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ORIGINAL RESEARCH PAPER

Underground transportation system risk assessment to mitigate vulnerability against natural disasters through intelligent urban management

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ABSTRACT

Quantitative and qualitative monitoring and evaluation of risk management programs will play an important role in the development of Tehran metropolitan railway transport. Considering the tectonic studies, seismic zones, land degradation and faults in north and south of Tehran, the development of underground railway lines, the assessment of the vulnerability of subway stations and the escalation of the crisis with the destruction of urban exhausted earthquakes is very important with the occurrence of earthquake and flood. This study, focusing on the issue of risk assessment and vulnerability of the development of the rail transport network and the approach to physical and aerospace hazard monitoring of metro stations. For this purpose, three selected metro stations in Tehran were studied. In the research, a combined method based on library studies, review of records and records, Delphi technique, AHP method, and overlaying of layers have been used. The results of the vulnerability assessment indicate that each of Tajirish, Nawab and Darvazeh Shemiran, with a risk number of 5.10, 5.76, and 5.79, are in the risk limit range, respectively. In fact, all stations need to adopt smart measures and management and executive solutions to reduce potential damage.

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INTRODUCTION

Expansion of rail transport network, both intra-city (the metro) and intercity, is always prone to natural and human disasters due to its special aspects, and reducing the consequences of such disasters constant has always been a concern to. The natural disasters are the types of accidents caused by natural phenomena or anthropogenic activities that could occur suddenly or gradually with considerable economic damages, human losses and psychological disorders (Khaledi, 2001; Rafee *et al*., 2008). In general, two perspectives matter: pre-disaster and post-disaster. Intelligent management plays a key role in sustainable development of settlements as well as mitigating vulnerability of urban infrastructures. The nature of natural disasters such as earthquakes and floods necessitates making immediate, precise decisions and monitoring vulnerable spots within urban context, transport network, and infrastructures, which holds certain quantitative and qualitative aspects when it comes to underground transportation. Goodchild (2010) developed a map in GIS environment where information such as topography, faults, sensitive infrastructures, and population distribution were

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used to build a vulnerability model. Antonioni et al investigated the impact of seismic activities on industrial facilities by using previous seismic data to introduce an algorithm (Shiae *et al*., 2010). Rashed and Weeks (2003) modeled seismic vulnerability by employing indicators, including minimum resilience of bridges, emergency medical services, hospitals, highways, the metro network, maximum cost of rebuilding buildings, and so forth, fed into analytic hierarchy process (AHP) in GIS environment. Askarizadeh *et al.* (2017) investigated the earthquake damage in Ray. In this study, the past earthquake incidence in Ray was reviewed using hazards United States tool as a geographic information system-based natural hazard analysis tool. Fujino and Takada (2009) presented a method for estimation of destruction debris and evaluation of available options for debris management in Tokyo. Nouri *et al.* (2011) studied the utilizable methods for controlling the generation of destruction debris in building sites. Lessening vulnerability of urban communities against earthquakes is realized only if seismic safety is considered throughout planning levels, among which the middle-level physical planning is particularly effective (Habibi *et al*., 2008). Deficiency in physical planning and intelligent disaster management has led to so irreversible physical and mental toll that the human loss caused by earthquakes accounts for 6% of the whole mortality in Iran during the last 100 years while it has claimed 1% of the world population in the past 100 years. Within the underground transportation system, stations are of outstanding importance due to their high population density. The advent of disasters with multilateral aspects, e.g. natural disasters, lead to secondary disasters in the metro system, instances of which include explosion of gas pipes, leakage of gasses, permeation of hazardous waste from sewer pipes, leak from wells followed by large flooding, deformity of rails, and derailing of trains (Al-Sheikh, 2007). Seismic statistics of Tehran indicate that every 158 years one great earthquake occurs. The last quake in Tehran, attributed to the Mosha Fault, took place in 1830. Now after 185 years since this with no incident of earthquakes, probability of a severe quake is expected to increase. Population growth followed by infrastructure development to fulfill human amenity can also result in risk. While natural disasters on average incur a 60 to 100-billion-dollar loss, if a massive disaster happens in the center of a metropolis, the loss is projected to be even more extravagant (JICA, 2006). The current study attempted to investigate the role of intelligent disaster management in the expansion of underground transportation network and accordingly introduce suitable approaches and new tools to decrease and cope with natural disasters (earthquakes and floods).

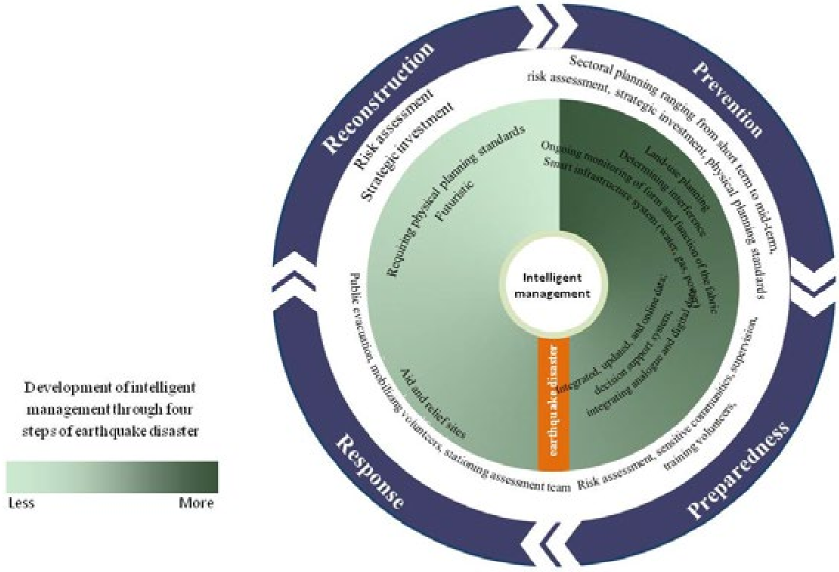


Fig. 1. Intelligent management model for urban physical planning against earthquakes(TUSROC, 2014)

Other aims include gaining access to the information on the fault lines, the streams, the metro stations; and planning for smart monitoring in case of incident as well as identifying the nearest medical centers, the urban open spaces in Tehran – according to the types of disasters. In the present research, the relationship between physical planning, transportation network as well as infrastructures with vulnerability against earthquakes was analyzed – an intelligent disaster management policy to reduce vulnerability (Fig. 1).

