

# Management of post-earthquake construction debris in Tehran Metropolitan

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**Abstract** Earthquakes can lead to different levels of damages and subsequently produce significant volume of debris. Management of such huge amount of debris needs special attention. Thus, it is vital to develop a comprehensive and cost-effective management plan. The present study was carried out to estimate post-earthquake debris volume in the 22 districts of Tehran under various earthquake scenarios [magnitudes of 5, 6.5, and 7.5 on the moment magnitude ( $M_W$ ) scale]. Subsequently, required machineries and manpower and equipment for removal of debris were calculated. Finally, best practical methods for reduction and recycling were also examined. The shortest routes for transportation of post-earthquake to disposal sites were also proposed using network analysis. Results showed that about 83, 321 and 4802 million cubic meters of debris will be generated at 5, 6.5 and 7.5  $M_W$ , respectively. Disposal site of about 13 km<sup>2</sup> is marked within the area of study for the management of debris. Preparedness, emergency operations, rehabilitation and reconstruction are among the main activities that can reduce the earthquake-induced damages.

**Keywords** Debris depot · HAZUS · Network analysis · Post-earthquake · Management

## Introduction

Earthquake could be the primary cause of the damage to structures, loss of life, and injuries (Bird and Bommer 2004; Edrissi et al. 2013). Consequences of earthquakes in urban areas that are prone to damage, necessitate risk assessment for development of mitigation plans (Erdik et al. 2005; Rafee et al. 2008; Mikoš et al. 2006). Such plans are vital for management and urgently responding to the crisis (Xu et al. 2014). Earthquake intensity is the most important factor in terms of damage production (Pramudita et al. 2014). A common challenge of all severe earthquakes is the generation of massive amounts of building debris. As reported by Xiao et al. (2012), a huge amount of building waste ( $38,124.9 \times 10^4$  t) was generated by collapsed dwelling houses after earthquake that occurred on May 12, 2008, in Sichuan Province in China. According to Inui et al. (2012), approximately 23 million tons of debris was generated as a result of the Pacific Coast of Tohoku Earthquake and tsunami.

The removal of huge amount of debris is a costly and complex operation that may take months or even years to complete (Pramudita and Taniguchi 2014). Poorly managed post-earthquake waste can have adverse environmental and public health impacts (Brown et al. 2011). Large amounts of building debris act as a major obstacle in relief operations (Coronado et al., 2011). The reconstruction process could also be hindered. In emergency situations, it is extremely important to secure traffic flow immediately. Chang et al. (2012) proposed a constructive heuristics to generate roadside debris cleanup plans for a limited number of equipment in the post-disaster road recovery planning issues (Ozdamar et al. 2014). Deaths caused by people pinned down under the wreckage in the Van earthquake on October 23, 2011, at 13:41 has been

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evaluated by (Hekimoglu et al. 2013). Experiences around the world show that a significant portion of the debris can be recycled and reused during the cleanup phases. In addition to economic benefits and savings, this will reduce the volume of the debris disposed into landfill sites.

Fetter and Rakes (2012) developed a decision support system with recycling incentives to locate temporary disposal sites; Hu and Sheu (2013) proposed on-site storage and treatment of debris to reduce risk-induced and psychological impacts of post-disaster debris.

Disaster management of the large post-earthquake waste is a real challenge for developing countries with inadequate technical and financial capacities (Karunasena et al. 2012). According to statistics, six percentages of the world's natural disasters occur in Iran, making the country one of the most prone areas in the world, especially regarding earthquakes (Amiri et al. 2013). Considering Iran's position in a seismic-prone region, the country has always been at risk of earthquakes with potentially catastrophic results (Omidvar et al. 2014). Mass volume of building debris, blocked passages, and damages on airport, electricity and telecommunication networks, and water distribution systems are only few issues reported after the large earthquakes in the country. There are clear evidences coming from the past severe earthquake observations to support this claim, including Bam earthquake at 05:26:56 local time (01:56:56 GMT) on Friday December 26, 2003 (Manafpour 2008), Manjil–Rudbar earthquake at 00:30:09 on June 21, 1990 (Berberian et al. 1992), Bou'in-Zahra earthquake (Asnafi and Pakdaman Naeini 2012), etc. Since the repetition of disasters is very likely, pre-crisis preparedness would be critical in mitigating possible losses (Ghodrati Amiri et al. 2007). Accordingly, the present study was carried out to formulate a comprehensive management plan for post-earthquake debris disposal in Tehran Metropolitan City which is highly vulnerable to earthquakes.

