Lifelines Interaction Effects on Seismic Vulnerability of Urban Environments
Case Study: a Selected District of Tehran Metropolis

Mahmood Hosseini, and Hossein Labibi

Abstract**—**Lifeline interaction is the mutual effect between a lifeline system and other lifeline systems in an urban environment under seismic conditions. In fact, reliability of a lifeline system is not only dependent on that system itself but also on the reliability of other lifeline systems which have functional connectivity or physical proximity with it. This paper presents the interaction effects of water, gas, power and transportation systems on seismic vulnerability of a selected district of Tehran metropolis, as the most important city of Iran both economically and politically. For this purpose the maps of selected area, potable water network and hazard map have been overlapped using ArcGIS. Then, the damaged parts of potable water network along the streets were identified using HAZUS method. Finally, the water logging volume in the main boulevard of the selected district has been calculated to determine the effect of water logging on the traffic capacity.

Keywords**—**Reliability, functional connectivity, water logging, ArcGIS, HAZUS

I. Introduction

TODAY the lifelines interaction phenomenon is well known among experts working in the field of Lifeline Earthquake Engineering. The adverse effects of this phenomenon on emergency response in large urban earthquakes have been observed. For example, the function of water supply system relies on the function of power supply system [1]; the bridge collapse in transportation system results in the breakage of the correspondence electric cables and pipes fixed on the bridge [2]; and failure of the gas supply system results in the excessive requirement for the power supply system [3]. Obviously, developing the earthquake scenario as a prerequisite for emergency response planning, as well as earthquake damage prediction and post-earthquake loss estimation of lifeline systems and other urban component, seismic upgrading strategies for urban environments, developing earthquake resistant design standard, and finally, secondary disaster controlling strategy and disaster reduction resource allocation cannot be performed with enough precision without considering the lifelines interaction effects.

Many researchers have studied the lifeline interaction effects, and have tried to propose some solutions for limiting them in urban environments. Kameda (1991) expressed that the water system has the most inauspicious interaction effect on the function of transportation system [4]. Hosseini and Mirzahessabi (1999) reported that the functionality of transportation system, particularly roads and highways, can be interrupted by other lifelines in the following ways [5]:

- Traffic signal disorder and lack of illumination because of damage to electric power supply
- No passing due to repair work of gas pipelines
- No passing due to repair work and also flooding of water supply as well as sewage disposal systems
- No passing due to damage or collapse of bridges
- No passing due to instability of tranches

Also Yao and his colleagues (2004) introduced a method for comprehensive study of lifeline system interaction under seismic condition [6]. Hosseini and Labibi (2014) worked on lifelines seismic interaction and presented a classification for lifelines interaction [7].

Regarding that each urban environment has its own geological, geotechnical, topographical, technological and seismic specifications, studying and particularly limiting the interaction effects of lifeline systems for each urban environment should be done in a specific way. In this study it has been tried to find out the interactions between various lifeline systems in a selected district of Tehran metropolis, in which, water, gas, electricity, and transportation lifelines have been considered; and some solutions have been proposed for limiting those interaction effects. Considering that based on previous studies, among lifelines interactions water-transportation-interaction has the most significant effects on post earthquake activities, including emergency response as well as reconstruction works, in this study the water-transportation-interaction has been considered as the main focus of the work. Details of the study are briefly presented in the following sections.

II. Introducing The Selected District Of Tehran Metropolis

Tehran, as the capital of Iran, is the most important city both economically and politically, and 12.1 million people live in this city. Furthermore, uncontrolled development and expansion of this city, has caused the concentration of the country's majority of economic resources inside it, and high density of industrial plants around it. As Fig 1 shows, there are

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several seismic active faults around this city, putting it in the zone of highest level of seismic hazard of the country (the study area has been shown in the Fig as well). This is while Iran is among the most seismically active countries of the world, and had suffered from destructive earthquakes during history. As Fig 2 shows, Iran has had 5 major earthquakes per year during 2000-2008 time period [9].