The smart city approach is emerging as a way to solve tangled and wicked problems inherited in the rapid urbanization (Pardo and Burke, 2008). City leaders can develop a social infrastructure for collaboration through which multiple organizations join their efforts across boundaries of jurisdictions and sectors (Kanter and Litow, 2009). Among concepts pertaining to the smart city, four are relevant to seismic management through urban management information system (UMIS) concerning underground transportation as follows:

- Smart health and medical care
- Smart construction
- Smart infrastructure
- Smart technology

Any normative claim about the future of cities is necessarily contextual (Dawes *et al*., 2004). Context characterizes and matters for innovation to a substantial degree (Borja, 2007). Each city has unique contexts regarding innovation for a smart city, and the way any city designs its strategy can be unique (Hartley, 2005).Both innovation and risk should be identified in context. A thorough characterization of a set of likely risks given the context of a particular initiative should complement the presentation of strategies (Giffinger and Gudrun, 2010). As shown in Fig. 2, the basic infrastructural tool for intelligent urban management (IUM) is information and communication technologies (ICTs) – indeed it is the key to a smart city (Hollands, 2008). Integrating ICT into development projects allows for changing the face of a city and producing new capacity (Vasseur, 2010). ICTs are highly capable of enhancing urban management system (Odendaal, 2003).

Urban management information system (UMIS) forms the final link in the IUM and SC chain. UMIS contains concrete data and statistics on to a city that can be updated and overlaid according to predetermined goals. As a matter of fact, urban information is considered as a basic tool for IUM (Fig. 3).

Intelligent management model is considered a decision support system that helps decrease earthquake vulnerability of underground transportation network. It determines extent and

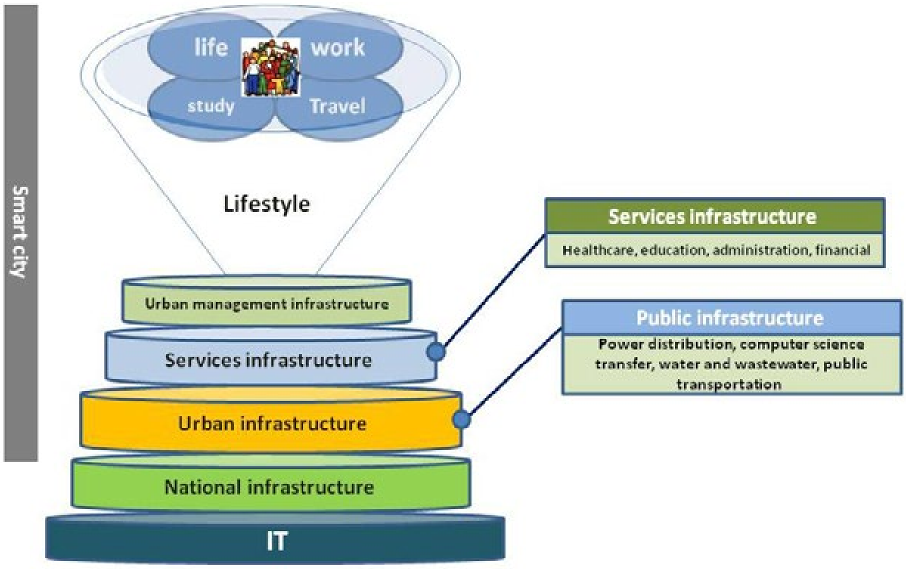


Fig. 2. Subordinates of urban management and smart cities in regard to citizen lifestyle (European Commission, 2015)

form of interference of the urban management in the network by analyzing physical risk and vulnerability of the city. This model assists with assessing various indicators associated with underground transportation to prevent, prepare for, and mitigate seismic hazards. The aim of establishing urban intelligent management is to manage urban crises (earthquake) where not only potential loss and toll is minimized but also rapid reconstruction is made possible. In addition, prevention of energy and capital wastage is pursued. There are numerous indicators and criteria to be assessed and measured. These determine vulnerability and resilience of the urban environment and the underground transportation infrastructure (Fig. 4).

The above mentioned issues define basic principles of “intelligent management within urban physical planning to prepare for earthquakes”. In the first place, prevention and preparedness hold priority in order to deal with earthquakes. This should be an ongoing process to be considered in a city comprehensive plan. Having a smart city requires a super-smart plan in which necessary capacity to respond to earthquakes needs to be considered (Habibi, 2008). Risk is defined as the potential inflicting threat upon safety, a system, or a project. Risk is known as probability of an incident and its hazards which are inevitable (Jozi, 2012). Risk management is known as identification, analysis, and optimized monitoring of risks associated with a process, system, or project. Its aim is, therefore, to eliminate or limit hazards in order to prevent their occurrence, and to compensate financial loss afterwards (Kent, 2004). Unluckily, most of managers do not believe in risk management, a fact that originates from ignorance. It is a systematic process that controls hazards by their determining, analyzing, and monitoring, If hazard are managed timely, their loss can be prevented and efficiency can be enhanced (Glaesser, 2006). This network and main arteries play a significant role in quick respond to seismic disaster and rescue operations - timely rescue may decrease human loss by 25% - for escape from hotspots and access to safe zones is made possible. However, previous experiences and world records of natural distastes in metropolitan and average-sized cities suggest that decentralized communication centers, or in other terms balanced distribution of urban transportation network, matters to a great extent. If metro tunnels are lying upon loose sediments that contain large amounts of sand and silt, then they may suffer massive damage because of sliding; this can be worsened by adjacency to faults (Aydan *et al.*, 2011). Construction in the north of Tehran, even if relatively safe and resistant, is prone to greater