## Materials and methods

Tehran is the largest and capital city of Iran situated within the latitudes 51°02'–51°36'E and the longitudes 35°34'–35°50'N, over an approximate area of 730 km<sup>2</sup>. Tehran remains the world's twenty-fifth most populous city. According to the municipal division, Tehran is divided into 22 districts, 134 sub-districts (North Ray and Tajrish), and 370 neighborhoods. Regarding seismicity, the city is categorized among high-risk areas (8°–10° on the Mercalli scale). There are five major active faults in a radius of 150 km from the city center and suburbs, namely Mosha, North Tehran, Rey, Taleghan, and Eyvanakey. Historical data on earthquakes in Tehran reveal that the city has suffered from several severe earthquakes with a return

period of 150 years. Considering that since the year 1830 the city has not experienced any catastrophic earthquake, seismologists warn of a severe earthquake in the near future taking into account the 35-year lag time over mean return period of 150 years.

In this research, HAZUS model was used to estimate possible post-earthquake damage and to calculate the extent of earthquake-induced debris at 22 districts of Tehran City. For this purpose, on-site impacts of earthquake were estimated by attenuation relationships, and damage occurrence probability was calculated based on fragility curves. Three sets of data such as the data on the target site, earthquake scenarios, and processing are needed to run the HAZUS model. The data on the number of building floors (short, intermediate, and tall buildings), structure systems (steel, reinforced concrete, all wood, cement blocks, and mixtures of brick, wood, and mud), building age, soil type (stone, hard alluvial, soft alluvial, and soft soil), and the location of faults (Mosha, North Tehran, and Rey) were gathered and archived for each 22 districts of Tehran City. Subsequently, three earthquake scenarios were designed under magnitudes of 5, 6.5, and 7.5 on the moment magnitude scale. These earthquakes are supposed to happen by the activation of the Ray, Mosha, and North Tehran faults.

According to the attenuation formula, the effect of earthquakes with the magnitude of  $M$  at a point to the distance of  $R$  from the center of the earthquake depends on soil characteristics, earthquake tectonic focus and finally the path of the seismic waves. In this research, attenuation equations of Campbell and Bozorgnia (1994) and Khademi (2002) were used to specify earthquake magnitude. Campbell and Bozorgnia (1994) used worldwide acceleration records of earthquakes with a magnitude of 4.7–8.1 torque to model strong ground motion as follows:

$$\begin{aligned} \ln(\text{PGA}) = & -3.512 + 0.904M_w \\ & - 1.328 \ln \sqrt{R^2 + [0.149 \exp(0.64M_w)]^2} \\ & + (1.125 - 0.112 \times \ln(R) - 0.957M_w) \cdot F \\ & + (0.94 - 0.171 \ln(R))S_{\text{SR}} \\ & + 0.405 - 0.222 \ln(R) \cdot S_{\text{SR}} \end{aligned} \quad (1)$$

If  $M \leq 7.4$ ;

$$\sigma_{\ln(\text{PGA})} = 0.889 - 0.0691M$$

and if  $M > 7.4$ ;

$$\sigma_{\ln(\text{PGA})} = 0.38$$

$R$  the closest distance (less than 60 km) to rupture in km;  $F$  is a parameter influenced by fault type so as for reverse and thrust faults  $F = 1$ ;  $M_w$  moment magnitude;  $S_{\text{SR}}$  is a site-affected parameter so as for soft site  $S_{\text{SR}=1}$ , and for alluvial site  $S_{\text{SR}=0}$ ;  $S_{\text{HR}}$  is a site-affected parameter so as for

crystalline and metamorphic rocks  $S_{HR=1}$ , and for alluvial sites  $S_{HR=0}$ .

Khademi (2002) developed the following equation for Iran.

$$Y = C_1 \exp(C_2 M)(R + C_3 \exp(C_4 M))^{C_5} + C_6 S \quad (2)$$

The experimental–theoretical ground motion relation coefficients for different periods for vertical components and sites made of stones or soil, in fourteen periods from the time zero to the time 4 s, for earthquakes with a magnitude from  $M_w = 5$  to  $M_w = 7.5$  and distance  $r_{jb} \leq 150$  km are as follows:

The coefficients of this equation are as follows:

$$\begin{aligned} C_1 &= +0.040311, & C_2 &= +0.417342, \\ C_3 &= +0.001000, \\ C_4 &= +0.650000, & C_5 &= -0.351119, \\ C_6 &= -0.035852, \end{aligned}$$