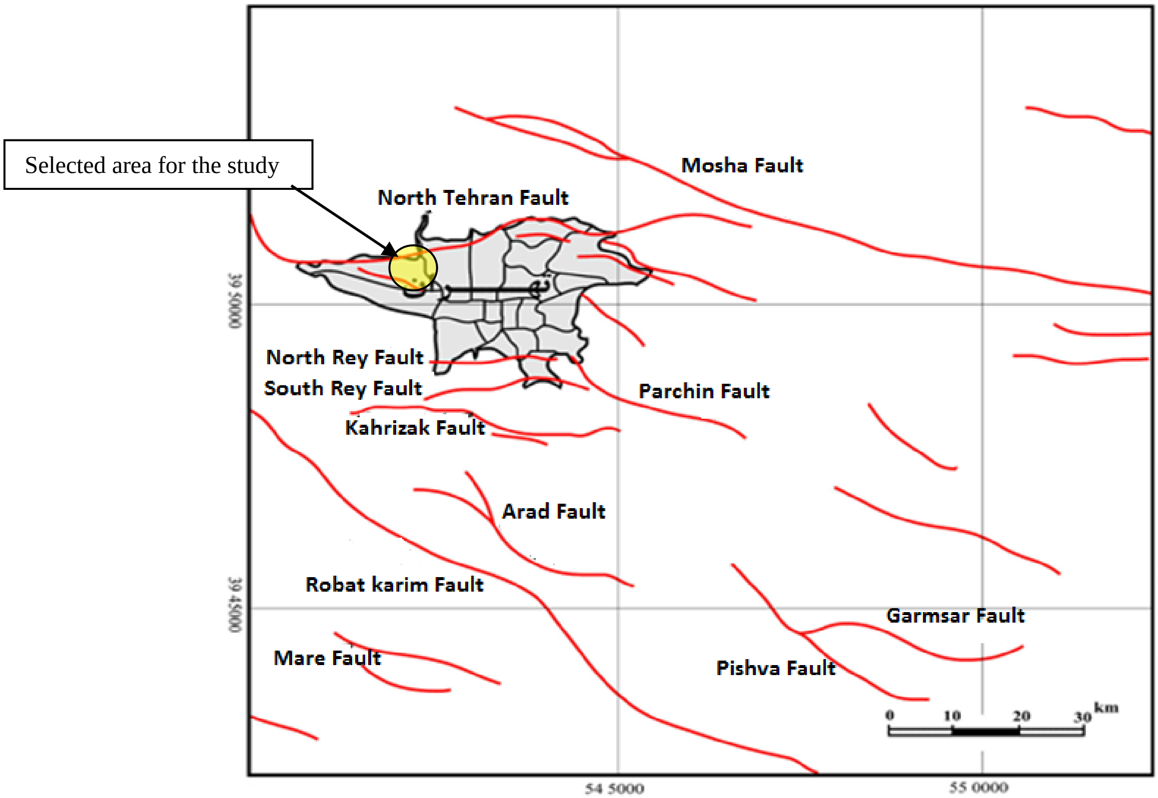

Fig. 1Seismic faults in Tehran metropolis region [8] (the study area is indicated by a yellow circle.)

