Earthquake risk in urban street network: an example from region 6 of Tehran, Iran

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Abstract

Purpose – Zone 6 of Tehran, with a populations of 220,000 people (3.6 per cent of the city population) and 20 km^2 area (3 per cent of the city area), is one of the main municipal zones of Tehran. Major land-uses, like ministries, embassies, universities, general hospitals and medical centers, big financial firms, and so on, manifest the high importance of this region on a local and national scale. Thus, it is necessary to pay close attention to issues concerning crisis management in this area.

Design/methodology/approach – In this paper, by using indexes such as access to medical centers, street inclusion, building and population density, land-use, peak ground acceleration and building quality, vulnerability degree of street networks in zone 6 against the earthquake is calculated through overlaying maps and data in combination with inversion hierarchical weight process method and geographic information systems.

Findings – This article concludes that buildings alongside the streets with high population and building density, low building quality, far to rescue centers and high level of inclusion represent high rate of vulnerability, compared with other buildings. Also, by moving from north to south of the zone, the vulnerability increases. Likewise, highways and streets with substantial width and low building and population density hold little values of vulnerability. Thus, streets with high level of inclusion, building and population density present further vulnerability.

Originality/value – It is expected that the results of this paper be used by the urban decision-makers. Due to high vulnerability of most parts of the urban textures of Tehran, similar researches will have importance for preparation for the future possible earthquakes.

Keywords Vulnerability, GIS, Earthquake, IHWP, Street network

Paper type Case study

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Introduction

After earthquake, due to fall down of buildings and possible street blocks, efficiency of street networks substantially falls (Chen *et al.*, 2002). While, in case of any incident or great urgency, street networks play a critical role in saving lives, speeding up the reconstruction operations and the recovery of the city to stabilize the condition (Liu *et al.*, 2003). In other words, street networks are of crucial importance in the aftermath of earthquake, especially in restoration and recovery of the city. As in recent earthquakes, because of damage to street networks, traffic circulation was completely blocked, urban activities were knocked down and immediate recovery of the city was nearly impossible (Nojima and Sugito, 2000).

Physical expansion and high density of the big cities will result in catastrophic conditions in case of an earthquake. Selecting seismic vulnerable areas for construction, poor street network hierarchy, insufficient road width, inaccessible health care centers and services can intensify the calamitous results. In urban textures with the mentioned characteristics, occurrence of earthquake with great magnitude will destroy the street network efficiency and cause great human casualties and financial damage.

However, controlling the earthquake strike is impossible, but mitigating its damages is quite feasible. The most important point is to save people's lives against such disasters; taking this in account, the role of street networks during the earthquake is indisputable. Also, after the earthquake, the main problem is to rescue and aid the wounded people. The street networks have profound effect in this process. In other words, roads and paths trapped between demolished buildings play a key role in the aftermath of the earthquake.

The high number of earthquake casualties in Iran makes the planning for the aftermath of the earthquake complicated. Although 1 per cent of world population is accommodated in Iran, victims of earthquake in Iran make up 6 per cent of world casualties (Ablaghi, 2004). The necessity to mitigate the social damages of earthquake (victims and injured people), economic damages (reconstruction costs and shutdown of financial activities in city) and physical damages (demolishing of buildings) is obvious. In addition, there will be many other concerns such as demolition of fabrics, delay in evacuation of residents, blockage in street networks, absence of on time rescue and digging out trapped people under the wreckage. Many of these people may die if immediate access and rescue do not take place. This means the vulnerability of street networks will cause serious difficulties in the first 72 hours of rescue operations (Chen *et al.*, 2002).

Importance of the mentioned concerns and the necessity to quick reaction makes the street network planning an essential practice. This requires roads with special access, which can maintain their functionality after the crisis, suffer the least damage and expand their area of operation. It is clear that under such conditions, street networks must retain their efficiency and safety. Earthquake will bring about several difficult situations like destruction of residential areas, buildings, structures, infrastructures, bridges, roads, railways, power lines and water supply. These damages will have considerable effects on the neighboring access networks.

Items such as land use, building quality, road width, building height, hierarchy of roads and distance to medical care centers have a profound effect in controlling earthquake damages. Hence, detailed study of these factors and identifying safe or vulnerable roads and areas significantly mitigate the damages and provide the possibility of proper planning for the city. This requires a comprehensive study on the mechanisms and techniques of alleviation of earthquake effects.