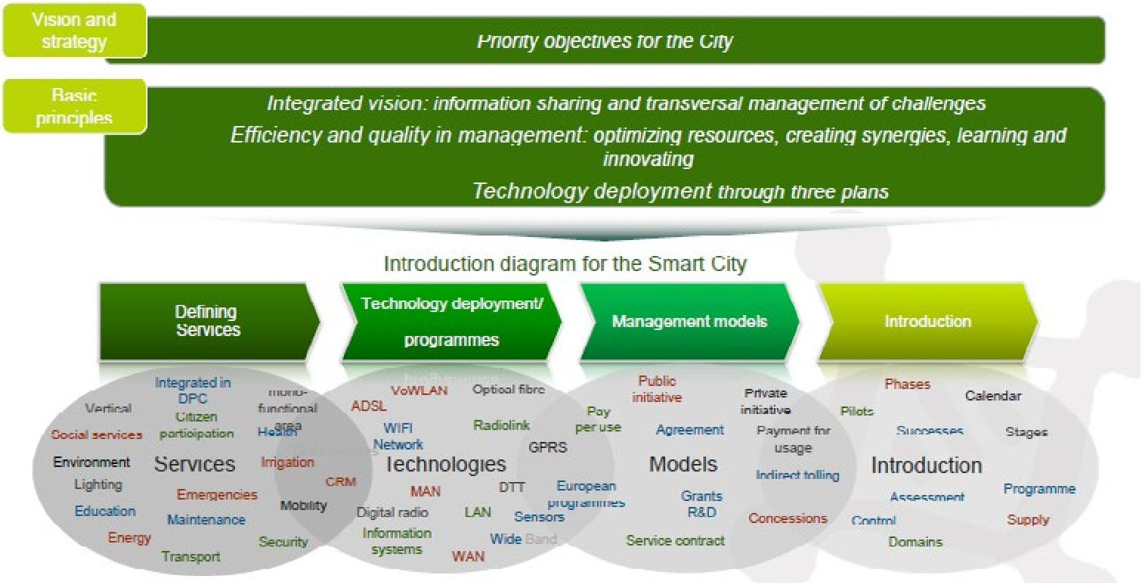


Fig. 3. Relationship between smart cities, urban intelligent management, and urban information management (European Commission, 2015)

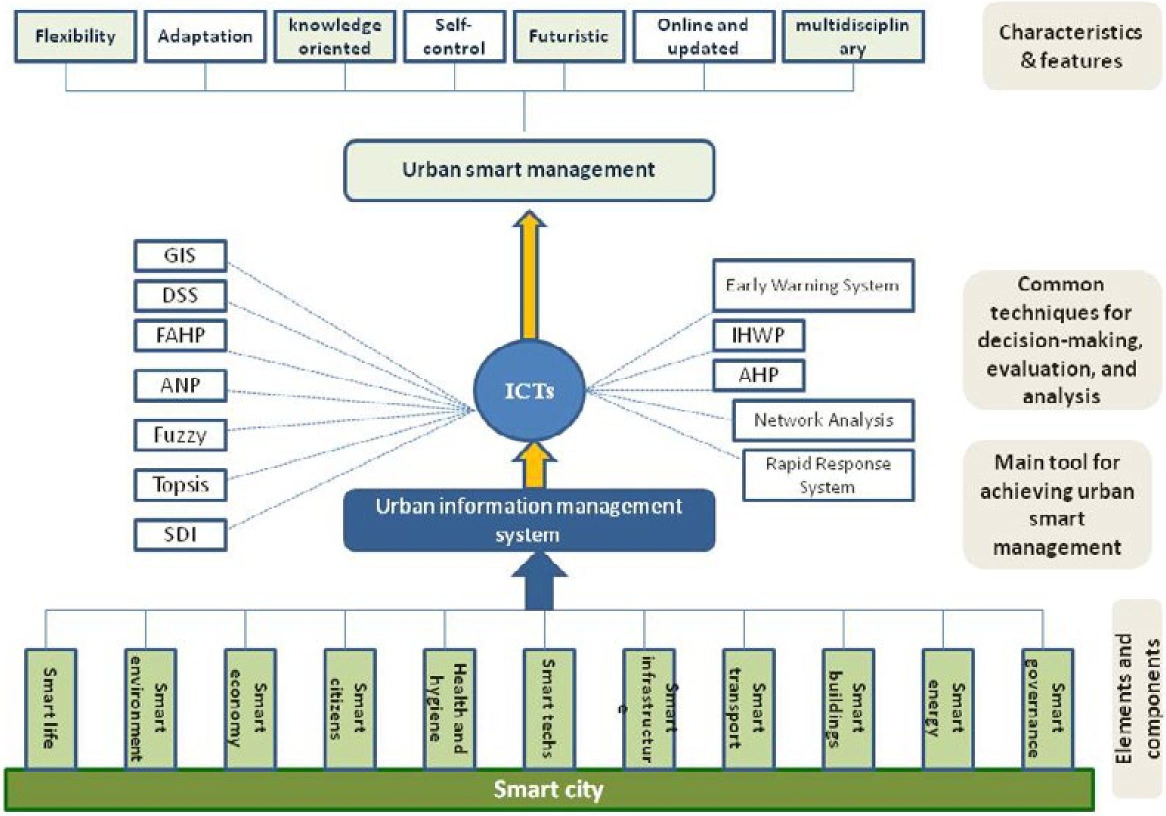


Fig. 4. From smart city to intelligent urban management

Table 1. Four seismic scenarios in Tehran (JICA, 2006)

