DEVELOPING A GIS-BASED MODEL FOR ROAD BLOCKAGE ASSESSMENT

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ABSTRACT

Road plays a significant role in evacuation in post-earthquake emergency. This study looks at the function of road networks in post-earthquake scenarios. A methodology is developed to estimate the possibility of road blockage after earthquakes. Factors of building damage, characteristics of the building, and relative distance between the building and the road are taken into the estimation. This research brings upon two novel approaches in modeling the road blockage. Firstly, the debris caused by damage to buildings are treated separately according to different building typology (including structural type, height, age…) and the associated proximity to the roads considering each building footprint widths. And secondly, the potential blockage share of each building is estimated by the relative debris heap and the road width.

The methodology is implemented with the actual data of the road network in District 17 of Municipality of Tehran. At first, the geospatial information for buildings and road inventories were compiled and processed as to generate a geodatabase. In the next phase, ground shaking maps are produced for scenario or actual earthquakes considered for the case studies. The third phase emphasizes on the vulnerability modeling of the building stock. In the final phase, the estimate of the building damage is calculated for these two earthquake scenarios. Residential building loss and the road blockage are calculated for two important earthquake scenarios produced by North Tehran Fault (NTF) and Rey Fault (RF) for Tehran as case study. Based on the result of implementation, up to 10 percent of the roads with width more than 15 meter will be blocked.

INTRODUCTION

Immediately after disastrous earthquake events, the knowledge regarding the status and the potential performance of the road network is essential in managing related emergency activities such as search and rescue and evacuation of injured and dead people. In most urban settings of Iran, especially in old fabrics, buildings are densely packed within their neighborhood while surrounded by relatively narrow or congested roads. A large number of constructions are severely vulnerable and potentially subject to collapse resulting in the spread of large amount of debris around them after severe ground shaking. Although the collapse of some network elements such as bridges, overpasses, tunnels, etc…, are very important; but, the debris spread can be regarded as the major cause of transportation failure in such urban settings and considered for this study. Transportation infrastructure system has important spatial characteristics, because it connects different locations with various attributes. Geographic Information Systems (GIS) is a useful tool in creating efficient databases and for analyzing complex transportation systems as utilized in this study for implementation.

Blockage indices for completely collapsed buildings which shows the severity levels according to the building height and road width were first introduced by using Manjil (Iran earthquake of 1990) field data (Bahreini, 1993) in Iran. Mansouri et al. (2008) implemented a comprehensive GIS-based methodology for modeling and estimating the severity and the spatial distribution of road blockage as probability measures, for each road segment (between consecutive intersections) and for the given scenario earthquake. Determining the spatial distribution of the estimated completely damaged buildings using the vulnerability function sets, a Road Blockage Index (RBI) was assigned for individual buildings. The probability of a building being completely damaged was combined with its RBI value. For each segment of the road, all contributing parcels were considered and their combined indices were aggregated. The result was presented as a risk map for road blockage by a simplified computed index.

In the following sections, the methodology for developing the road blockage model including the creation of geospatial databases and the procedure in deriving the vulnerability functions are described. The implementations lead to the vulnerability and road blockage assessment for the study area that can be expanded for other locations as well. As case studies, risk assessment results for Tehran concerning important earthquake scenarios are reported in this paper. Briefly, this required the development of ground motion maps, building inventory databases and vulnerability functions to be used in an earthquake loss estimation routine where the building damage estimation was fed as an input to the road blockage estimation module.

METHODOLOGY

There are many factors affecting possible road blockage. However, taking all these factors into account is not always feasible mainly because of the lack of data. For that reason, this study only focuses on the aspect of road blockage caused by collapsed buildings. The possibility of road blockage by debris from buildings depends on the following issues:

- The number of collapsed buildings. The higher this number, the higher the possibility of road blockage.
- Characteristics of buildings along the road. For example, the presence of weak buildings (adobe, brick-mud buildings), stronger buildings (reinforce concrete, steel buildings) and the presence of buildings with soft story or without cantilever hanging parts toward the road.
- The ratio between building height and the distance from front walls or facades of the buildings to the road center line. The higher this ratio, the higher the possibility of debris blocking the roads.

In this research the following indicators have been considered for estimation of debris volume caused by building damage. Figure 1 presents a flowchart of the methodology indicating the importance of density of collapsed buildings, the type of buildings, and the relative distance between the roads and the buildings into road blockage.