Identifying major environmental challenges has made the urban transportation planning face many difficulties. Design of corridors, streets and roads is to provide safe mobility and access for people and to resolve economic, social and environmental problems (Kennedy *et al.*, 2005). One of the biggest natural disasters that man faces is an earthquake.

The structure of the urban texture has multi-layer characteristics including human activities, amenities and infrastructures. This will lead to inconsistency within the city. In such a situation, a noteworthy notion to think of is street network. People may prefer to move from unsafe areas to privileged ones; but in case of environmental catastrophes, especially earthquake, street networks will break apart. In this case, street networks should provide the least service to save residents' lives. As a result, street networks must be designed to retain the accessibility of different parts of the city during any environmental disaster (Huang, 2003, p. 96).

Urban street network has a huge impact on the vulnerability of city against the earthquake. If the urban street network remain intact and maintain its functionality after the earthquake, number of casualties, due to access to safe spots and free circulation of rescue vehicles, will substantially drop (Abdollahi, 2001).

Recent earthquakes of Iran indicate the vulnerability of urban and rural areas against the earthquake. The earthquakes of Buinzahra (1962), Roodbar (1990) and Bam (2004) have each resulted in massive losses. Only the last one, Bam earthquake, had the casualties of more than 30,000 deaths, 10,000 wounded, more than 100,000 homeless and destruction of more than 80 per cent of the city and social infrastructures with total damage cost about $800 million (Iranian Bureau for Research and Coordination of Safety and Reconstruction Affairs, 2005, National report of the Islamic republic of Iran on disaster reduction, p. 8). Four days after the earthquake in Bam, an earthquake of similar scale hit San Robles in California, which left only two victims (United Nations International Strategy for Disaster Reduction, 2005).

Region 6 of Tehran (Figure 1), with a population of 220,000 (3.6 per cent of city population) and a 20 km^2 area (3 per cent of city area), is one of the main municipal regions of Tehran (Iran Center of Statistics, 2006). The major land uses, like ministries, foreign embassies, universities, general hospitals and medical centers,

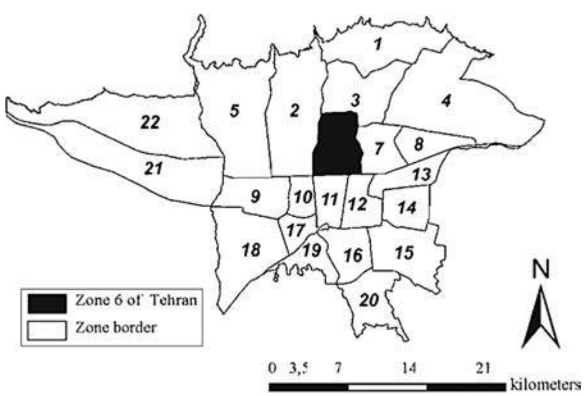

Figure 1.

big financial firms, and so on, manifest the high importance of this region on a local and national scale. Thus, it is necessary to pay close attention to issues concerning crisis management because any possible damage to this region, caused by natural disasters, will cause various economic and social damages to official workers and residents. A set of these facts and factors made this region an adequate case study to investigate.

Urban vulnerability against earthquake depends on human attitude, which indicates the degree of exposure or resistance of economic, social and physical units of the city against earthquake (Rashed and Weeks, 2003). Earthquake of Kobe in Japan on January 17, 1995, was a milestone in studying the role of street networks in mitigating hazards of earthquakes (Minami *et al.*, 2003). This incident considerably affected the planning process for preparation against the earthquake in Japan. Delayed reaction and absence of adequate preparation against such a devastating earthquake held the local and central government's responsible (Habibi *et al.*, 2010). After this earthquake, the role of street networks came to attention and various researches, such as the work of Chang and Nojima (1998), Tsukaguchi and Li (1999), Odani and Uranaka (1999), Chen *et al.* (2002), Lee and Yeh (2003), Liu *et al.* (2003), Minami *et al.* (2003) and Samadzadegan and Zarrinpanjeh (2008), were conducted to put this new concept under consideration.

Baghvand *et al.* (2006) in their article identified main factors which threatened the access networks after earthquake. They proposed a number of recommendations to increase the efficiency of street networks in urban areas and particularly in dilapidated urban fabrics after the disaster. Chang and Nojima (1998, p. 12) studied the functional conditions of highways after the earthquake in the USA and Japan (earthquakes of 1989 in Loma Prieta, 1994 in Northridge and 1995 in Kobe). After the earthquake of Hanshin, Avaji, Tsukaguchi and Li developed a model to identify the factors resulting in blockage of roads and presented an improved version of their model to enhance the design and the structure of street networks (Tsukaguchi and Li, 1999). Liu *et al.* (2003) proposed an algorithm to evaluate the traffic capacity of street network using demand control criteria like traffic regulation for damaged street networks.