$S = 0$  for stony sites, and  $S = 1$  for earthen sites

Fragility curves in HAZUS are modeled as a cumulative lognormal distribution, indicating the probability of reaching the excess of structural damage to the threshold of a given damage state.

$$P[\langle d_s, S_d \rangle] = \varphi \left[ \frac{1}{\beta_{ds}} \times \ln \left( \frac{S_d}{\bar{S}_{d,ds}} \right) \right] \quad (3)$$

$\bar{S}_{d,ds}$ : the median spectral displacement at which the structure reaches the threshold of the damage state (ds),  $\beta_{ds}$ : standard deviation of displacement logarithm related to the damage state (ds),  $\varphi$ : standard normal cumulative distribution function.

A model called HAZUS was used for the prediction and estimation of the debris after earthquake. This model provides estimations for two kinds of debris:

1. The first kind is structural debris such as elements of steel or reinforced concrete.
2. The second kind is smaller debris such as irons, woods, bricks plastics, glasses and et cetera.

Estimation of debris could be done by the investigation of the following methods:

1. General Occupancy Class
2. Specific Occupancy Class

The amount of debris produced by the damage of buildings in metric tons depends on the following factors:

1. Weight of the structural and non-structural elements: For each of the sampled buildings, it is calculated based on tone per a thousand square foot.
2. The debris produced from the structural and non-structural elements related to the situation in different phases of the damage caused by the earthquake

3. The first step in calculation of debris is to conflate the debris produced from the different regions of the damaged with the debris produced from different buildings

To estimate the weight of the debris of structural or non-structural elements, the following formula based on ton per a thousand square feet is used:

$$EDF_s(i, k) = \sum_{j=2}^5 P_s(j, k) \times DF_s(i, j, k) \quad (4)$$

$$EDF_{ns}(i, k) = \sum_{j=2}^5 P_{ns}(j, k) \times DF_{ns}(i, j, k) \quad (5)$$

$i$ : indicates the type of the debris; if  $i = 1$ , then the debris is from woods, bricks, glasses or et cetera, and if  $i = 2$ , then the debris is from elements of steel or reinforced concrete.  $j$ : indicates the level of damage ranging from 1 to 5.  $k$ : indicates the type of the building ranging from 1 to 36.  $DF_s(i, j, k)$ : indicates the amount of debris of type  $i$ , for building of type  $k$  when the damage level is  $j$  and it is obtained from the tables from (NIBS 2012).  $P_s(j, k)$ : indicates the probability of being situated in the damage level  $j$  for a building of type  $k$ .  $EDF_s(i, k)$ : indicates the debris of type  $i = 1$  caused by damage to a building of type  $k$ .  $EDF_{ns}(i, k)$ : indicates the debris of type  $i = 2$  caused by damage to a building of type  $k$ .

These values indicate the percentage of the expected debris of type  $i$ , caused by structural or non-structural damage to the building of type  $k$ . If the values of  $SQ(k)$ ,  $W_s(i, k)$ ,  $W_{ns}(i, k)$  are given by using statistics, the percentage of the expected debris is calculated from the following equation:

$$DB(i) = \sum_{k=1}^{36} [EDF_s(i, k) \times W_s(i, k) + EDF_{ns}(i, k) \times W_{ns}(i, k)] \times SQ(k) \quad (6)$$

$W_s(i, k)$ : weight of structural debris of type  $i$  per a thousand square feet.  $W_{ns}(i, k)$ : weight of non-structural debris of type  $i$  per a thousand square feet.  $SQ(k)$ : SQUARE foot of debris related to building of type  $k$  per a thousand square feet.

The bare land areas within the 22 districts of Tehran were proposed as disposal sites for the building debris. After the occurrence of an earthquake, building debris should be transferred to the depot site through the shortest possible route in the shortest possible time. The most important factors in selection of evacuation routes sorted in the order of their importance are (1) invulnerability and sustainability of nearby buildings in the routes network, (2) inexistence of dangerous facilities or constructions, (3) low

population density in construction blocks near the route network.

As the size of the resident population in blocks near the route network increases, its feasibility for optimum evacuation is reduced. In other words, routes with higher population density are less suitable for the optimization process of the routes.

Presence of bridges or tunnels across the evacuation routes can be dangerous or even very dangerous. Therefore, presence of bridges across these routes was strongly avoided or at least, the minimum requirements for securing and strengthening these bridges were fulfilled.