Since only the debris from collapsed buildings in close proximity to the route and facing directly the same route influence the blockage, thus only homogenous unit consisting of those buildings are selected.

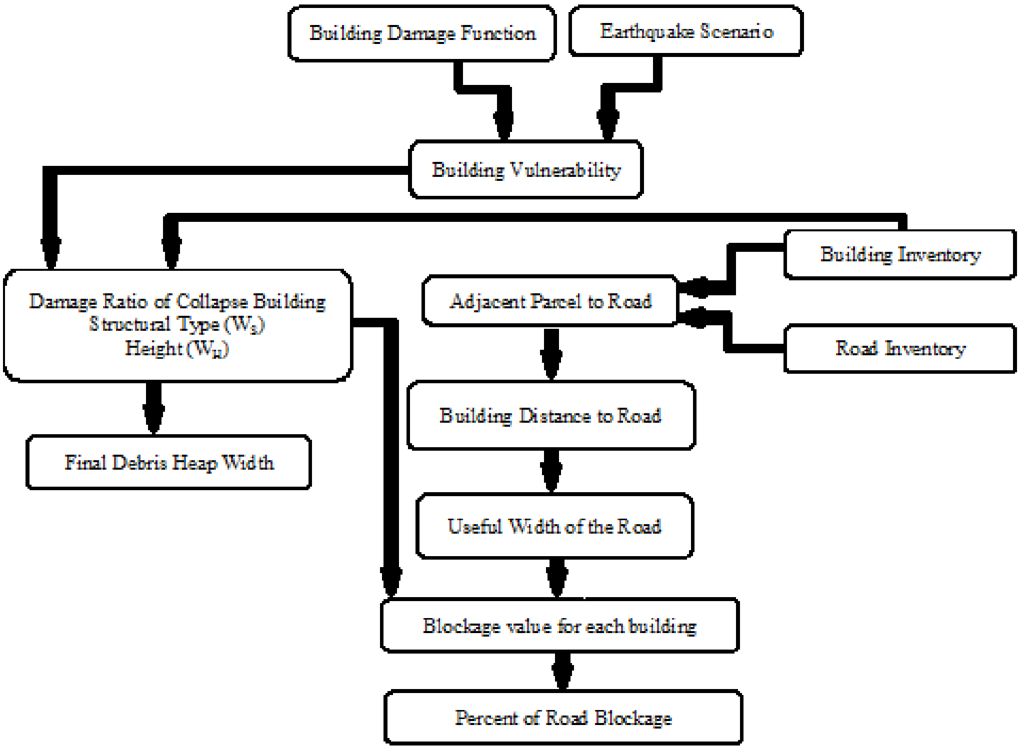


Figure 1. Flow diagram of road blockage by building damage into GIS

VULNERABILITY MODELING

The increase in the percentage of collapsed buildings and the amount of debris on the road, affects directly the road blockage. Thus, due to direct impact of this factor, the percentage of very heavy damage and destruction were considered as a major indicator for building debris volume leading to the severity in the road blockage level.

The procedure includes the derivation of vulnerability curves for some most common structural types in Tehran. Empirical fragility curves are generally preferred for regions that have experienced devastating earthquakes in the past. But, because such data is not available for Tehran, some analytical results are proposed. Some of such curves were compared and adjusted with the empirical data from the devastating Manjil-Iran Earthquake (Tavakoli and Tavakoli, 1993) and also with the vulnerability results for the concrete buildings destroyed in Kocaeli-Turkey earthquake of 1999. Additionally, some other sets of vulnerability or fragility curves were presented for the existing building typologies for Iran. These functions are derived using the RISK-UE (2003) procedure but with some modifications according to empirical or analytical (Capacity Spectrum Method) results or expert judgment (Mansouri et al., 2014). In the following sections, the methodology for developing the building damage estimation is described.

Firstly, using the Capacity Spectrum Method (CSM), structural fragility curves were developed for the building taxonomy and site conditions for Tehran (Mansouri and Kiani, 2011). The capacity curve is a simplistic representation for the dynamic behavior of the entire structure by considering a SDOF system. The capacity curves are determined by two sets of points, the yield and the ultimate capacity points, where the first indicate the limit for linear response and the second is related to the nonlinear part of the capacity curve. The seismic demand spectrum was derived according to NEHRP-97 procedure were the spectral acceleration was calculated for 0.3 s and 1.0 s periods (*Sa@0.3s*, *Sa@1.0s*) for different zones within the study area. Utilizing the selected GMPEs (described in the previous section), three different spectral acceleration maps were created and the average values of the spectral accelerations were calculated for each earthquake scenario.