Scenario	Explanation
Ray Fault model	About 20-km long; in this model an earthquake of magnitude IX and magnitude of VII to VIII hit the south and north, respectively.
Northern Tehran Fault model	About 90-km long; in this model an earthquake of magnitude IX and magnitude of VII hit the north and south, respectively. Most of the city experiences magnitude VIII.
Mosha Fault model	About 200-km long; in this model most the city experiences magnitude VII.
Floating model	Most of the city experiences magnitude VIII and some area IX.

destruction because of being located on steep slopes. But the issue leading to more demolition in the south is resonance effect which will multiply destruction in that alluvial soil forming Tehran Plain is able to resonate seismic waves. Tehran is vast enough to see one area suffering massive damage and another doing less. It is vital that emergency response be formulated considering this fact. Accordingly, a number of scenarios were defined in this study as illustrated in Table 1.

Every year, Swiss Re introduces a list of the most dangerous metro line in the world. Eight out of the ten most dangerous metro lines come from cities across south-east Asia, where residents constantly experience flood, storm, landslide, and temblors. Japan, owning the most rapid and popular metro lines in the world, with three dangerous metro lines stands on top of the list. Furthermore, the Kyoto-Yokohama line in Japan comes first, followed by the Manila metro, the Philippines, because of earthquakes and flood. The Tehran's 230-kilometer-long metro is also on the list (TUSROC, 2014). Map overlay integrating the faults and the metro lines in Tehran is shown in Fig. 5.

MATERIALS AND METHODS

Site selection of important infrastructures such as electricity, water, fire stations, telecommunication centers, police stations, decision making and management premises, their relevant networks, old urban fabrics as well as locating potentially hazardous sources near to metro stations were considered as determining factors in evaluating and monitoring efficiency of IDM. The maps and findings of the study carried out by JICA were used to analyze spatial data and does reality check. The process of IDM within Tadjrish, Darvazeh-Shemiran, and Navab stations was conducted based on GIS by employing spatial analyst tool in ArcView and ArcGIS environments. It should be noted that the analysis is based on the databank built on data from Seismic Zoning of Tehran, Center for Seismic and Environmental

Table 2. Indicators of risk assessment in detail

Indicator	Explanation
safety	Safety against hazards arising from a given natural crisis such as earthquakes and floods that can cause a combination of incidents like fire, explosion, electrocution, gas leak, flooding, debris, and landslide; To achieve safety, metro stations need to be located far enough from hazardous centers and zones, including faults, streams, steep and unstable land, urban facilities, infrastructures (gas pipes, power lines, water resources) as well as hazardous activities.
Efficiency	Suitability of the site selected for the station; to fulfill this, the location should enjoy easy access to allow rapid evacuation transportation of the injured in case of expansion of crisis.
Facilities	Stations should be equipped enough to fulfill the first needs of the injured. This includes emergency exits, fail-safe ventilation and power, adequate space on the upper stories for the injured individuals (staircases, escalators, and elevators). So it is necessary that stations be close to aid and relief centers, fire stations, etc. to provide timely and rapid service.