In this research, debris evacuation routes were designed using network analysis. Together with the main critical route network, consisting of freeways, highways, and main streets, a network of prioritized sub-routes was also plotted to further ease the access from the main routes to the target places in the city for relief and debris evacuation. To find the optimum way to transfer the debris to the proposed sites by the shortest routes and in the shortest possible time, the short pass and short time analyses were used. For this purpose, the center of gravity at each district was considered as the initial point (source) and the depot sites were assumed as the destination. In short pass analysis, it is necessary to take movement speed of different types of passages into account. The average speed limit on most highways and main streets in Tehran is 80 and 50 km/h, respectively. Accordingly, the average speed for highways and main streets is 60 and 30 km/h, respectively. The initial network system was modified by the experts familiar with the location using objective judgment analysis method. Subsequently, prioritized debris removal routes were specified using three criteria of net area of the district, the need of the district, and the impact of the old fabric. It is clear that the length of the critical paths at each district could be a function of its entire area defined as parameter B (Eq. 7).

$$B = \frac{L_{c.r.}}{A_n} \quad (7)$$

$L_{c.r.}$  is the length of the critical route, and  $A_n$  is net area of the district.

The need of the district is a function of its vulnerability. To quantify this criterion, the parameter  $c$  was defined as Eq. (8).

$$c = \frac{T_{db}}{A_n} \quad (8)$$

where  $T_{db}$  is the total of damaged buildings, and  $A_n$  is the net area of the district.

As it is evident, extended areas of old urban fabric at each district will increase the length of routes prioritized to be reopened urgently. To determine the effect of old fabric,

$J$  parameter was defined according to Eq. (9) in which the  $Uf$  parameter addresses the area of old fabric in each district in percentage.