Secondly, Intensity-based vulnerability curves were developed in this research for calculating buildings' Damage Factor. The process for developing such curves usually requires detailed empirical damage data that is generally missing for Iran earthquakes. However, the intensity-based curve parameters are derived by comparing the results of the capacity spectrum modelling and some available damage curves.

Macroseismic method is a semi-empirical method where the mean damage of a specific building type is determined by the vulnerability and quality indices and the earthquake intensity. Using these parameters and considering the Beta distribution function, damage probability matrices and fragility curves are derived. Table 1 lists the vulnerability indices as calculated based on RISK-UE (RISK-UE, 2003) methodology for the designated for some typical buildings considered for Iran (Mansouri et al., 2014).

Table 1. Calibrated vulnerability indices for building stock (Mansouri et al., 2014)

Typology	Description	Earthquake Resistant Design Level	Building Height	Quality Index	Regional Modifier	Total Vulnerability Index
Ad	Adobe	-	Low	1.80	0.160	1.00
M1	Reinforced Masonry Walls	(High Code)	Low	2.3	0.179	0.63
M2 & M3	Unreinforced Masonry	(Pre or Low Code)	Low	2.00	0.114	0.89
RC1	RC Frame + Infill Walls	(High Code)	Medium	2.3	0.338	0.62
RC2	RC Frame + Infill Walls	(Medium Code)	Medium	2.0	0.248	0.69
RC3	RC Frame + Infill Walls	(Pre or Low Code)	Medium	2.0	0.218	0.82
S1	Steel Braced Frame + Infill Walls	(High Code)	Medium	2.3	0.106	0.59
S2	Steel Frame + Infill Walls	(Medium Code)	Medium	2.1	0.266	0.75
S3	Steel Frame + Infill Walls	(Pre or Low Code)	Medium	2.0	0.336	0.82

COLLAPSE IN DIFFERENT BUILDING TYPE

Note that the type of building is also taken into account. Even in the estimation of the number of collapsed buildings, the type of building was considered. However, the debris shape or collapse forms are different for different building types. In the evaluation of the road blockage possibility, another factor was considered as related to different construction material of the structure. The masonry buildings (brick-cement, brick-mud, adobe) are likely to disintegrate and collapse vertically, so the debris is likely not to be displaced far away from the building footprint. Reinforced concrete and steel structures are likely to lean or collapse towards one side. These buildings, even though they seem to be stronger than the masonry buildings, they are likely to lean forward to the collapsing side, once they collapse, causing debris to go far away from the original building footprint. Consequently, this leads to a larger width of the debris heap, and a the higher possibility of blocking the road. Based on reviewing some satellite images and visiting some hard hit zones caused by earthquakes, using some expert opinion (Thanh, 2004 and RISK-UE, 2003), the values for the material based factor W_S (affecting the debris heap) for reinforced concrete and steel buildings was assigned 30% more than other material types.

BUILDING HEIGHT EFFECT

Another important factor is related to the height of the buildings along the road. It is estimated that the average debris width depends on the height of the buildings. Considering building arrangement in Tehran overally, the average height of one story is estimated as 3.20 meters. The width of the debris away from the building is estimated based on debris shape and size from collapsed buildings in past earthquakes relative to the height of the building and the type of the buildings. Based on some studies (Thanh, 2004 and RISK-UE, 2003), the angle between the building frontal wall and the line that connects the top of the wall and the furthest point of debris, is estimated as 20 . Based on this assumption the debris heap is about 30% of the height of the building. Thus, width of the debris heap is calculated as a function of height of the building and consequently the number of story so the coefficient W_H is as follows:

$$W_H = No.\ of\ Story \times 3.20 \times \tan 20^0 \qquad (1)$$

ROAD BLOCKAGE

A final debris heap width W_D is a function of *DF*, W_S and W_H and is calculated as follow:

$$W_D = DF \times W_S \times W_H \tag{2}$$

Where *DF*, W_S and W_H stands for coefficients of damage factor, structural type and height of the building respectively.