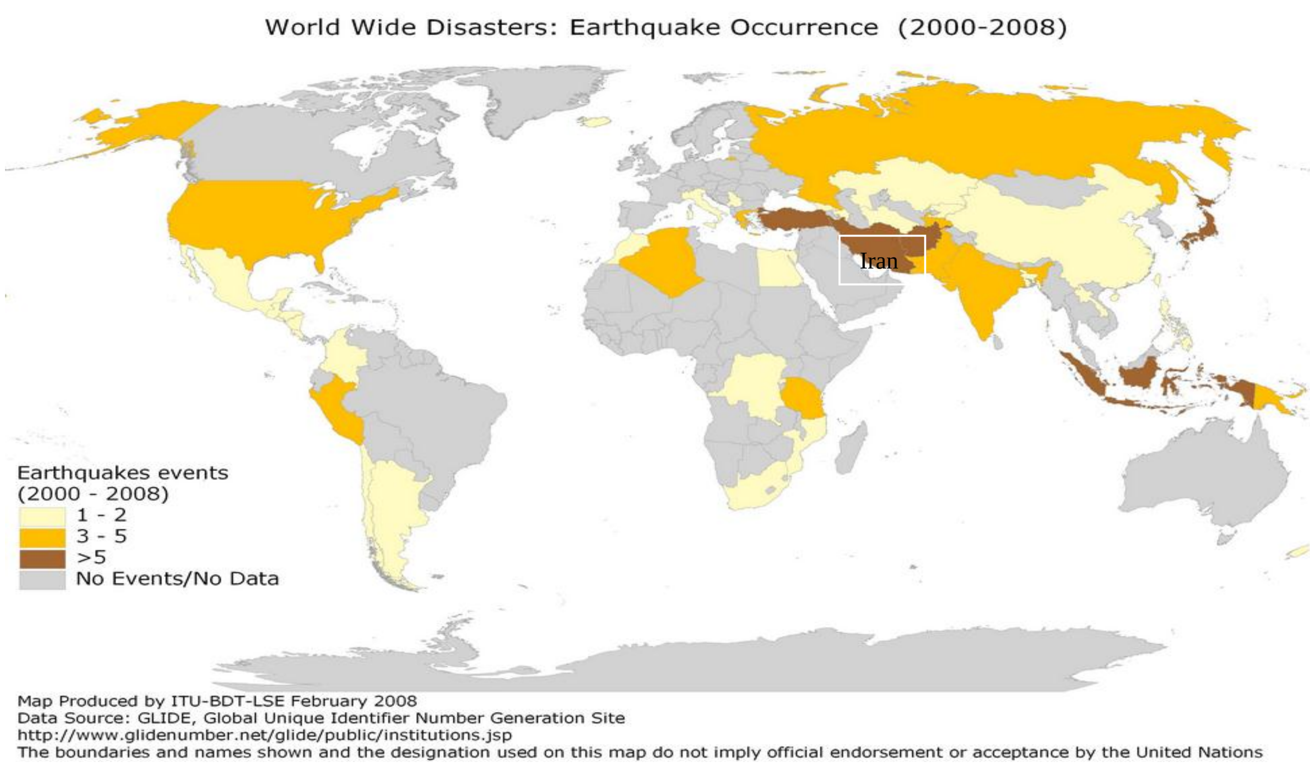

Fig 2.The world-wide earthquake occurrence map showing Iran region as one the most seismically active areas of the world [9]

In fact, 17.6 percent of world destructive earthquakes occur in Iran, which is 3 times of Japan destructive earthquakes. History of the Tehran region shows the occurrence of a large earthquake in 1830, resulting in complete destruction of Rey city (at that time Rey has been the major city, and Tehran has been a village in north of Rey) (Ambraseys and Melville 1982) [10]. Tehran metropolis has 22 districts, among which the last one, district No. 22, is the most recent developed one, in which the urban development criteria have been taken into consideration to a great extent. This district is a pilot for the master development plan and renovation program of the city. Therefore, district No. 22 was selected for this study, to see how lifelines interaction affects the emergency response and reconstruction works in case of a probable earthquake. Dehkadeh Boulevard is the main avenue of this district and water mains of the water supply system have been installed along this boulevard (Fig. 3).

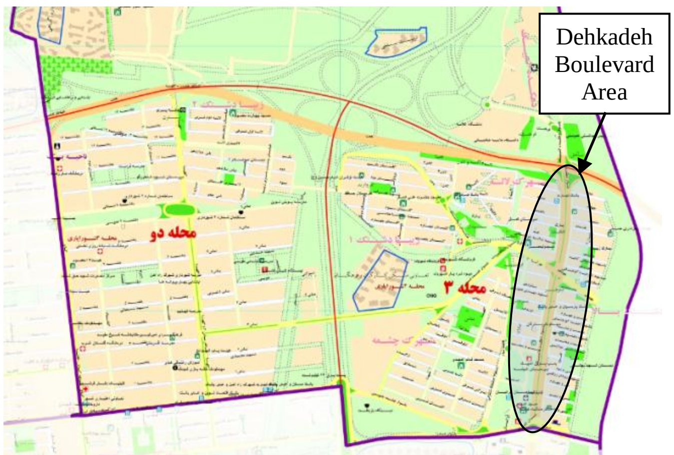

Fig 3 Municipal map of district No. 22 of Tehran

By using ArcGIS software and overlapping the maps of seismic faults (Fig 1), potable water network (Fig 4), seismic hazard microzonation map (Fig 5), and the municipal map of the district, on which the transportation network is shown (Fig 3), the more vulnerable areas of the district can be identified.