$$J = C \times (1 + 2 \times Uf) \quad (9)$$

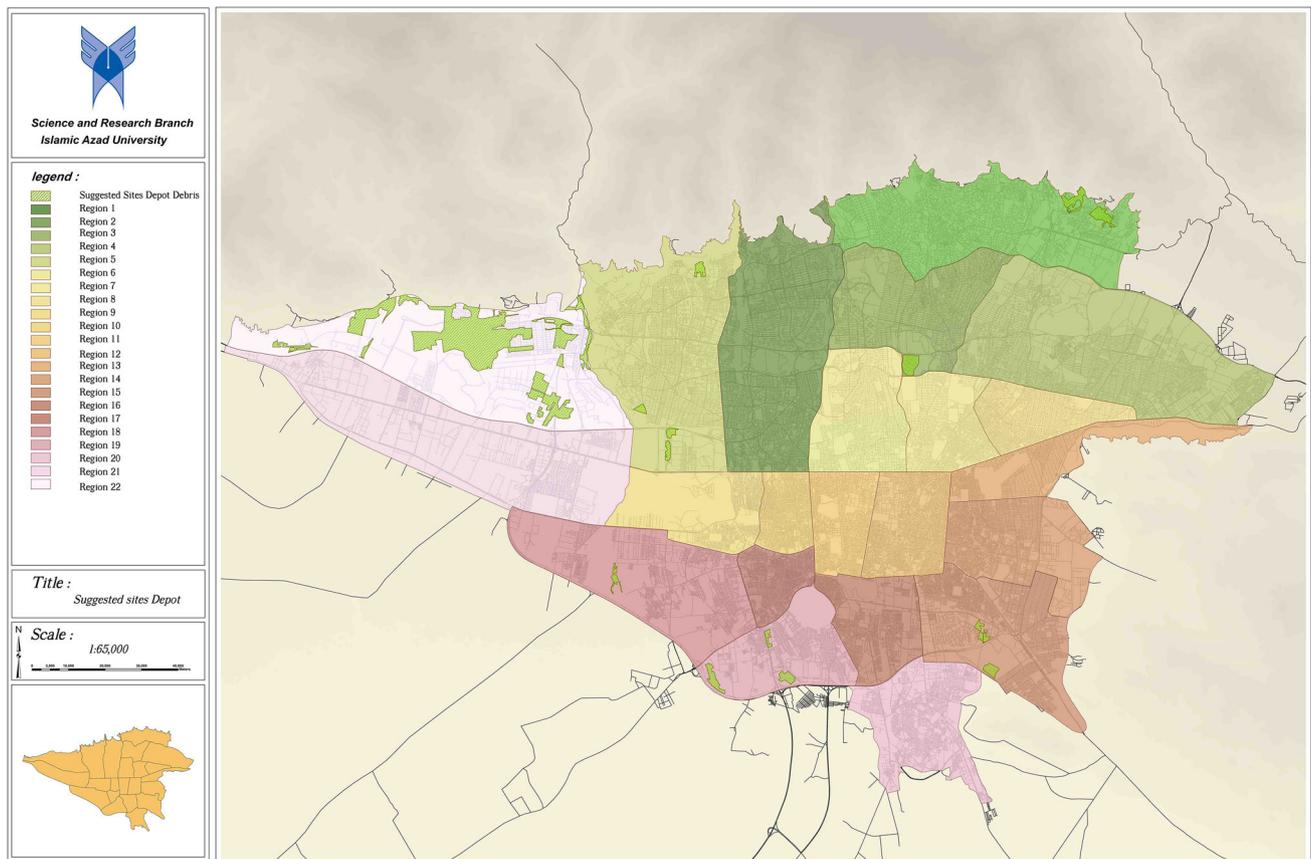
## Results and discussion

According to the HAZUS results, in the event of a 5-magnitude earthquake on Rey Fault, the debris volume would be about 182,668,536 m<sup>3</sup>. As a result of this earthquake, 21 % of Tehran's buildings will be destroyed and about 1,818,121 people will be made homeless. Furthermore, the casualties are estimated at 5907, and also 194,047 people will be injured. Damage to the 8 % of the buildings, over an area of 71,079,968 m<sup>2</sup>, is assessed as heavy. Approximately 13 % of the buildings over an area of 10,043,744 m<sup>2</sup> will suffer moderate damage. The remaining buildings (about 57 % over an area of 372,354,272 m<sup>2</sup>) will stay almost intact after the earthquake. The 6.5-magnitude earthquake on Rey Fault will generate about 3,211,338,400 m<sup>3</sup> of debris and leave 329,354 residents injured, 14,910 killed, and 2,984,685 homeless. It will also heavily demolish 24 % of the buildings over an area of 128,852,112 m<sup>2</sup>. The damage to the 21 % of the buildings in an area of 190,317,808 m<sup>2</sup> is estimated to be average, while in an area of 202,796,272 m<sup>2</sup> covering 22 % of the entire city area will be slight. Approximately 33 % of the total buildings over an area of 112,397,824 m<sup>2</sup> would not be damaged. According to the results, it is expected that 4,802,307,200 m<sup>3</sup> of debris will be produced if an earthquake of 7.5 magnitude occurs. As a result, 54 % of buildings will be damaged and 3,306,104 residents lose their homes. This is coupled with 190,510 casualties and also 363,442 injuries.

The 7.5-magnitude earthquake can heavily damage 23 % of buildings over an area of 194,082,104 m<sup>2</sup>. The damage to 21 % of the buildings, within an area of 194,179,104 m<sup>2</sup>, is estimated average. About 19 % of the buildings will undergo minor damage. The remaining buildings (28 % of the total, over an area of 90,534,912 m<sup>2</sup>) will remain intact.

In the event of a 5-magnitude earthquake on Moshfa Fault, a total debris of 6,972,296,192 m<sup>3</sup> would be generated that is resulted from damages to 18 % of buildings. This earthquake leaves 2,760,103 people homeless. Casualties and injuries will be around 6709 and 277,932, respectively. Approximately 6 % of the buildings, over an area of 52,013,408 m<sup>2</sup>, are highly vulnerable to the earthquake. The damage to the 12 % of the buildings, within an area of 100,685,088 m<sup>2</sup>, is estimated as an average. More than 23 % of the buildings covering an area of 206,914,592