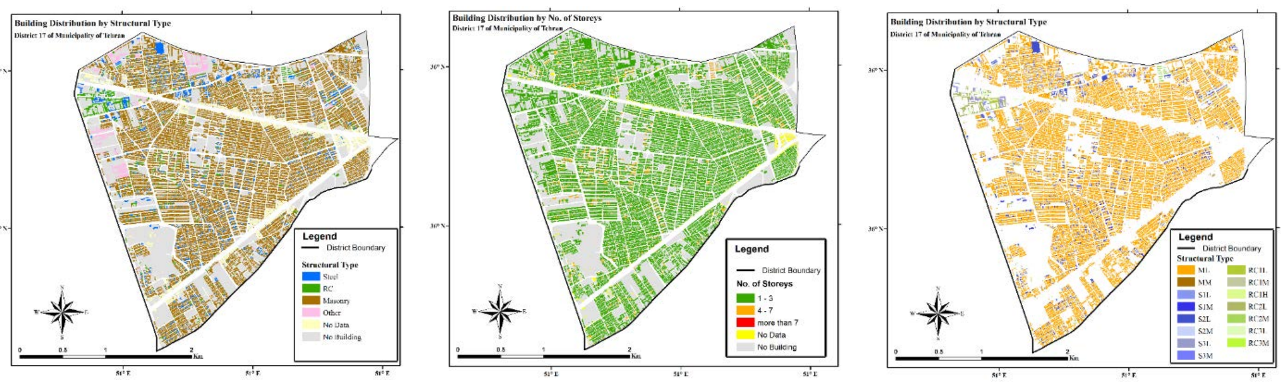
The distance between the buildings and the road influences the possibility of the road blockage, the longer distance, the lower the possibility of road blockage. W_R presents the passable width of the road in a post-earthquake scenario, when vehicles might be allowed to travel even on sidewalks. The blockage assessment tries to quantify the probability of debris filling the road and is based on the debris heap and the relative distance between the road and the buildings. A ratio between the debris heap width, on one side of the road, and the useable width of the road W_R is used to evaluate the lateral blockage by debris on the road surface at the corresponding road segment. The road blockage ratio (RB) is calculated as follows:

$$RB = \frac{W_D}{W_R} \tag{3}$$

IMPLEMENTATION AND RESULTS

The road network for district 17 of Tehran municipality is chosen due to its old vulnerable buildings and the availability of building and road data sets. In previous studies, this district was estimated as one of the most vulnerable districts within Tehran in terms of catastrophic building damages and human losses. Thus, it was decided to focus on its road blockage as well.

Using collected database, the existing building typologies in the study area were divided into 15 structural types. The four major building categories are adobe, masonry, reinforced concrete and steel. Distribution of buildings in the study area are based on building categories, number of stories and structural types as shown in Figure 2. The existing road network of the study area has been extracted based on their width as shown in Figure 3.



(a) by structure (b) by story (c) by building types

Figure 2. Building distribution by structure, story and building types in District 17 of Municipality of Tehran

Based on some previous studies (JICA, 2000), the most important hazardous faults are known as Mosha (MF), North Tehran (NTF) and South Rey (RF) faults. More recently, Gholipour et al. (2011) have reported these faults' parameters as shown in Table 2. For this paper, two scenario earthquakes, namely Ray Fault Model and North Tehran Fault (NTF) Model were considered and implemented.

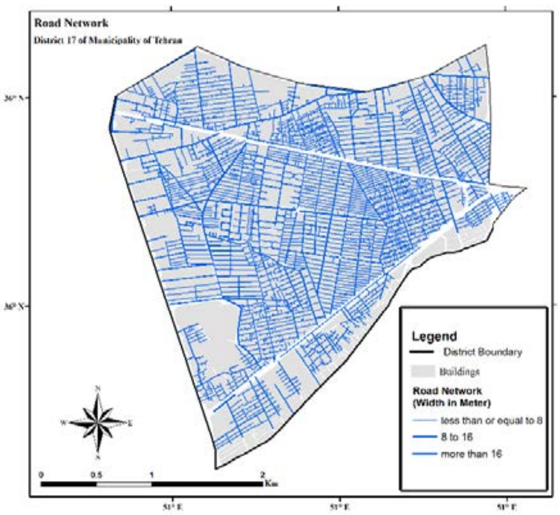


Figure 3. Road network according to road class (road width)

Table 2. Seismic parameters for three major faults in greater Tehran region (Gholipour et al., 2010)

Fault Name (Abbreviation)	Fault length (km)	Moment Magnitude	Mechanism	Elastic Thickness (km)	Horizontal slip rate (mm/y)
Mosha (MF)	79	7.0	S	15	-
N. Tehran (NTF)	59	7.1	T/S	15	0.70-1.00
N. Rey (RF)	25	6.7	T	15	0.30

Also, for the case study, Boore et al. (1997) relationship is chosen for predicting the ground motion and Wald et al. (1999) equation is used for producing the instrumental intensity at the ground surface. A major benefit in using such a methodology is the speed and the ease of implementation. The distribution of housing unit damages (damage grades of D4+D5 in EMS-98 damage grade scale) is shown for North Tehran Fault and Ray Fault scenarios in Figure 4.