Fig 4 Potable water network of district No. 22 of Tehran

III. SEISMIC VULNERABILITY EVALUATION OF WATER, GAS AND POWER SYSTEMS OF THE SELECTED DISTRICT

As mentioned in the previous section, the main transportation path of the selected district is Dehkadeh Boulevard along which the main pipes of the water and gas supply systems as well as a part of the high-voltage electric lines are all located in this boulevard. With regard to electric power system, in addition to the toppling of high voltage transmission towers (Fig 6), a previous study of Hosseini and his colleagues (2009) showed the high vulnerability of low-voltage or distribution substations [11].

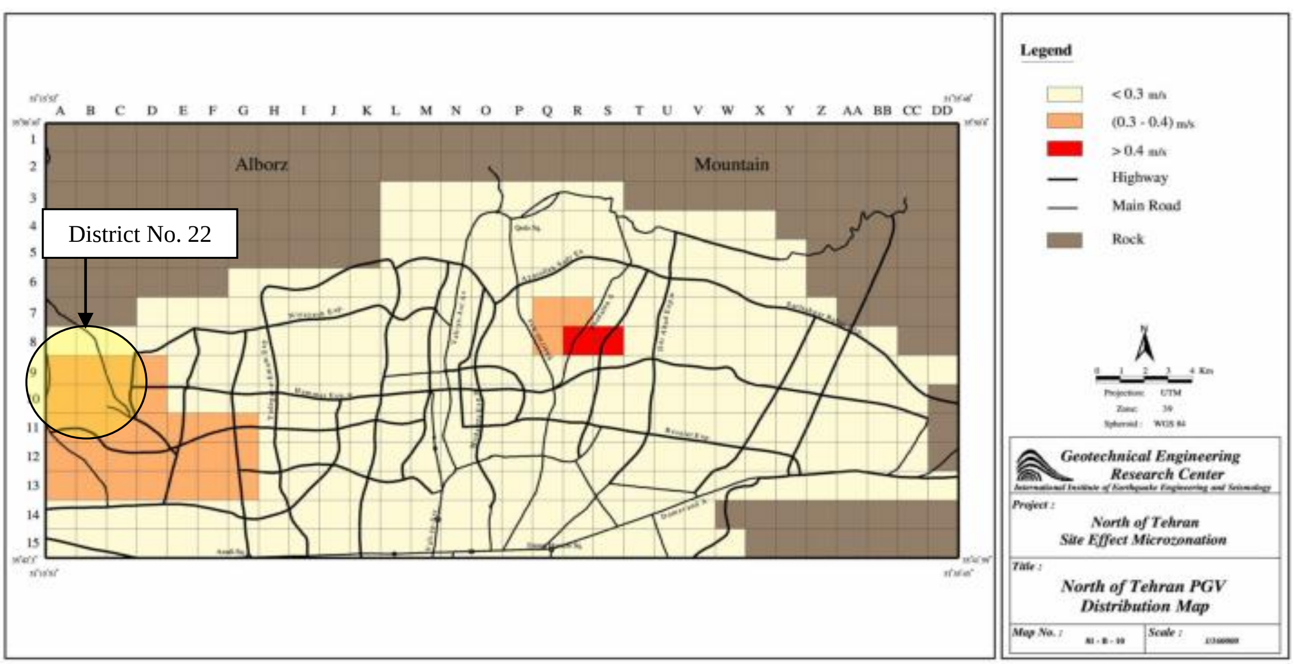

Fig 5 Peak Ground Velocity (PGV) seismic hazard microzonation map of northern Tehran [12]

Fig 6 Failure of high-voltage transmission tower in earthquake [13]

Fig 7 shows a schematic diagram of a typical 20kV distribution substation in Tehran, studied by Hosseini and his colleague [11], and Fig 8 presents the developed fragility curve obtained based on that study.

