could be assumed total closures for roads crossing the junction. In this cases, the combine probability of road closures as the results of both building and bridge damages can be represented in the following form:

$$PC(\textit{At least one moderate closure on the road section}) = 1 - \left[\prod_{i=1}^{n}(1-P_i(MC))\right] \times \left[\prod_{j=1}^{m}(1-P_j(MC))\right] \qquad (3.3)$$

In which $P_j(MC)$ represents the probability that bridge j suffers enough damages to put the road section into moderate closure (MC). In other words PC represent the probability of at least one moderate closure on the road section as the results of a potential damages to n buildings and m bridges on the road section. Similarly, it is assume that the damages to building and bridges are independent.

4. CASE STUDY

A GIS-based software tool is designed and implemented in this study to convolute these probabilistic distributions. This tool plus building and road inventory for a district in northern Tehran are used to test the performance of this model. There are 24 main bridges in this district which are mostly providing crossing in the main highway intersections. It is therefore, expected that damages in these bridges cause major disruption on the road network in this district. All the road segments in this district are presented by 1650 links connected by 2310 nodes as shown in Figure 5-a.

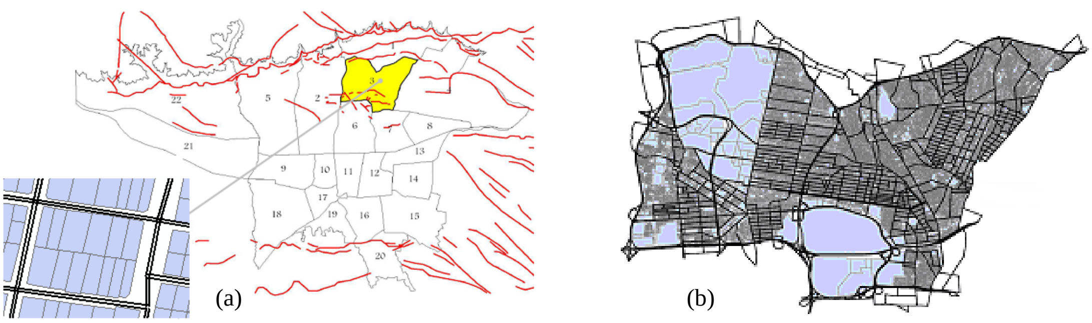

Figure 5. District 3 in northern Tehran a) Location of the district surrounded by sources of moderate to large earthquakes, b) Built environment and road segments in the district

In order to generate probabilistic maps of road closure, a synthetically generated earthquakes catalogue of 522 earthquake scenarios, representing 1000 years of seismicity in this vicinity of the study area is used. Following the algorithm presented by Equation 3.3 for all buildings and brides on each segment, for all road segments and for all synthetic earthquake scenarios, maps showing probability of closure states are generated. Figures 6 shows an example of such maps, showing the probability of at least one heavy closure (*HC*) on each road segments, with return period of 200 years.