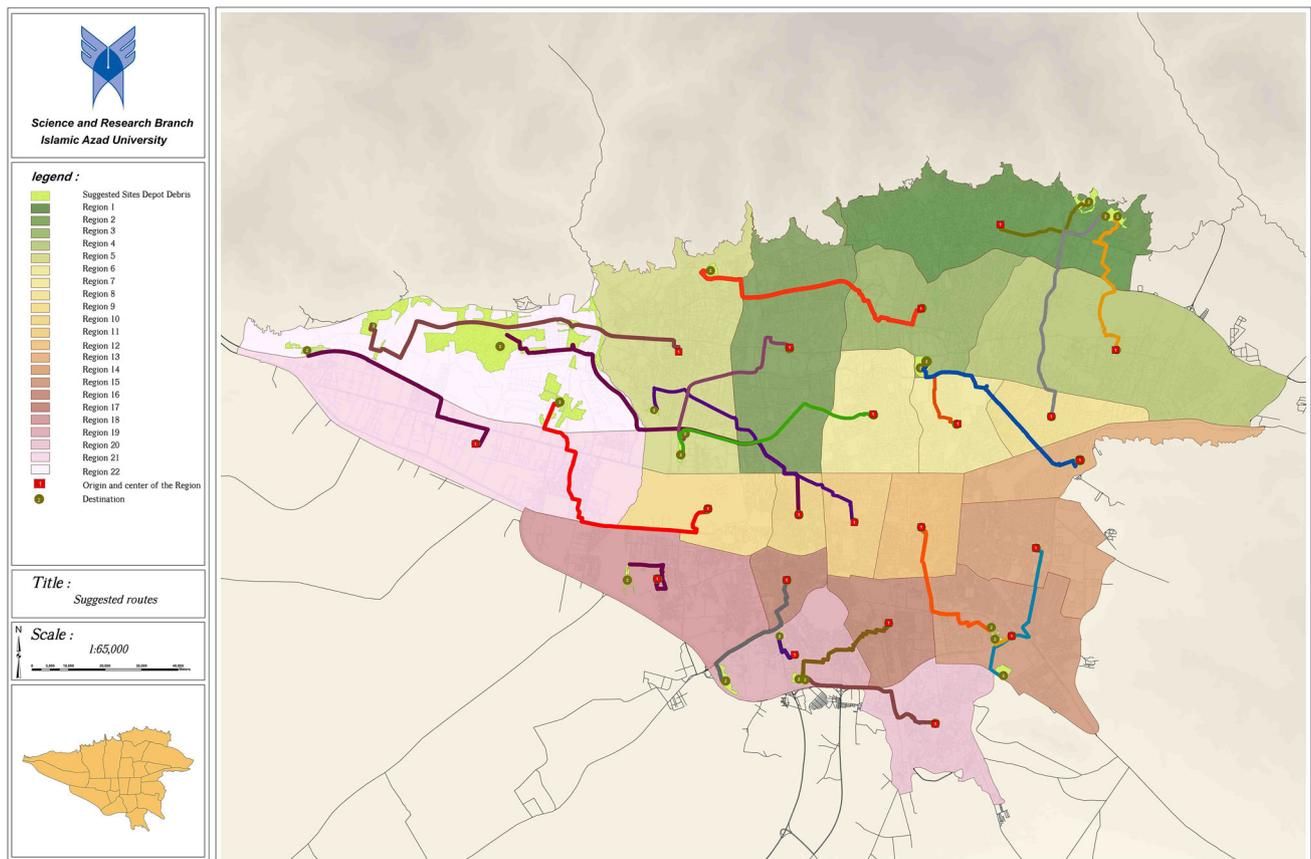
**Fig. 1** Distribution of depot sites for the disposal of post-earthquake debris in Tehran

will be slightly damaged. About 50 % of the buildings are expected to remain intact after the earthquake. An estimated 9,451,494,656 m<sup>3</sup> of debris will be produced after a 6.5-magnitude earthquake on Moshafault causing 30 % of the buildings damaged. The death toll of the earthquake will reach 13,199, and the number of the injured will be 415,746. Overall, 12 % of the buildings (114,606,256 m<sup>2</sup>) will be destroyed heavily, 18 % (152,219,344 m<sup>2</sup>) moderately, and 25 % (221,405,712 m<sup>2</sup>) slightly. Approximately 45 % (246,132,736 m<sup>2</sup>) of the buildings are expected to remain intact. In case of a 7.5-magnitude earthquake on Moshafault, about 12,106,525,697 m<sup>3</sup> of debris will be generated as a result of the destruction of 53 % of the buildings. The number of earthquake casualties will reach 17,154. A total number of 3,257,441 and 363,334 will be homeless and injured, respectively. Furthermore, damage to 30 % (276,702,144 m<sup>2</sup>) of buildings is estimated to be heavy, 23 % (194,179,104 m<sup>2</sup>) is moderate, and 19 % (171,639,952 m<sup>2</sup>) is slight. There will not be any damage to 28 % (91,832,832 m<sup>2</sup>) of the buildings.