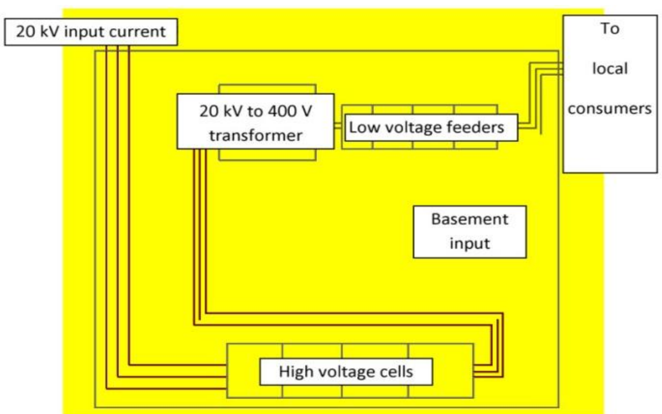

Fig 7 A schematic diagram of a typical 20kV distribution substation

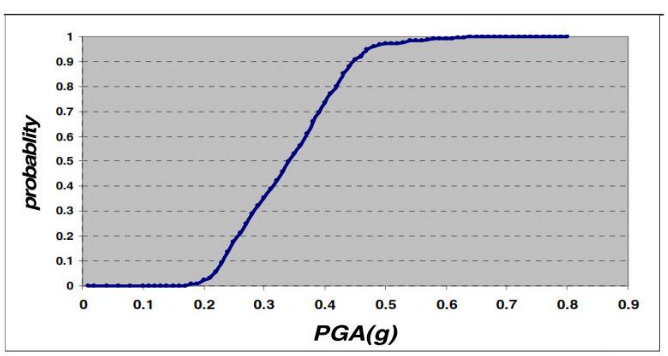

Fig 8 The fragility curve developed for the electrical power transformers in low-voltage substation of Tehran [11]

Based on the PGA map of Tehran, prepared by JICA [14], the PGA of the district No. 22 is 0.46g, so referring to Fig 8, the failure probability of low-voltage substations is obtained around 90%, which is really high. On this basis all other lifeline systems will suffer extensively for the power outage.

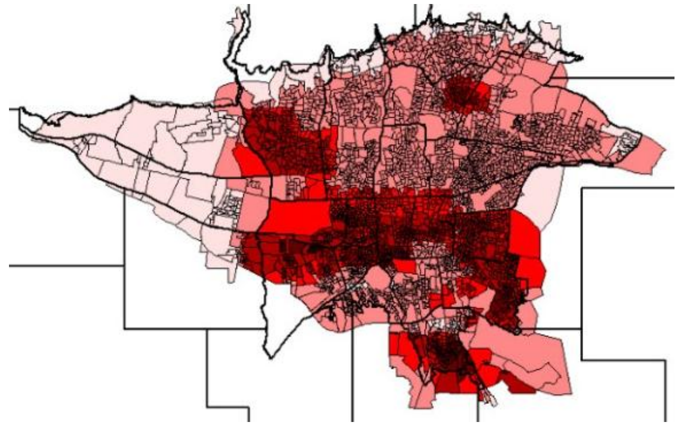

Fig 9 JICA PGA map of Tehran [14]

Even if the power outage due to low-voltage substations failure is not much likely, the weak performance of urban power distribution network will cause the city to be deprived from the electric power service as shown in Fig 10.

Fig 10 Inter-twisted cables of electric system in Nepal 2015 earthquake (Photo: Dr. Mehdi Zare from IIEES)

With regard to gas supply system, according to the PGV map, shown in Fig 5, and using the HAZUS (2010) damage algorithm given in Table I, the vulnerability of gas pipes in terms of repair rate are estimated.

TABLE I
DAMAGE ALGORITHMS FOR PIPELINES ACCORDING TO HAZUS 2010 [15]

	PGV Algorithm		PGD Algorithm	
	R. R. ≅ 0.0001 x PGV$^{(2.25)}$		R. R. ≅ Prob[liq]xPGD$^{(0.56)}$	
Pipe Type	Multiplier	Example of Pipe	Multiplier	Example of Pipe
Brittle Pipes (PWP1)	1	CI, AC, RCC	1	CI, AC, RCC
Ductile Pipes (PWP2)	0.3	DI, S, PVC	0.3	DI, S, PVC

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Assuming the total length of gas pipes to be almost equal to that of water pipes, which is 8.64 km, and referring to PGV map, shown in Fig 5, which gives a PGV value of 40 cm/s for the area under study, three or four cases of damage is likely to occur in gas pipes of the selected areas of district No. 22. Furthermore, the gas pipes, branching form the distribution lines, and entering the buildings, either in case of relatively old buildings (Fig 11), or relatively new ones (Fig 12), can be damaged due to the failure of facades or walls of buildings.