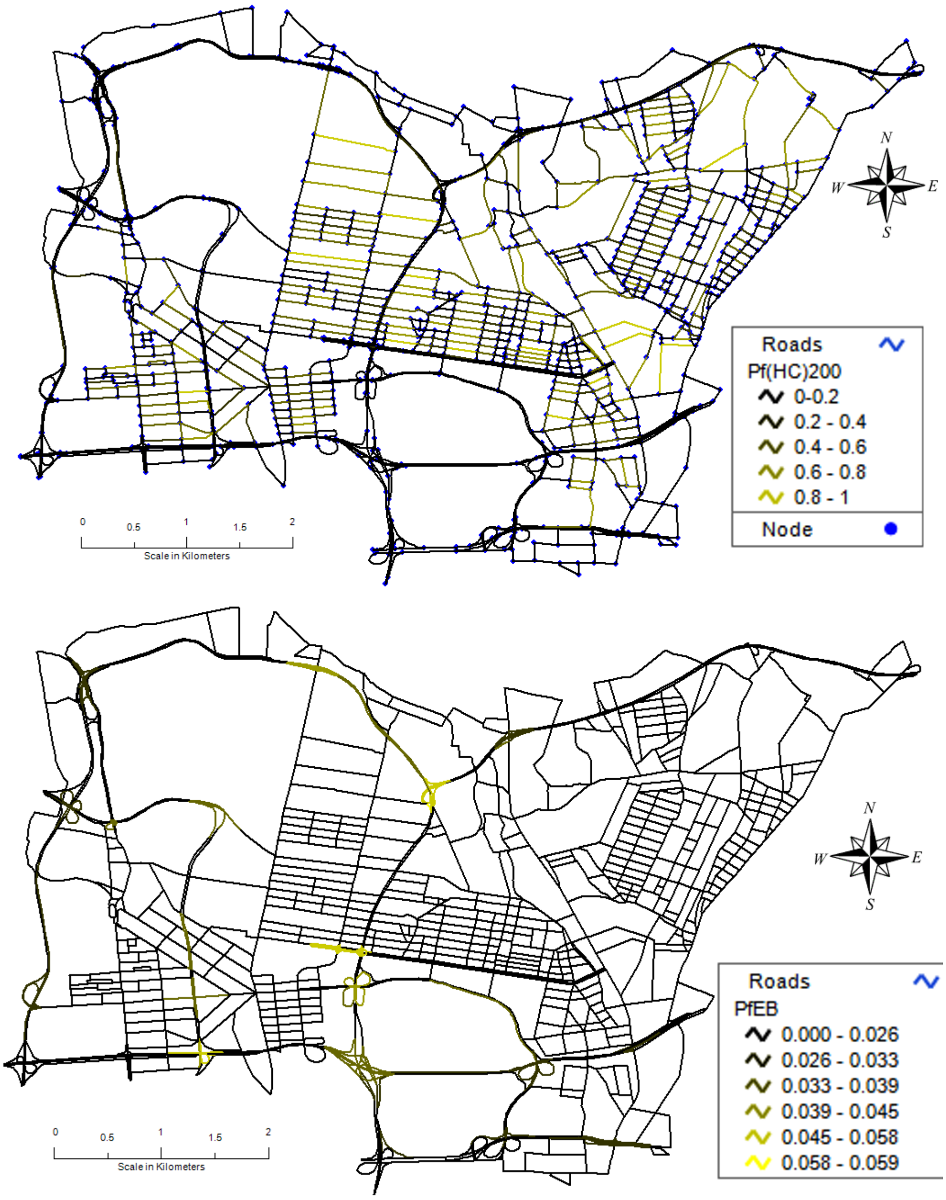

Figure 6. Probabilistic map showing the probability of at least one heavy closure (*HC*) on each road segments for event with 200 years return period: a) cumulative effect of both building debris and damaged bridges, b) effect of damaged bridges only

CONCLUSION

In this paper a probabilistic algorithm is proposed for estimation of urban road network performance following earthquakes. The approach takes into account the effects of both building damages as well as bridge damages on each road segment. The methodology, the developed GIS-based computer tool and the building inventory for a district in northern Tehran are used to test the performance of this approach. The preliminary results presented here show that damages to buildings could be of a major issue for the roads in this area. Mid and high rise buildings and relatively high density of built area in this district are main reasons for such results. Efficiency of emergency response in hours and days after earthquakes is directly related to the performance of urban road network and therefore, similar studies could help the authority to develop their risk reduction and mitigation measures. Such studies could also be used in the site selection process for new emergency centres (fire stations, medical and health centres, emergency storage centres, etc.) The tool developed here can be also used for performing realistic deterministic earthquake scenario, usually used for preparedness and design of post-disaster management measures.

REFERENCES

Argyroudis, S. and Momge, O. and Finazzi, D. and Pessina, V. (2003). Vulnerability assessment of lifelines and essential facilities (WP06), *methodological handbook – Appendix 1: Roadway transportation system, Risk UE Final Report, Report n◦ GTR-RSK 0101-152av7, February.*

Campbell, K,W and Bozorgnia, Y. (2006). Campbell-Bozorgnia NGA empirical ground motion model for the average horizontal component of PGA, PGV, PGD and Sa at selected spectral periods ranging from 0.01-10.0 second. *Pacific Earthquake Engineering Research Center University of California, Berkeley.*