Minami *et al.* (2003) collected data from Yube in Japan, such as building name, number, type of structure and number of floors, backyard type and height, distance from street, street width and length and sidewalk width, and analyzed them in a geographic information system (GIS) environment. Lee and Yeh (2003), after examining 921 great earthquakes of world, concluded that the main reason of street blockage during the earthquake is the road width less than 4 meters.

Samadzadegan and Zarrinpanjeh (2008) focused on design and development of a method to evaluate the vulnerability of street networks using digital photogrammetric maps prior to the earthquake and high quality aerial photographs after the earthquake.

A brief literature review shows that recently conducted surveys lack focused and detailed analysis of governing parameters such as street inclusion, building quality, building and population density, land use, sidewalks structures and easy access to medical centers despite their significant importance. The above-mentioned factors play an important role in reduction of earthquake destructions, while investigation of vulnerability of street networks regarding their effects can be very helpful in decreasing the earthquake destructive effects.

Methodology and analysis

Assessing street network vulnerability studies, the spatial structure of the street network and the areas of city which have high exposure and generally is used in evacuation of city have been identified. This vulnerability is significantly connected with network structure, environment and traffic (Husdal, 2006). The vulnerability of network structure depends on street network and its concerning factors like topology and geometrical form. Natural and environmental conditions affect the street networks by altering circulation in the network especially during rush hours. Various factors influence the evacuation process. Identifying the weakness, vulnerability and critical condition of urban areas is important, especially in areas, in which vulnerability may shut down the whole network. Studying street networks discover vulnerable areas during the evacuation. Thus, accessibility plays a central role (Miriam and Shulman, 2008, pp. 16-20).

Despite this, various points have been presented on vulnerability of street networks. Most of these standpoints have concentrated on destroying vulnerable areas or networks (Taylor *et al.*, 2006). Also, street networks have been studied by applying optimum comparison methods of failure scenarios to find the best possible circumstances (Shen *et al.*, 2007). Identifying critical situations is an approach to evaluate different alternatives of network downgrade during an incident (Taylor *et al.*, 2006). The critical point of an area in street network is a place that if it is downgraded or shut down, it will dramatically affect the access circulation within the network (Miriam and Shulman, 2008, pp. 16-20).

In studying street network vulnerability two concepts have been frequently referred to; the first one is redundancy and the other is flexibility. Redundancy refers to areas, in which various paths between origin and destination exist (Sohn, 2006). The purpose of flexibility is to promote the possibility of rapid evacuation through streets. Construction of roads and streets causes high expenses, but as long as safety is concerned, streets with redundancy provide more escape possibility. As a result, when a road is unusable, there exist various ways to run off.

To mitigate vulnerability, another approach is to limit two-way roads during the evacuation operation. This provides continuous circulation of traffic and facilitates the locomotion of people out of the damaged areas (Cova and Johnson, 2003). This method is not applicable in large cities. Within a neighborhood, residents are aware of available amenities; thus, they can be easily controlled. But in a large city, this method cannot be applied (Miriam and Shulman, 2008, pp. 16-20).

To access the vulnerability of case study against earthquake, seven indexes were picked out:

(1) *Road width to building height ratio (closure degree)*: This is a critical factor because increase in closure degree (higher buildings and limited road width) escalates the possibility of blockage in streets. This will result in accumulated debris on roads and considerably impede the rescue operations and sheltering.

(2) *Population density*: An index, which indicates the distribution of population over the roads and streets during the earthquake. High density of population will slow down the rescue operation and finding a safe place.

(3) *Building density*: Another important factor that if increased, will cause more damage and vulnerability.

(4) *Land-use*: Type of street-side land uses may increase or decrease the vulnerability of street. Hence, land uses of the case study area are categorized in three classes of high risk, medium risk and low risk.
(5) *Building quality*: This factor profoundly affects the vulnerability of the building. Newly built buildings seem to have more resistance against the earthquake rather than repaired or dilapidated ones.
(6) *Peak ground acceleration (PGA)*: One of the major factors in building design and consequently building vulnerability is the magnitude of PGA during the earthquake. PGA is calculated by a coefficient derived from the earth gravity acceleration, which is represented by *g* (Ghodrati, 2007, p. 19). This article measures PGA by cm/s^2.
(7) Access to health and service centers: access to medical centers is provided through street networks. This speeds up the process of rescue and service providing. Thus, by getting away from health and service centers, vulnerability increases.