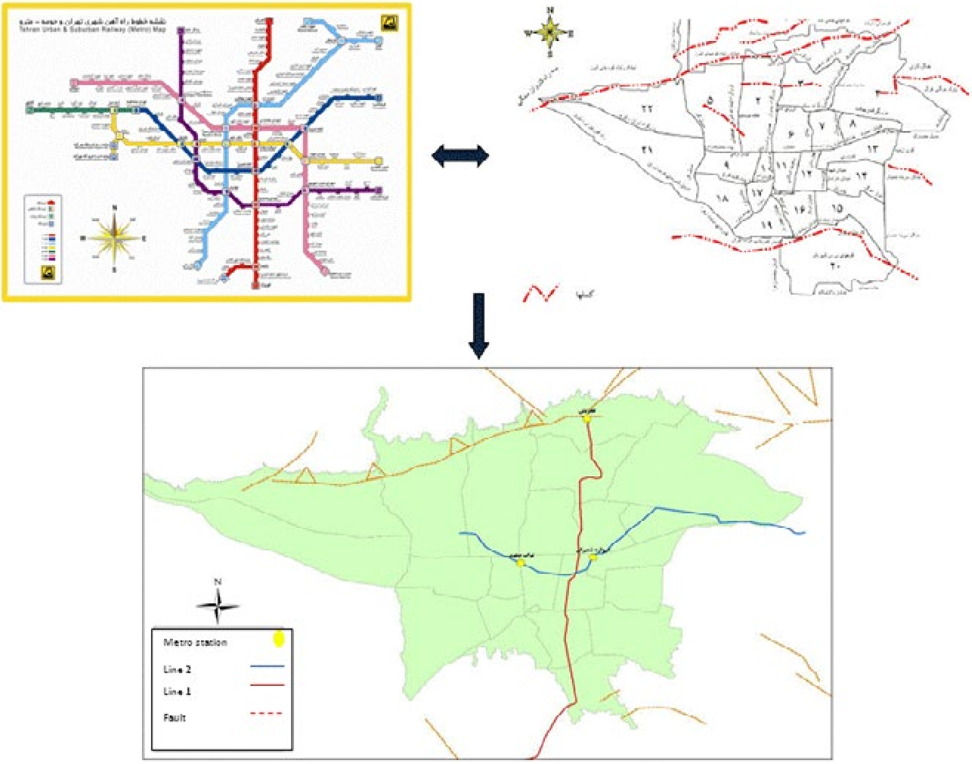


Fig. 5. Map overlay integrating the faults and the metro lines in Tehran

Table 3. Characteristics of the stations selected in this study

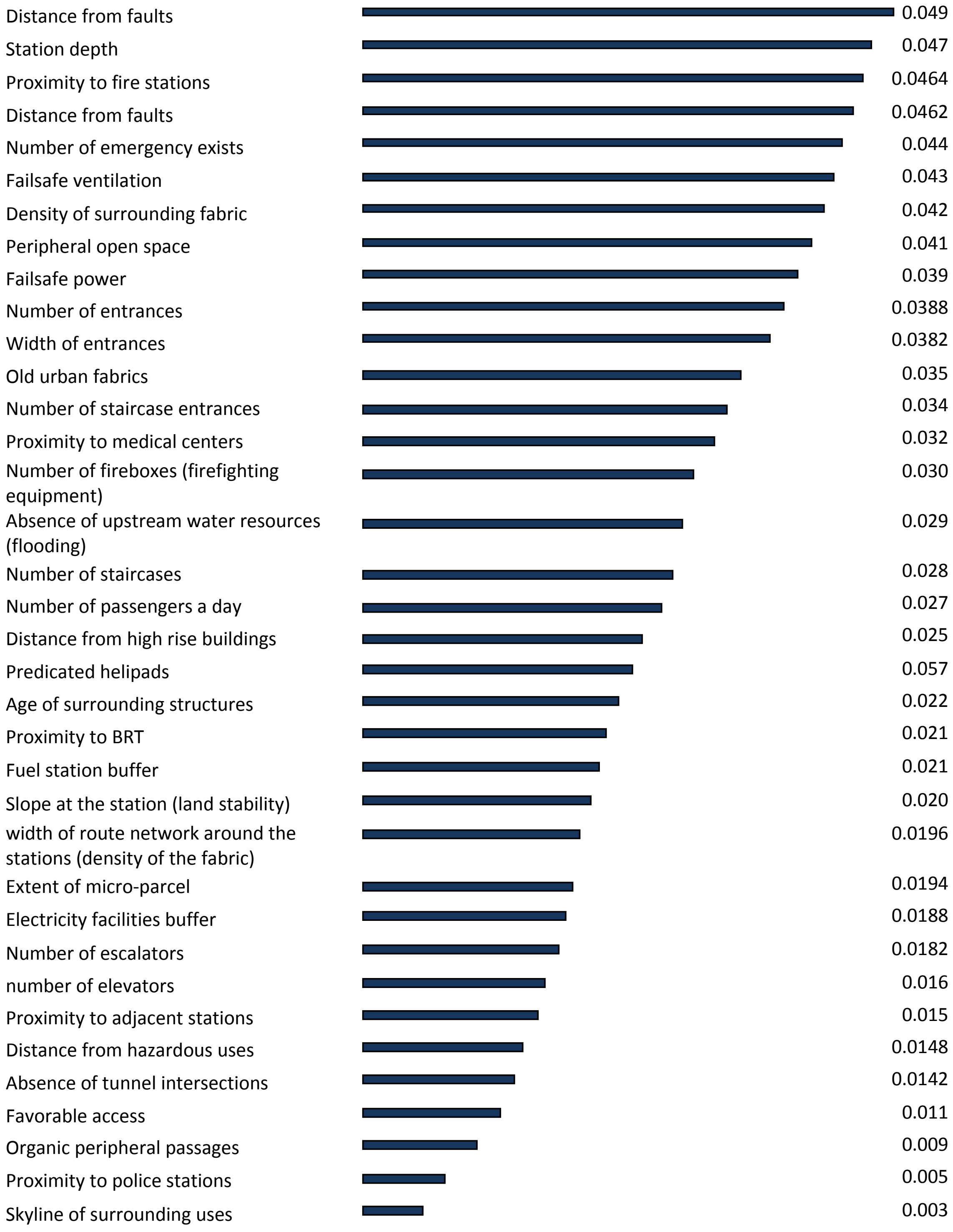
Station	Eslators	Elevators	nearby hospitals	Nearby fire stations	Nearby police stations
Tadjrish	8	30	Tadjrish Hospital	None	None
	0	6	1	None	None
Navab	4	0	Eghbal Hospital Lolagar Hospital	None	Haft-Chenar Police Station – Precinct 111 Abu-Saeed Police Station – Precinct 112
	4	0	2	1	2
Darvazeh-Shemiran	13	0	Moayeri Hospital	None	1
	11	0	1	None	1

Table 4. weighting range

Range	
1	Little important
2	Moderately important
3	Very important
4	Extremely important