A 5-magnitude earthquake induced by North Tehran Fault will result in 24,256,800 m<sup>3</sup> of debris that is the

result of collapse of 9 % of buildings. This will lead to the death of 1413 residents and the injury of 78,843 people. About 910,747 people will be homeless. Around 2 % (27,376,642 m<sup>2</sup>) of the buildings will undergo severe damage and 7 % (63,859,956 m<sup>2</sup>) will suffer moderate damage. The damage to 17 % (163,839,200 m<sup>2</sup>) is estimated to be slight, while about 74 % (479,288,256 m<sup>2</sup>) will remain intact. The estimated debris after a 6.5-magnitude earthquake on North Tehran Fault will reach 712,023,376 m<sup>3</sup>. In the event of the earthquake, 28 % of the buildings are expected to be destroyed, leaving 2,093,908 people homeless. Among other post-earthquake impacts, the death of 6190 residents and the injury of 218,315 people can be pointed out. The damage to the 25 % (133,434,592 m<sup>2</sup>) of buildings is heavy, 16 % (154,631,856 m<sup>2</sup>) is average, and 12 % (226,025,472 m<sup>2</sup>) is slight. About 47 % of the buildings in an area of 220,272,096 m<sup>2</sup> will remain intact.

The 7.5-magnitude earthquake on North Tehran Fault will generate 953,407,968 m<sup>3</sup> debris, resulting from the collapse of 36 % of buildings. The number of injuries and death toll will be as many as 15,108 people and 479,813



**Fig. 2** Routes of debris evacuation in Tehran

people, respectively. Quake-related damage is evaluated heavy in 15 % of buildings over an area of 160,049,920 m<sup>2</sup>, average in 21 % of buildings over an area of 202,136,624 m<sup>2</sup>, and slight in 26 % of buildings over an area of 232,451,872 m<sup>2</sup>. Furthermore, the damage to 38 % of the buildings within an area of 139,725,632 m<sup>2</sup> is negligible.

Once estimating the magnitude of debris and extent of the damage, unoccupied lands in the city were allocated as debris depot sites. Figure 1 depicts distribution of the depot sites in Tehran. According to the results, the western part of Tehran accounts for the largest depot area of 12,039,252 m<sup>2</sup>. The depot area of 2,231,875.426 m<sup>2</sup> is stretched in south. The area of the depot sites in the central and northern Tehran is about 1,209,261.047 m<sup>2</sup>. They also cover an area of 974,599.1406 m<sup>2</sup> in the east of Tehran.

Debris removal and evacuation operations after the earthquake are necessary to eliminate possible threats or potential dangers, as well as for the reconstruction phase to ensure safety and security of people. Determining debris

deposit and evacuation spaces is one of the most important urban management factors in dealing with an earthquake crisis which should be done according to the population density and the reachability of the location (Abbasi and Farbod 2009).

In this study, arid lands in the 22 districts of Tehran were determined for evacuation and temporary deposition of the debris where the debris will be recycled for an interval of time or it will be sent to the outside of the city for burial.

Considering the volume of debris and the constraint of cleaning and reopening operations, waste disposal routes should be as short as possible. Accordingly, network analysis was used to determine the debris removal routes by finding shortest possible paths between the center of gravity at various districts as the starting point and the depot sites as destination. Figure 2 demonstrates the routes of the debris evacuation in Tehran.

Debris Removal Specialized Committee (DRSC) is in charge of post-earthquake crisis management in Tehran. About 200, 160 and 80 m<sup>3</sup>/building has been computed as



**Table 1** Required equipment for post-earthquake debris removal in Tehran

Equipment type	Earthquake scenarios																
	Required equipment declared by DRSC for removal of debris	Number of equipment				Required equipment induced by Rey Fault				Required equipment induced by Moshafault				Required equipment induced by North Tehran Fault			
		18,936,440 m <sup>3</sup> of debris	Required for removal of debris induced by 5-magnitude earthquake	Required for removal of debris induced by 6.5-magnitude earthquake	Required for removal of debris induced by 7.5-magnitude earthquake	8391	321,693	321,128,400 m <sup>3</sup>	4,802,307,200 m <sup>3</sup>	6,972,296,192 m <sup>3</sup>	9,451,494,656 m <sup>3</sup>	12,106,525,696 m <sup>3</sup>	24,256,800 m <sup>3</sup>	712,023,376 m <sup>3</sup>	953,407,967 m <sup>3</sup>		
Truck	1897	8391	321,693	481,082	1,212,798	946,825	698,465	2430	71,329	95,510							
Bobcat (mini-loader)	190	840	32,220	48,184	69,957	94,832	121,472	243	7144	9566							
Loader	200	885	33,915	50,720	73,639	99,823	127,865	256	7520	10,070							
Bulldozer	190	840	32,220	48,184	69,957	94,832	121,472	243	7144	9566							
Dumper	200	885	33,915	50,720	73,639	99,823	127,865	256	7520	10,070							
Hydraulic Excavator	180	796	30,524	45,648	66,275	89,841	115,078	231	6768	9063							
Fuel tanker	200	885	33,915	50,720	73,639	99,823	127,865	256	7520	10,070							
Crane	40	177	6783	10,144	14,728	19,965	25,573	51	1504	2014							
Passenger car	140	840	32,220	48,184	69,957	94,832	121,472	243	7144	9566							
Motorcycle	180	796	30,524	45,648	66,275	89,841	115,078	231	6768	9063							