Estimating potential vulnerability is usually surrounded by obscurities and uncertainties because the Boolean sets do not let the vulnerability factors to be a member of a continuous spectrum. Thus, inversion hierarchical weight process (IHWP) model is applied.

After selecting desired layers based on the importance value of each factor, chosen indexes are ranked using entropy index (collecting expertise opinions). Then, the reversed score of each layer is considered as its weight in the IHWP model. In the Delphi model, with respect to experts' opinion, the mentioned seven indexes are ranked based on the importance value of each. Thus, the most important index, in connection with seismic vulnerability, gains 7 and the less important index gains 0 value (Habibi, 2006).

At this stage, one or two assumptions are assigned to each index. For instance, for calculating closure, the main assumption is that short buildings along wide streets (minor closure) provide better movement capability due to low pile of wreckage on streets. But in the areas with high degree of closure, high level of destruction and vulnerability is expected. The closure degree map is classified into seven categories. Regarding the rank of this index, among other indexes, buildings with low level of closure will gain the least score and buildings with high level of closure are expected to gain the highest score. Access to medical centers has a crucial effect on mitigating negative consequences derived from natural and non-natural incidents. The main responsibility of medical centers during the earthquake is reducing the number of victims. Therefore, distance and access to medical centers during urban crisis will change the vulnerability degree of an urban area (Habibi, 2006).

Also, this rule applies to every community; increase in vulnerability is expected when there are increases in building density, closure degree, inconsideration of construction criteria, PGA, age of building, land-use inconsistency, unattainable evacuation of land-uses and length of infrastructures networks like gas or oil lines. Table I shows the rank and the inverse of rank of the selected indices according to Delphi's model.

The calculation of selected layer scores using IHWP model is done in the following manner:

$$X = \frac{D}{N}$$

Where

X = primary score of each index,
D = score derived from Delphi model,
N = number of classes of each index.

$$j = D - (N - i)X$$

Where

j = score calculated for different classes of each index,
i = assigned number to different classes of each index.

In Figure 1, Table II of selected indexes and their classification and score are presented. Embraced numbers with parentheses under index column indicate scores derived from Delphi model (D) and numbers in parentheses under classification table show the number assigned to different classification of each index (i). In the end, score of each class of indexes is calculated.

At this stage, according to reversed score gained, the classes of each layer are weighted and by applying the Raster Calculation tool, score columns of data layers add up. Thus, seven columns represent seven data layers and determine the score of vulnerability and stability of each building unit in every lot relative to the other lots. The mathematical operations on data are done at one stage.

Results and discussion

The final map of vulnerability against earthquake is created with data classified at five levels (including very low, low, medium, high and very high). In other words, score of each lot is calculated by adding up seven indexes and categorization classes. Thus, the vulnerability map of region against the earthquake is created. The modeling procedure of Tehran's region 6 communication networks vulnerability versus earthquake is depicted in Figure 2. Figure 3 shows the final vulnerability plan according to the IHWP model.

Considering the vulnerability map of street networks in region 6 (Figure 4), streets with sufficient width, which provide better access to rescue centers, possess an

Index	Score	Reversed score	Weighting assumptions
Inclusion degree	4	4	Less closure = less vulnerability
Population density	3	5	Less population density = less vulnerability
Building density	2	6	Less building density = less vulnerability
Land-use	5	3	Less risky land-use = less vulnerability
Building quality	1	7	More building quality = less vulnerability
PGA	6	2	More PGA = less vulnerability
Access to medical centers	7	1	More access to medical centers = less vulnerability

Table I.