Table 5. Risk assessment of Tadjrish Station

No.	Indicator	Weight	Score	Weight * score	No.	Indicator	Weight	Score	Weight * score
1	Distance from faults	4	0	0	19	Failsafe ventilation	3	7	21
2	Station depth	4	1.3	5.28	20	Proximity to adjacent stations	2	10	20
3	Number of staircases	3	3.9	11.64	21	Distance from hazardous uses	1	8	8
4	Number of escalators	2	8	16	22	Density of surrounding fabric	3	4	12
5	Number of elevators	2	5.5	11	23	width of route network around the stations (density of fabric)	2	4	8
6	Peripheral open space	3	6	18	24	Proximity to BRT	3	1	3
7	Number of entrances	3	2	6	25	Predicted helipads	3	6	18
8	Width of entrances	3	6.8	20.25	26	Absence of upstream water resources (flooding)	3	3	9
9	Number of emergency exists	3	0	0	27	Number of passengers a day	3	6	18
10	Proximity to medical centers	3	9	27	28	Distance from high rise buildings	3	8	24
11	Proximity to fire stations	4	6	24	29	Absence of tunnel intersections	1	8	8
12	Slope at stations (land sustainability)	2	3	6	30	Organic peripheral passages	1	4	4
13	Electricity facilities buffer	2	6	12	31	Skyline of surrounding uses	1	7	7
14	Favorable access	1	5	5	32	Age of surrounding structures	3	5	15
15	Fuel station buffer	2	7	14	33	Old urban fabric	3	6	18
16	Proximity to police stations	1	7.5	7.5	24	Distance from streams	4	3	12
17	Number of fireboxes (firefighting equipment)	3	8	24	35	Extent of micro-parcel	2	8	16
18	Failsafe power	3	7	21	36	Number of staircase entrances	3	6.5	19.5



Inconsistency Ratio = 0.0

Fig. 6. Pair wise comparison of parameters considered in risk assessment

Studies of Tehran, Tehran Metro Company as well as field observations with reference to a panel of experts. This study addresses earthquake risk zoning within Tehran Metro, identification of the vulnerable spots, identification of hotspots within the stations, determining the relevant agencies responsible for the earthquake management of Tehran Metro, and eventually the consequences of earthquakes for underground transportation development.

Determining indicators of risk assessment in Tehran Metro

As any incident occurs with certain likelihood and severity, one indicator considered was risk that is defined as likelihood of incident multiplied by severity of impact (Kahneman and Tversky, 2013).

When gathering expert opinions (Delphi technique), the term "potential" was used instead of "likelihood" to record opinions. In fact, the expert opinion regarding occurrence or lack of occurrence cannot represent likelihood because it was not based on empirical records, but rather on expertise that in modeling terminology is known as "expert's mental probability," or potential. Risk assessment of the studied stations was done through spatial modeling and analysis of various information layers defined by risk model indicators. The major indicators include safety, efficiency, and technology. The Table 2 below

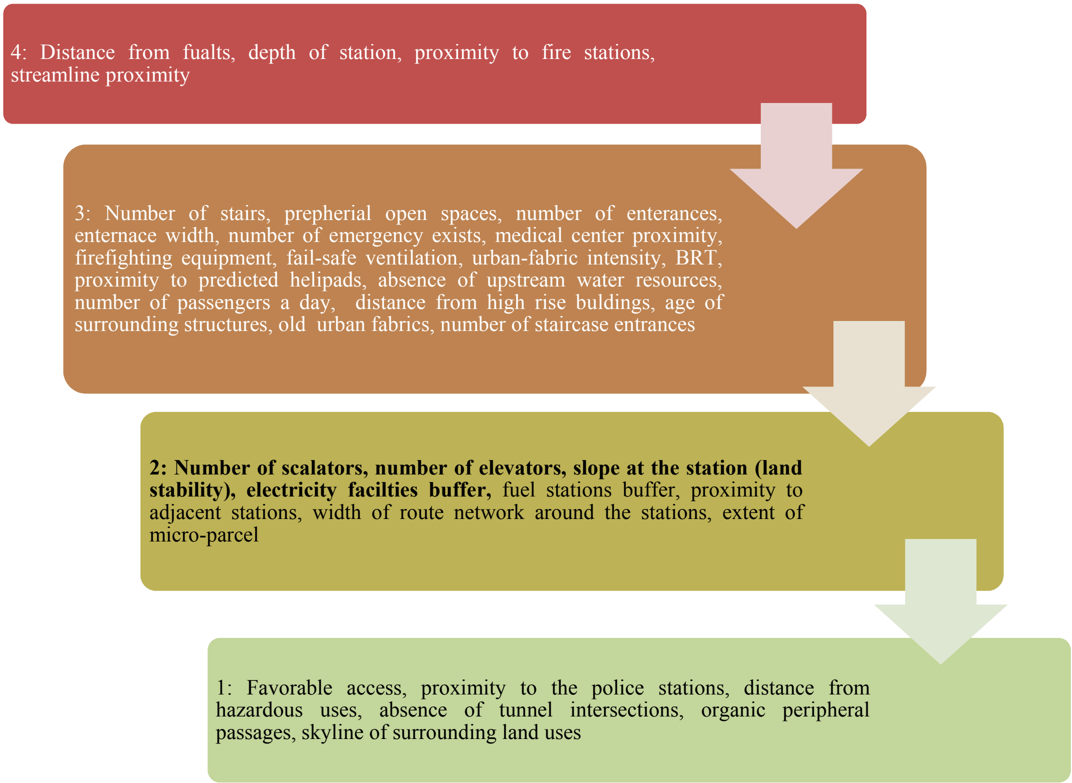


Fig. 7. Weight of each assessment parameter in pair wise comparison

Table 6. weight of the stations based on risk assessment

Station	Overall weight	Total score	Final average
Tadjrish	92	469.17	5.10
Navab	92	529.59	5.76
Darvazeh-Shemiran	92	532.55	5.79

Table 7. indicators defining risk

Score	Risk	Color code
0-2	Extremely hazardous	🟥
2 – 4	Hazardous	🟥
4 - 6	Hazard threshold	🟨
6 – 8	Outside hazard zone	🟩
8 – 10	Safe	🟩