Fig 11 Spreading of old buildings' gas supply pipe over the walls, since the building has been built before gas supply establishment (Photo: Authors)

Fig 12 Entering of gas supply pipe into the wall of new buildings (Photo: Authors)

Damage to gas pipes can result in fires, and regarding the water lack due to damages imposed to the water system, as explained hereinafter, the fire fighting system will not be able to distinguish the probable post earthquake fires. This can cause the consequent losses of the earthquake to be even more than the direct losses.

Finally, with regard to water system, it can be said that if the water main of the selected area gets heavy damage due to earthquake, most probably a large amount of water will be discharged into the avenue, and will cause traffic flow interruption, and even blockage. Therefore, the seismic vulnerability of this water main was considered as the main section of the seismic vulnerability evaluation of the district.

Fig 13 shows the selected water main and its branches on which the vulnerability analysis was performed.

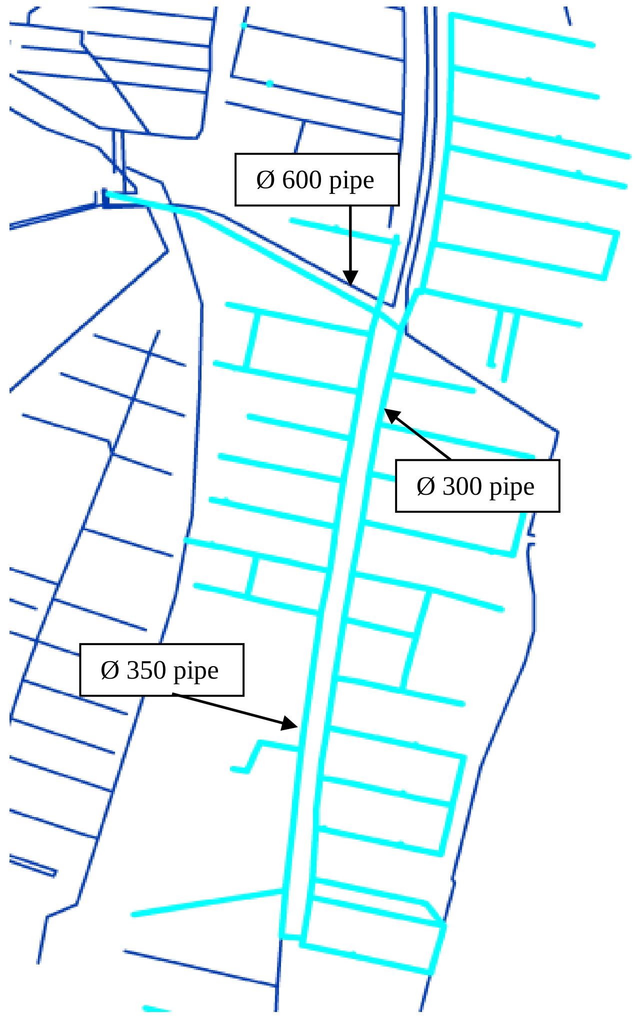

Fig 13 The selected water main of district No. 22 and its branches

To evaluate the seismic damage of the selected network, HAZUS method was used. For this purpose, the pipes with diameters of 80 to 350 mm were considered as shown in Tables II and III.

TABLE II
PIPES OF THE SELECTED NETWORK AND THEIR LENGTH BY DIAMETER

Pipe Diameter(mm)	Length(km)
80	3.845
100	1.315
150	0.880
200	0.475
300	1.787
350	0.340

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TABLE III
PIPES MATERIAL SPECIFICATIONS

Material	Asbestos Cement
Modules of Elasticity	2.35E+8 (kPa)
Bending Strength	24516.6 (kPa)
Poisson Ratio	0.3

According to Table II the total length of the selected network' pipes is 8.64 km. By using the PGV map of Tehran, shown in Fig 5, and base on the HAZUS formulas, given in Table I the repair rate of the considered network in Fig 6 were calculated. Table IV shows the results.