Score	Classification	Index
0.55	0-50 (1)	Building density (layer score = 6)
1.09	50-100 (2)	
1.64	100-150 (3)	
2.18	150-200 (4)	
2.73	200-250 (5)	
3.27	250-300 (6)	
3.82	300-350 (7)	
4.36	350-400 (8)	
4.91	400-450 (9)	
5.45	450-500 (10)	
6	More than 500 (11)	
1.4	0 (1)	Building quality (layer score = 7)
2.8	New (2)	
4.2	Maintainable (3)	
5.6	Fixed (4)	
7	Dilapidated (5)	
0.1	0-50 (1)	Access to medical centers (layer score = 1)
0.2	50-100 (2)	
0.3	100-200 (3)	
0.4	200-300 (4)	
0.5	300-400 (5)	
0.6	400-500 (6)	
0.7	500-750 (7)	
0.8	750-1,000 (8)	
0.9	1,000-1,250 (9)	
1	more than 1,250 (10)	
0.83	less than 100 (1)	Population density (layer score = 5)
1.67	100-200 (2)	
2.50	200-300 (3)	
3.33	300-400 (4)	
4.17	400-500 (5)	
5	more than 500 (6)	
0.57	less than 0.3 (1)	Inclusion degree (layer score = 4)
1.14	(2) 0.3-0.6	
1.71	(3) 0.6-0.9	
2.29	(4) 0.9-1.2	
2.86	(5) 1.2-1.5	
3.43	(6) 1.5-2	
4	more than 2 (7)	
0.5	(1) 244.05-255.37	PGA (layer score = 2)
1	(2) 255.37-260.69	
1.5	(3) 260.69-277-07	
2	more than 277.07 (4)	
1	low risk (1)	Land use (layer score = 3)
2	medium risk (2)	
3	high risk (3)	

Table II.

Source: Google maps

Figure 2.

acceptable degree of vulnerability. In other words, these streets are located in areas which have gained vulnerability score of low or very low. On the fringe of these streets, population and building density are usually low and building quality is moderate. These routes include highways of region 6, which are located at the boundaries of regions, like Modarres and Chamran highways, and those which are located inside of the region like the Kordestan highway (Figure 5). The big problem with the highways is the traffic volume, which produces heavy traffic at specific hours in these routes (on horizontal routes in the mornings east to west and in the evenings west to east, on vertical routes in the mornings south to north and in the evening north to south have the heaviest traffic of day).

In general, streets located at the north of the region have a low level of vulnerability. By moving on from north to south over the region, vulnerability raises. The reason is that northern areas of the region, compared to southern areas, have streets with adequate width and reinforced and new buildings. The congestion of ultra-regional land uses, such as Tehran and Amirkabir universities and also ministries, in the southern part of the region and existence of commercial land uses absorbing traffic, particularly in Enghelab and Valiasr streets, both have made the southern part of the region more vulnerable to earthquake. Likewise, the Kargar Street, due to narrow width, being dead-end, abundance of intersections with red lights and the lack of elevated separations, is not in a good condition. The vulnerability of Kargar Street, especially after Jalal-e-Al-e Ahmad Avenue at the eastern side, is observable. The reason is the high-density land uses located at the eastern side of the street.

Existence of land uses with large areas, low population and building density and little closure in highways, lead to slight vulnerability and better conditions. These highways, as vital arterials, play a critical role in the aftermath of earthquake and the