Table 8: Minimum and maximum scores of indicators

27 to 32 - Distance to faults - Station depth - Proximity to fire stations	Maximum	24 to 27 - Distance from streams - Station depth	Maximum	27 to 32 - Proximity to medical care centers - Proximity to fire stations - Number of fireboxes - Distances from high rise buildings	Maximum
22 to 27 - Number of staircases - Number of fireboxes - Proximity to BRT - Number of staircase entrances		20 to 24 - Distance from faults - Number of staircases - Width of exits - Proximity to fire stations - Failsafe power - Failsafe ventilation - absence of water resources upstream - Distance from high rise buildings - Old urban fabrics - Number of fire boxes		20 to 24 - Failsafe ventilation - Proximity to adjacent stations - Width of exits - Failsafe power	
0 to 5 - Number of escalators - Peripheral open space - Lack of intersection with underground tunnels - Skyline of surrounding uses	Minimum			0 to 5 - Proximity to BRT - Favorable access -Organic peripheral passages	Minimum
0 - Number of elevators - Number of emergency exits		0 - Number of elevators - Number of emergency exits	Minimum	0 - Proximity to faults - Number of emergency exits	
Navab		Darvazeh-Shemiran		Tadjrish	

shows details of the indicators.

The characteristics of the stations selected are presented in the Table 3.

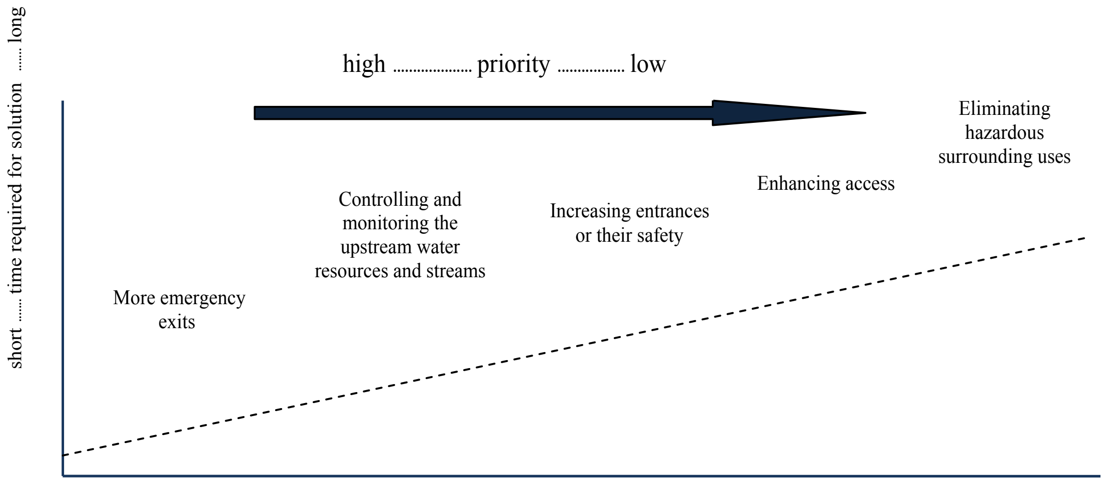
Risk assessment

The assessment process was based on modeling of the status quo and the predicted scenarios. Inspection of the selected stations was conducted by spatial analyst tool to produce “favorable-station maps. Each map illustrates suitability of the station weighed against certain indicators (faults, streams, surrounding urban old fabrics, distance to relief and aid stations, etc.) to decide suitability of the current location and efficiency. However, as each layer had a different effect on the risk assessment, it was essential that each one be given a certain weight. To do so, calculations regarding the weight of each layer were performed in AHP based on importance and through determining number of layers in each category and its effect on the assessment (Table 4). The following equations were employed to normalize scores and calculate relative weights as Eqs. 1 and 2, respectively.

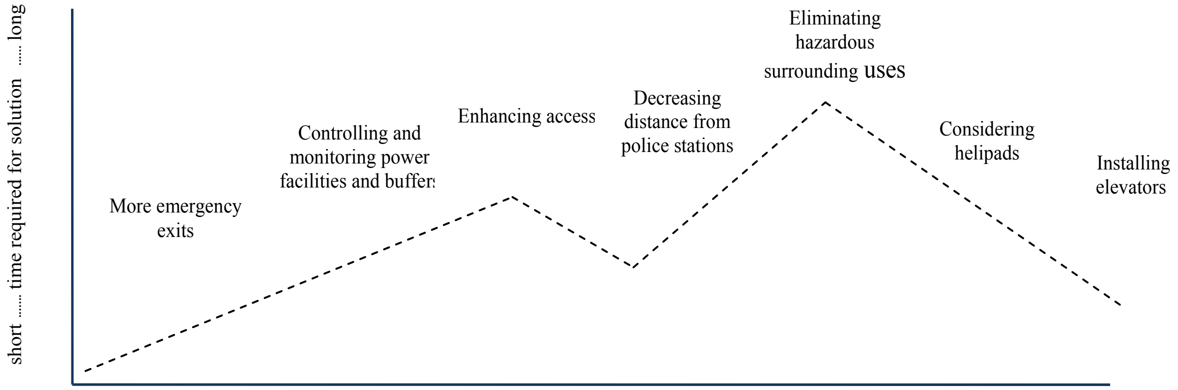
$$r_{ij} = \frac{x_j}{\sum_{i=1}^{m} x_j} \qquad (1)$$