TABLE IV
CALCULATED REPAIR RATE OF THE CONSIDERED NETWORK

Pipe Diameter (mm)	Pipe Length (km)	Repair rate per kilometer
80	3.850	1.550
100	1.310	0.529
150	0.880	0.354
200	0.475	0.191
300	1.786	0.719
350	0.339	0.136

According to the results, shown in Table IV, it is expected to have at least three cases of pipe failure due to the probable earthquake. In addition to these three cases, the a more detailed finite element analysis on the main feeding pipe of considered network (Labibi 2015) shows that in case of the probable earthquake this main pipe will fail due to the fault rupture [16] . Due to these failures lack of potable water as well as lack of water required for post-earthquake fire-fighting are very likely. Furthermore, due to the runoff of the discharged water on the Dehkadeh Boulevard water logging will happen there, which will decrease the service level of the boulevard for the traffic flow, particularly for rescue and relief teams. The average velocity of discharged water to the avenue can be calculated by using the well-know Bernoulli Eq., which is as follows:

$$\frac{P_1}{\gamma_1} + \frac{{V_1}^2}{2g} + Z_1 = \frac{P_2}{\gamma_2} + \frac{{V_2}^2}{2g} + Z_2 \quad (1)$$

Considering the pressure of 4 bars in the water main, and neglecting the effect of surrounding soil, the velocity was calculated and then by using the following simple formula:

$$Q = A \times V \quad (2)$$

the maximum amount of discharged water to the avenue was obtained. Table V shows the results.

TABLE V
THE MAXIMUM AMOUNT OF DISCHARGED WATER TO THE AVENUE FROM DIFFERENT PIPES

Pipe Diameter (mm)	Pipe Cross-sectional Area (m^2)	Q (m^3/s)
600	0.28260	7.85
350	0.09616	2.67
300	0.07065	1.96
Sum	-	12.46

Of the total 12.46 m^3/s water runoff on the boulevard, which can continue for a few hours after the earthquake, a portion will flow on the east band of the boulevard and will spread to the neighboring streets and alleys, as shown in Fig 14.

Fig 14 Spreading a portion of runoff water on the Dehkadeh Boulevard to neighboring streets and alleys (the white arrow shows the direction of the water flow)

Fig 15 West band of the Dehkadeh Boulevard and its side garden

However, as shown in Fig 15, in the west band of the boulevard there is high potential of water logging, due to the existence of the blocks of the side garden which are 10cm high. According to the hydraulic calculations, the water logging phenomenon will occupy 10.1 meter of 12 meter width of boulevard (about 3 lanes out of 4 lanes), and the water will run in a triangular section according to the 8 percent longitudinal and 2 percent transverse slope of the pavement, and the maximum depth of water will be 20cm, as shown in Fig 16.

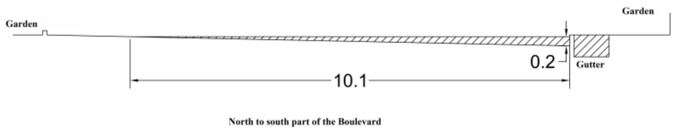

Fig 16 Cross-section of water current on the west band of the boulevard pavement

This amount of water logging relates to the condition in which boulevard is free of any means of transportation, but in post-earthquake condition, when the traffic is heavy, this depth of the water current will increase and more adverse effect will appear on the traffic flow. In fact, the scene shown in Fig 17 can be very likely in case of probable earthquake.

Fig 17 Water logging in a main street due to breakage of a water main in an M=6.0 earthquake which struck Napa city (California) in 2014 [17]

IV. Conclusions

Based on this study the following conclusions can be expressed:

- All of the lifeline networks in the studied district, including gas, electric power and water are highly vulnerable subjected to the probable earthquake.
- Breakage of water mains is very likely due to the probable earthquake, and lack of water for various consumptions, particularly fire fighting is a very unpleasant consequence of the earthquake in the studied area of district No. 22 of Tehran metropolis.
- The worst interaction effect is related to the transportation network and water system.
- Due to the estimated water logging in the main avenue of the studied district, and it adverse effect on the traffic flow, the rescue and relief activities will be done with difficulty and delay, and my stopped for some first hours (golden hours) after the earthquake.

As some mitigation measures, in addition to the general seismic upgrading of building and facilities, it can be recommended to increase the capacity of side gutters of the main street. This can help discharge of the runoff water due to main pipe breakage, and in this way can keep the traffic lane open for rescue and relief teams.

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