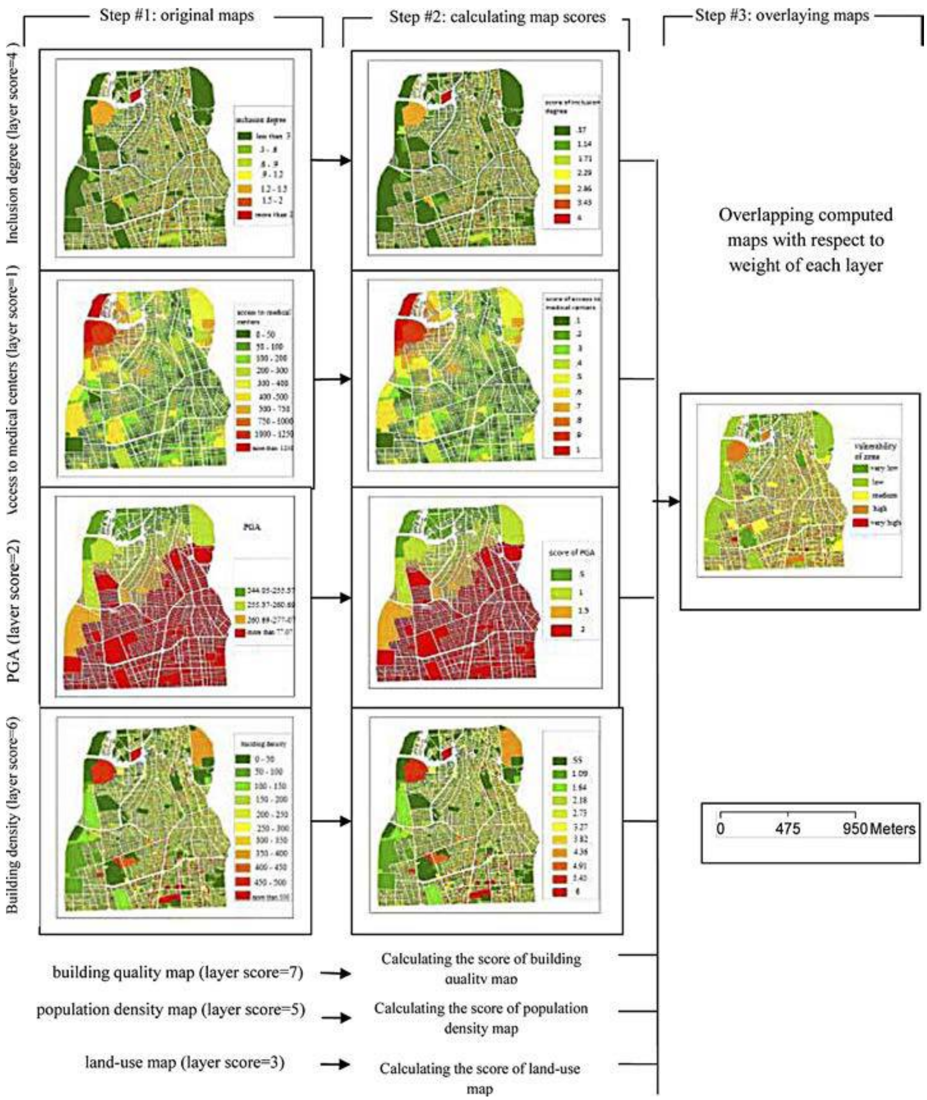

Figure 3.
Modeling steps for evaluating street network vulnerability against the earthquake in region 6 of Tehran

little vulnerability of them speeds up the rescue process. However, Resalat Tunnel in the north of the region has unraveled the traffic problems of the area, but absence of a horizontal road in this area will cause difficulties in access to rescue centers and open spaces.

Conclusion

Communication networks are a place for providing aid and safeguard. If communication networks excel at their duties, death toll and economic loss will be minimized in the city. A path can be efficient in aiding and safeguarding process, which itself experiences the

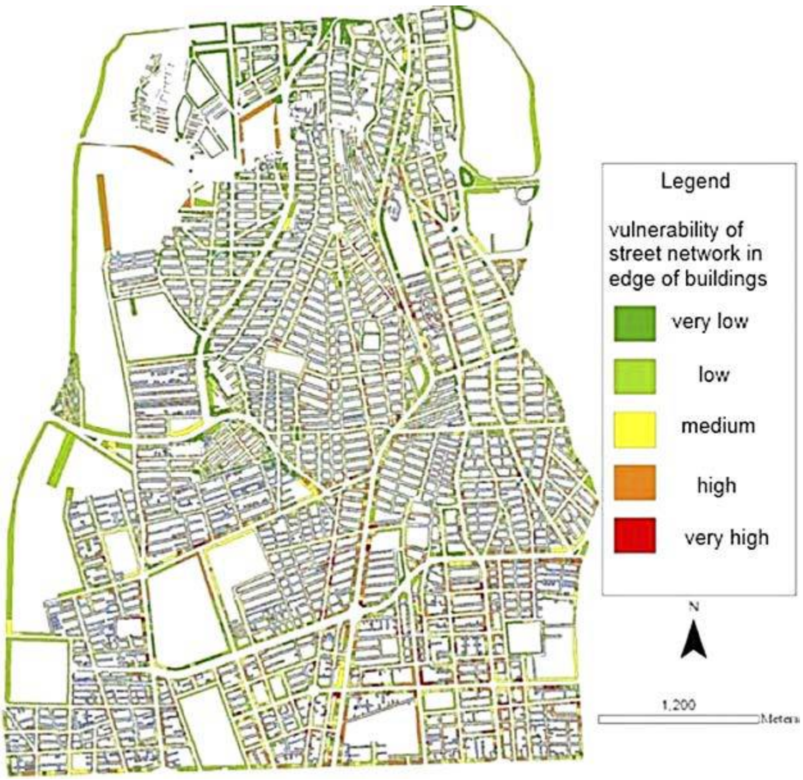

Figure 4.
Vulnerability of street network in edge of buildings

least destructions during disaster. Dominant specifications of a path efficient in reduction of earthquake destructions can be addressed as: less street inclusion, easy access to medical centers, hierarchical feature and not to be isolated, possessing no traffic issues, safety, robust structures, less population and building density, not to be located on earthquake-line and finally healthiness of structures' sensitive applications.