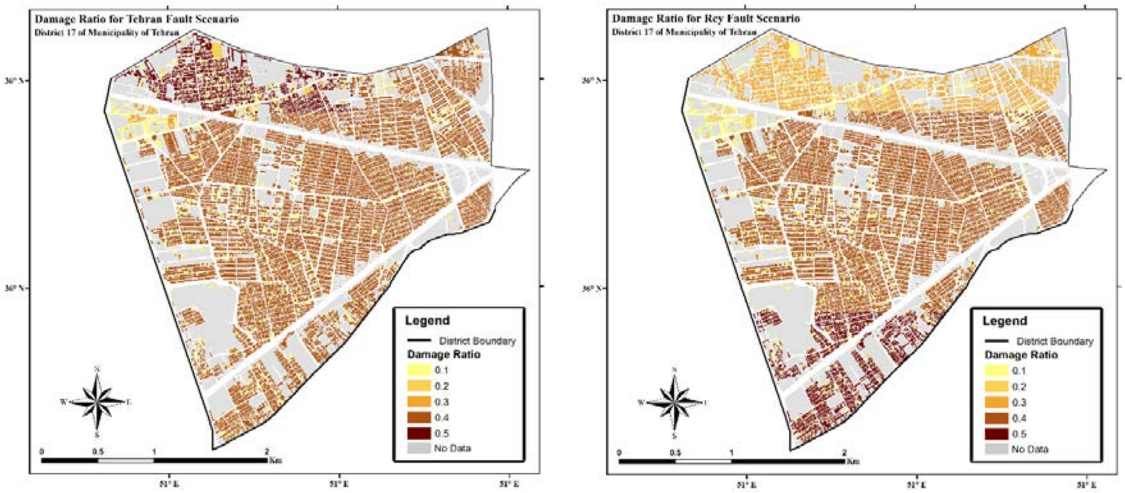


Figure 4. Distribution of damaged housing units for NTF and RF scenario (D4+D5 Grades)

Debris of the buildings that were adjacent to the roads was assumed to be the main cause of the road network blockage. Proximity analysis was performed in order to find the topology relationship to locate the parcels that are adjacent to each road and determine the parcel distance relative to the road and finally to calculate the blockage index. Figure 5 shows the result of the proximity analysis.

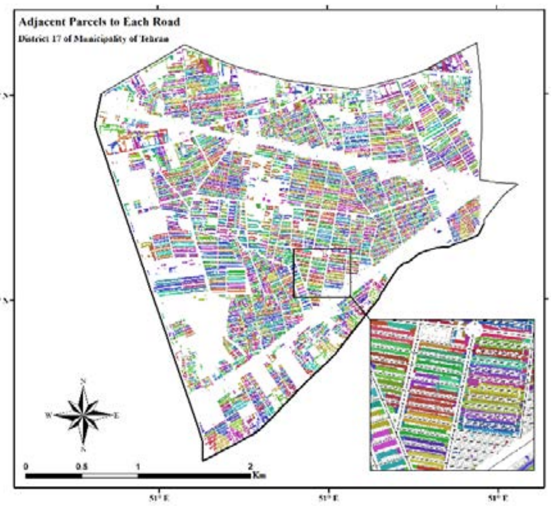


Figure 5. Proximity analysis results

Taking into account the mass of debris of a building to relevant passable width, the contribution of each building in blocking related road was determined. Figure 6 depicts the percentage of the contribution of each building in the road blockage for NTF and RF scenarios. In case, if the road is completely blocked by one of the adjacent buildings then the whole passage is blocked, thus the highest such value was considered of the obstruction (by surrounding buildings) of each road segment. The results of road blockage (highest percentage per segment) are shown for RF and NTF scenarios in Figure 6. Also Table 3 represents the total length (m) of the blocked road segment.