**Table 2** Required manpower for post-earthquake debris removal in Tehran

Occupation	Required manpower in person									
Required equipment	For removal of 83,761,368 m <sup>3</sup> debris induced by 5 magnitude Ray earthquake scenario	For removal of 321,128,400 m <sup>3</sup> debris induced by 6.5 magnitude Ray earthquake scenario	For removal of 4,802,307,200 m <sup>3</sup> debris induced by 7.5 magnitude Ray earthquake scenario	For removal of 6,972,296,192 m <sup>3</sup> debris induced by 5 magnitude Mosha earthquake scenario	For removal of 9,451,494,656 m <sup>3</sup> debris induced by 6.5 magnitude Mosha earthquake scenario	For removal of 12,106,525,696 m <sup>3</sup> debris induced by 7.5 magnitude Mosha earthquake scenario	For removal of 24,256,800 m <sup>3</sup> debris induced by 5 magnitude Niavaran earthquake scenario	For removal of 712,023,376 m <sup>3</sup> debris induced by 6.5 magnitude Niavaran earthquake scenario	For removal of 953,407,967 m <sup>3</sup> debris induced by 7.5 magnitude North Tehran earthquake scenario	
18,936,440 m <sup>3</sup> of debris										
Driver	15,247	584,542	874,164	1,269,167	1,720,455	2,203,751	4415	129,610	173,549	
Driver assistance	8391	321,693	481,082	698,465	946,825	1,212,798	2430	71,329	95,510	
Appraiser	796	30,524	45,648	66,275	89,841	115,078	231	6768	9063	

average volume of debris by DRSC for complete, heavy and moderate destruction of Tehran's building. Considering the time required for loading and transportation between the starting points and the depot sites, each truck would be capable of eight services a day to evacuate a volume of 5 m<sup>3</sup> per each service (or 40 m<sup>3</sup>/day). In order to estimate the required equipment for loading and transportation of debris and trash to the temporary depot sites, the following assumptions were considered:

1. Loading time is 1 h
2. Up and down travel time between the districts and temporary depot sites is 2 h
3. It is assumed that a 5-t trucks will be used to transport rubble and debris and that any truck can offer eight services in 24 h
4. Cleaning period is about 3 months
5. Considering a total capacity of 5 tons per truck, each truck can transport 40 t/day.

Accordingly, the required equipment for each earthquake scenarios was estimated. Table 1 presents the required equipment for the most likely earthquake scenario (5-, 6.5-, and 7.5-magnitude earthquake on Mosha, North Tehran, and Rey Fault).

The figures presented in Tables 1 and 2 are indicative of significant number of machineries and manpower. In other words, the existing capability is only about 3.22 % real needs.

## Conclusion

The present work brought out an estimation on post-earthquake debris volume in Tehran Metropolitan City. In order to reduce the earthquake-induced damages in the city, stringent efforts must be made in four stages. These include (1) preparedness (for planning to reduce damage in the event of an earthquake), (2) emergency operations (to mobilize relief operations, immediate and effective evacuation, and other necessary post-earthquake activities), (3) rehabilitation (to restore the vital passages of the city centers as soon as possible without compromising the security of the people), and (4) reconstruction (to reconstruct urban fabric in way to further withstand future earthquakes). Adequate funding is needed to support preparedness, emergency operations, rehabilitation, and reconstruction strategies. To fulfill these objectives, it is necessary to impose stricter building construction rules particularly for high-rise buildings in Tehran, with more emphasize on crisis management approaches. As another important management strategy, straightening and integration of spatial databases can further facilitate the early relief and rescue operations throughout Tehran City.



Finally, it has been suggested to enhance capabilities of the current Tehran Earthquake Damage Estimation System (TEDES) for rapid estimation of earthquake-induced losses at the moment of the occurrence and to stimulate earthquake scenarios. This can help prioritizing building retrofit projects at different districts of the city and provide the crisis managers with the opportunity of wise decision-making.

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