In this study, to evaluate the vulnerability degree of street networks, at the first stage, seven indexes of closure, land use, building density, population density, building quality, access to medical centers and PGA were selected and vulnerable lots to earthquake were identified. By applying these indices, the vulnerability map of street networks in region 6 was created. This map indicates that the streets in the south of the region have a great vulnerability to earthquake.

In general, the region 6 north communication network structures due to low population and building density and newly built structures have better situation regarding vulnerability. Also, these streets possess less inclusion and due to network safety and hierarchical feature have better access to medical centers. Path structure vulnerability increases from Shahid Ghomnam Street toward south and reaches its maximum at south of the region. So, it is obvious that networks which are located in southern region are inefficient as earthquake hitting. Highways located inside or boundary of region have less or moderate vulnerability regarding factors such as safety,

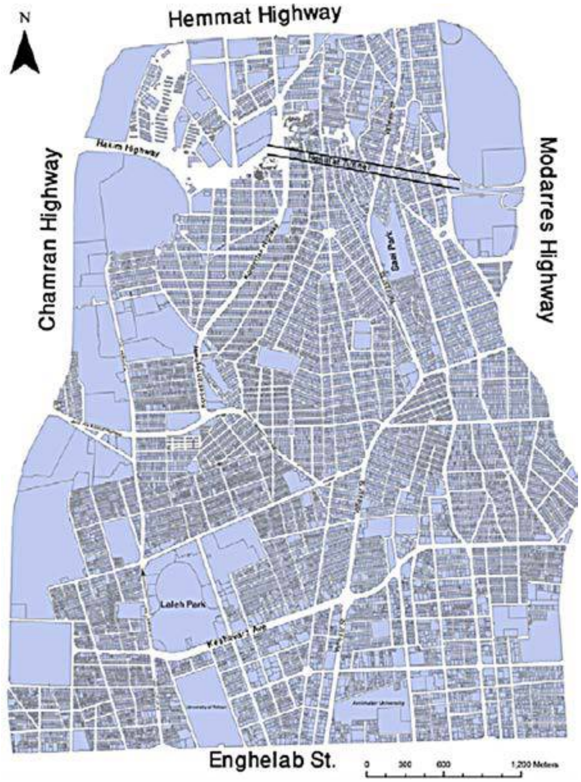

Figure 5.

speed, possessing less conjunctions, better structure quality, less inclusion degree and population density. The long streets such as the Kargar and Valiasr up to central regions are not safe enough and are considered as the most danger-exposed streets.

Inclusion is important in increase or decrease of path's vulnerability. As inclusion degree is greater than 1, the probability of street closure due to fall of destructions increases. This item increases the rescue time and earthquake death toll. Inclusion degree in southern region due to its high commercial and official role increases. The only streets that have good conditions are Enghelab Street and Karghar Street. The northern areas have less inclusion degree. Streets that have a better access to medical centers may reduce the rescue time in accordance with other factors. Hospitals and medical centers are target points in rescue operation. In other words, the final destination of ambulances is medical centers and hospitals. So, hospital buildings should be located along the streets, which play a critical role in rescue operation.

References

Abdollahi, M. (2001), *Crisis Management in Urban Areas*, Anvar Publications, Tehran, pp. 93-94.

Ablaghi, A. (2004), "Editorial note", *Haft Shahr Magazine*, Organization of urban construction and rehabilitation, No. 18 & 19.

Baghvand, A., Nazariha, M., Saffarzadeh, M. and Givechi, S. (2006), "Investigating the reasons and solutions of downgrade in function of urban transit system in the aftermath of the earthquake", *2nd Conference of Construction in Capital City, Engineering Faculty of Tehran University*, *Tehran*.

Chang, E.S. and Nojima, N. (1998), "Measuring lifeline system performance: highway transportation systems in recent earthquakes", *Proceedings of the 6th US National Conference on Earthquake Engineering*, *Seattle, WA*, Paper No. 70.

Chen, A., Yung, H., Lo, H.K. and Tan, W. (2002), "Capacity reliability of road network: an assessment methodology and numerical results", *Transportation Research*, Vol. 36 No. 3, pp. 225-252.

Cova, T. and Johnson, J. (2003), "A network flow model for lane-based evacuation routing", *Transportation Research Part A*, Vol. 37 No. 7, pp. 579-604.

Ghodrati, A.G. (2007), *Risk Evaluation of Structures against Earthquake*, Iran University of Science and Technology, Tehran.