$$w_j = \frac{\sum_{j=1}^{n} r_j}{n} \qquad (2)$$

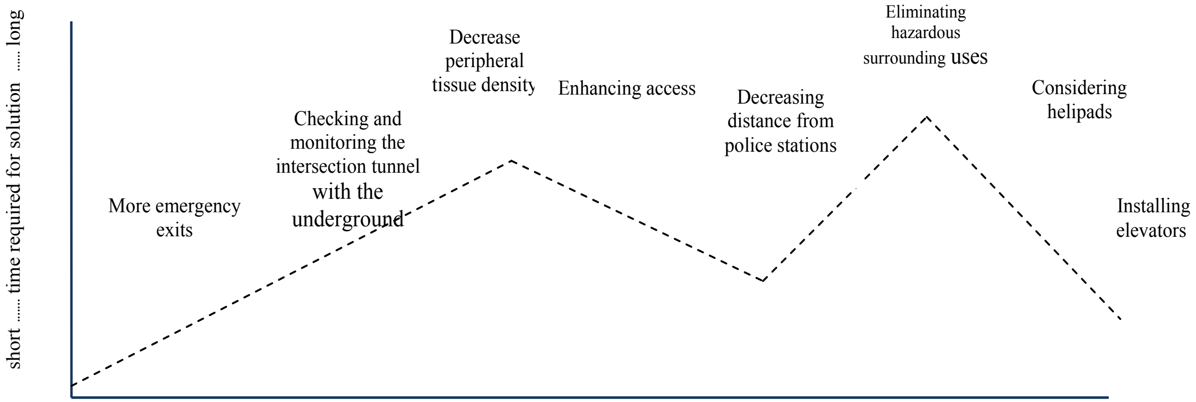
After being weighted, the score of each layer



a) Proposed solution for disaster management (preventive) in Tadjrish Station



b) Proposed solution for disaster management (preventive) in Darvazeh-Shemiran Station



Proposed solution for disaster management (preventive) in Navab Stationc)

Fig. 8 (a, b, c). Solution proposed for the stations – arranged by priority and implementation period was compared to the existing standards set by the Physical Planning and Urban Infrastructures as well as referring to Delphi technique – for 36 parameters. The lower the score, the weaker the indicator compared to the existing standards (Table 5).

RESULTS AND DISCUTION

All the 36 parameters underwent pair wise comparison in AHP environment (Fig. 6). Also, Delphi technique based on Table 4 was used to determine indicator weight (Fig. 7).

Given the complexity and extent of calculations associated with each layer, only one station is presented in the table below, and for the other two stations just the findings are provided (Tables 5 and 6).

The final average was overlaid on risk indicators (Table 7) and result showed the three stations were on the brink of hazard threshold, which highlighted the necessity of investigating issues that increased the risk at the stations.

The results showed that based on distance from faults and emergency exists Tajdrish Station received the lowest score. Further, Navab and Darvazeh-Shemiran received the lowest score concerning elevators and emergency exists. The Table 8 illustrates the lowest scores in each station.

CONCLUSION

The results suggest that despite years of research on the role of intelligent disaster management in reducing damage from natural disasters (earthquakes and floods) to underground transportation network, this approach has not been followed in Tehran, where circumstances such as tectonics, faults, old urban fabrics, etc. inflict high risk. Once risk in a metro station caused by earthquake crisis is investigated, proximity to faults, station depth, and techniques used in building tunnels are considered determining factors in decision on smart crisis management by their own, and synergy between other relevant parameters reveals the depth of crises. As a result, to eliminate or mitigate hazards associated with underground transportation development (from feasibility studies phase to site selection of stations and course selection), geological considerations (tectonics) and earthquake engineering (layers, proximity to faults, slope, and underground water) should be taken into account. To this end, it is recommended that seismic micro zoning maps, including acceleration-contour-line maps, liquefaction map, and landslide potential, be considered according to risk level. Because some stations are located near urban worn-out fabric or high rise buildings, an earthquake crisis can be intensified and accompanied by debris collapse and blockage of surrounding passages. So it is suggested that the vulnerability of urban facilities be determined, especially bridges, tall structures overlooking highways, passages around stations, water pipes, gas pipes, sewer pipes, and any facilities interfering with the tunnels in Tehran. The dependence of the metro facilities on the ground level infrastructures is a weakness, and in case they are damaged, either under normal or under critical circumstances, the whole metro facilities may fail, a fact that necessitates installation of emergency and smart systems. According to findings and crisis management approach (pre-incident) as well as current state, solutions can be proposed for each station investigated in this study – shown and prioritized in Fig. 8 (a, b, c). It can be seen that the proposed solutions in Tadjrish Station take less time, and are consistent in terms of priority. The key requirements of smart disaster management include an integrated, comprehensive approach; disaster management vs. crisis management; acceptable risk; modeling hazards and integrating elements; precise and up-to-date information that is reliable and effective on disaster management; accountability based on informed response; providing legal, financial, and technical infrastructures; enforcing regulations and applying knowledge; prioritizing risk mitigation plans; and extending accident insurance coverage in form of supportive, mandatory, and incentive (Giffinger *et al.*, 2007). Since this study emphasizes the role of intelligent disaster management (pre-disaster), the recommendations include use and development of modern tunnel technology (tunnel section, tunnel boring methods, earth reinforcement), tunnel sensitivity analysis, developing risk mitigation methods, and enhancing safety indicators in stations. If a station is located and built at a high risk site, the tunnels and station should immediately be reinforced, and equipment and facilities required during and after the crisis be installed by considering principles of planning and intelligent management.

Given the old urban fabrics and disordered none-geometric passages, catastrophic post-earthquake conditions and failure of ground transportation network is highly expected. Hence, air and underground transportation, i.e. helicopter and metro, may be integrated to provide the best alternative for rapid transportation of the injured, and further, turn the stations into well-equipped crisis management centers as well as temporary aid stations – provided that an open, safe space for helipad is cleared and the tunnels remain intact. The benefits of such provision are so great that if this approach is applied to construction phase of underground transportation networks as well as to the reinforcement of the currently operational stations, many of problems emerging during the first hours of crisis will be eliminated.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. In addition, the ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy have been completely observed by the authors.

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