Cheng, A,T. and Lee, Y,L. and Lin, C,Y. (2010). Urban Disaster Prevention Shelter Location and Evacuation Behavior Analysis, *Journal of Asian Architecture and Building Engineering/May 2010/220*

Firat, S. and Kubat, A,S. (2012). Syntactic Properities of Evacuation and Accesss Routes in Earthquake Vulnerability Settlement, *Eighth International Space Syntax Symposium Santiago de Chile: PUC, 2012.*

Franchin, P. and Lupoi, A. and Pinto, P.E. (2006). On the role of road network in reducing human losses after earthquakes. *Journal of Earthquake Engineering. 10(2), 195–206.*

Giovinazzi, S. and Nicholson, A. (2010). Transport Network Reliability in Seismic Risk Analysis and Management. *14th European Conference on Earthquake Engineering.*

Goretti, A. and Sarli, V. (2006). Road Network and Damaged Buildings in Urban Areas, *Short and Long-term Interaction. Bulletin of Earthquake Engineering. 4(2), 1573-1456*.

HAZUS99-SR2 Technical Manual, Chapter 7, direct physical Damage to Lifelines- Transportation System. *web source: http://nisee.berkeley.edu/response/hazusdamagetransport.pdf.*

Japan international cooperation agency (JICA) (2003) .The study on seismic micro zoning of the greater Tehran area in the Iran. Chapter 8.

Kim, Y,S. and Spencer, B,F. and Elnashai, A,S. (2008). Seismic loss assessment and mitigation for critical urban infrastructure systems. *Department of Civil and Environmental Engineering University of Illinois at Urbana Champaign, NSEL Report series.* Report No.NSEL -007.

Kiremidjian, A. and Moore, J. (2007) .Seismic risk assessment of transportation network. *Journal of earthquake engineering 11:371-382.*

Kyriazis, D,P. and Kalliopi, G,K. (2011). Seismic Risk Assessment and Management of Lifeline, Utilities and Infrastructure, *5th International Conference on Earthquake Geotechnical Engineering, Santiago, Chile.*

Lee, R. and Kiremidjian, A. (2007). Uncertainty and Correlation in Seismic Risk Assessment of Transportation Systems. *Pacific Earthquake Engineering Research Center College of Engineering University of California, Berkeley*. PEER Report 2007/05.

Nilsson, E. (2008) .Seismic risk assessment of transportation network in Charleston,SC. *A thesis presented to academic faculty, In Partial Fulfillment of the Requirements for the Degree Master of Science in Civil Engineering. Georgia Institute of Technology*.

Rossi, R. , Massimiliano, G. , Federico, C. , Carlo, P. and Claudio, M. (2012). Planning and management of actions on transportation system to address extraordinary events in post-emergency situations. A multidisciplinary approach, *European Transport, Issue 51, Paper N° 2, ISSN 1825-3997.*

Runzhou, L. and Junqi, L. and Xiaolan, Z. (2008) .Study on the Post Earthquake Conectivity of Transportation System Network. *The 14th World Conference on Earthquake Engineering: 06-0103.*

Stephanie, E. and Nobuoto, N. (1999). Measuring Post-Disaster Transportation System Performance: The 1995 Kobe Earthquake in Comparative Perspective, *Transportation Research*

WERNER, S,D. and Cho, S. (2007). Use of Seismic Risk Analysis of Roadway Systems to Facilitate Performance-Based Engineering and Risk-Reduction Decision Making.

Yongjun, N. and Wanhong, W. and Shimin,H. and Shengcong, F. and Xianren, O. (2008). GIS-Based Earthquake Disaster Prediction and optimum Path Analysis for the Urban Road Transit System. *The 14th World Conference on Earthquake Engineering: S02-047*.

Zhou, Y. and Banerjee, S. and Shinozuka, M. (2007). Seismic risk mitigation of spatially distributed urban infrastructure system and its impact on societal economy. *2nd International conference on urban disaster reduction.*

Zolfaghari, M,R. (2010). Definition of new Seismogenic Sources to Model Probabilistic Seismic Hazard for the City of Tehran, *14th European Conference on Earthquake Engineering, Ohrid, Macedonia.*