Habibi, K. (2006), "Evaluating physical development policies, renewal and rehabilitation of urban historical fabrics using GIS", Doctoral thesis in urban geography, Tehran University, Tehran.

Habibi, K., Ardakani, S.A. and Nazari, S. (2010), *Urban Vulnerability and GIS*, Emam Hossein University Press, Tehran.

Huang, Z. (2003), *Data Integration For Urban Transport Planning*, International Institute for Geo-Information Science and Earth Observation (ITC).

Husdal, J. (2006), "Transport network vulnerability: which terminology and metrics should we use?", paper presented at the *NECTAR Cluster 1 Seminar*, 12-13 May.

Iran Center of Statistics (2006), *Census of 2006*, Iran Center of Statistics, Tehran.

Iranian Bureau for Research and Coordination of Safety and Reconstruction Affairs (2005), "National report of the Islamic republic of Iran on disaster reduction", *World Conference on Disaster Reduction*, Kobe.

Kennedy, C., Miller, E., Shalaby, A., Maclean, H. and Coleman, J. (2005), "The four pillars of sustainable urban transportation", *Transport Reviews*, Vol. 25 No. 4, pp. 393-414.

Lee, Y.L. and Yeh, K.Y. (2003), "Street network reliability evaluation following the Chi-chi earthquake", in Bell, M.G.H. and Iida, Y. (Eds), *The Network Reliability of Transport, Proceedings of the 1st International Symposium on Transportation Network Reliability (INSTR)*, pp. 273-288.

Liu, B., Masuya, Y., Saito, K. and Tamura, T. (2003), "The restoration planning of road network in earthquake disasters", *Proceedings of the Eastern Asia Society for Transportation Studies*, Vol. 4, pp. 526-539.

Minami, M., Akatani, R. and Ando, A. (2003), "Street network planning for disaster prevention against street blockade", *Proceedings of the Eastern Asia Society for Transportation Studies*, Vol. 4, pp. 1750-1756.

Miriam, H. and Shulman, L. (2008), "Estimating evaluation vulnerability of urban transportation systems using GIS", Master thesis, Department of Geography, Queen's University Kingston, Ontario, Canada.

Nojima, N. and Sugito, M. (2000), *Simulation and Evaluation Of Post-Earthquake Functional Performance Of Transportation Network*, 12 WCEE, 1927/7/A.

Odani, M. and Uranaka, K. (1999), "Road block in area affected by the great Hanshin-Awaji earthquake and influence of blockage on traffic flow", *Journal of the Eastern Asia Society for Transportation Studies*, Vol. 3 No. 6.

Rashed, K. and Weeks, J. (2003), "Assessing vulnerability to earthquake hazards through spatial multicriteria analysis of urban areas", *International Journal of Geographic Information Science*, Vol. 17 No. 6, pp. 547-576.

Samadzadegan, F. and Zarrinpanjeh, N. (2008), *Earthquake Destruction Assessment Of Urban Roads Network Using Satellite Imagery And Fuzzy Inference Systems*, Part B8. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Beijing, Vol. 37, pp. 409-414.

Shen, W., Nie, Y. and Zhang, H. (2007), "A dynamic network simplex method for designing emergency evacuation plans", *Transportation Research Board of the National Academies*, pp. 83-93.

Sohn, J. (2006), "Evaluating the significance of highway network links under the flood damage: an accessibility approach", *Transportation Research, Part A*, Vol. 40 No. 6, pp. 491-506.

Taylor, M., Sekhar, S. and D'Este, G. (2006), "Application of accessibility based methods for vulnerability analysis of strategic road networks", *Network Spatial Economy*, Vol. 6 Nos 3/4, pp. 267-291.

Tsukaguchi, H. and Li, Y. (1999), "District and local distributor network to ensure disaster-resilient urban planning", *99th Shanghai International Symposium on Urban Transportation Proceedings.*

United Nations International Strategy for Disaster Reduction (2005), *World Conference on Disaster Reduction, Proceedings of the Conference*, Kobe, 18-22 January.

Further reading

Lee, Y.L., Ho, M.C., Huang, T.C. and Tai, C.A. (2007), "Urban disaster prevention shelter vulnerability evaluation considering road network characteristics", *2nd International Conference on Urban Disaster Reduction*, 27-29 November.

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2. Arman Nedjati, Bela Vizvari, Gokhan Izbirak. 2016. Post-earthquake response by small UAV helicopters. *Natural Hazards* **80**:3, 1669-1688. [CrossRef]