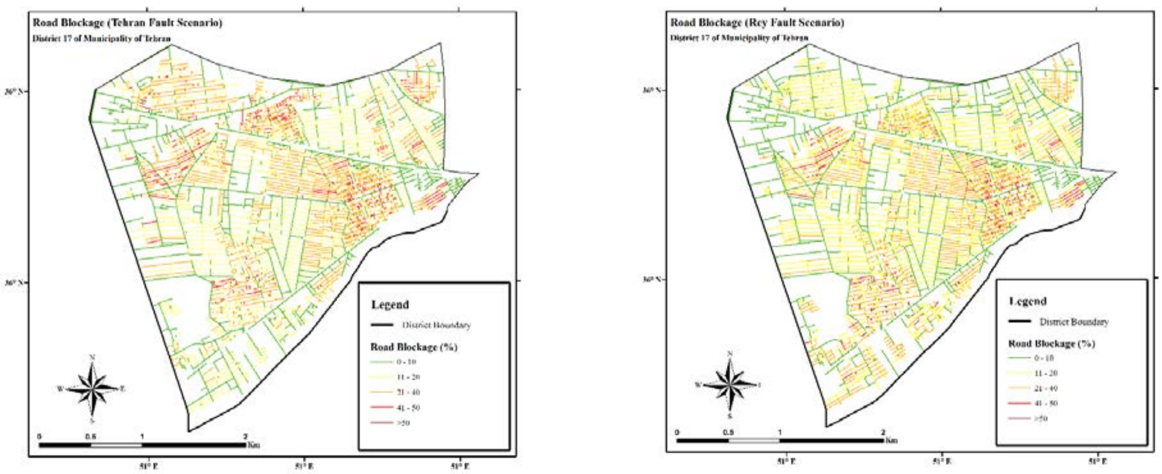


Figure 6. Road blockage for North Tehran Fault and Rey Fault scenarios

Table 3. Total length (m) of the blocked road for TF and RF Scenarios

Road Width (m)	TF scenario – blockage range percentage							RF scenario – blockage range percentage						
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	0-10	10-20	20-30	30-40	40-50	50-60	60-70
3	626.6	1514	13723	9191	12631	246.1	12.29	938.3	3400	17501	6815	8694	596.4	0.00
6	4441	32280	36177	281.6	0.00	0.00	0.00	5639	35304	32018	217.9	0.00	0.00	0.00
8	5303	34411	1308	0.00	0.00	0.00	0.00	8973	29914	2135	0.00	0.00	0.00	0.00
10	9142	10543	25.64	0.00	0.00	0.00	0.00	9448	10230	33.31	0.00	0.00	0.00	0.00
12	10304	6877	0.00	0.00	0.00	0.00	0.00	12725	5456	0.00	0.00	0.00	0.00	0.00
15	5994	75.94	0.00	0.00	0.00	0.00	0.00	6182	161.3	0.00	0.00	0.00	0.00	0.00
20	5423	0.00	0.00	0.00	0.00	0.00	0.00	5643	0.00	0.00	0.00	0.00	0.00	0.00
24	4006	0.00	0.00	0.00	0.00	0.00	0.00	4226	0.00	0.00	0.00	0.00	0.00	0.00
30	1246	0.00	0.00	0.00	0.00	0.00	0.00	1325	0.00	0.00	0.00	0.00	0.00	0.00
35	1941	0.00	0.00	0.00	0.00	0.00	0.00	2098	0.00	0.00	0.00	0.00	0.00	0.00
45	585.1	0.00	0.00	0.00	0.00	0.00	0.00	701.1	0.00	0.00	0.00	0.00	0.00	0.00

CONCLUSION

In order to have an optimal risk management plan considering all pre and post-earthquake phases in the disaster management, road network blockage estimation is crucial. These results potentially help in reducing the monetary loss and more importantly in reducing human loss. In this study, a new simplified methodology is proposed for the assessment of road blockage in urban settings. For this, it was required to develop structural fragility curves related to the building inventory as to estimate buildings that could experience heavy structural damages and that potentially result in debris spread into the road. The debris modeling was presented considering heavily and very heavily damaged buildings (EMS-98 scale) at both sides of each road segment and for the entire road network. The model was implemented for Tehran municipality district 17 considering two earthquake scenarios as North Tehran Fault (TF) and Rey Fault (RF). It was found that up to 10 percent of the roads with width more than 15 meters were blocked considering both scenario earthquakes. Fifty percent of the roads with 3m width were blocked in a range of 30%-50% for TF case. This figure for RF case was found as forty percent. About 41 percent of the total road blockage was estimated for a range of 10%-20% and about thirty percent of the total blockage was for road blockage values below 50%.

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