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PRIORITIZING THE RETROFIT OF VULNERABLE COMPONENTS OF URBAN TRANSPORTATION SYSTEM BASED ON THE OPTIMIZED RESCUE AND RELIEF TRAVELS

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SUMMARY

In this paper a method is presented in which the vulnerable components of transportation system are prioritized for retrofitting based on their service level to the rescue and relief traffic. At first, by considering the existing seismic sources in the area some scenarios are defined based on the occurrence time of the earthquake. Then, the damage and life loss distributions are obtained by considering the buildings vulnerability level and population density in different parts of the city. The available transportation network after the earthquake is simulated based on the fragility curves (HAZUS relationships) of the system components. The service level of the system components are determined and based on distribution and assignment of rescue and relief travels the main parameter for network evaluation is obtained. Simulation results are evaluated by @Risk computer program to find out which components have greater role in the improvement of the whole network. The proposed method is presently being applied to the case of Tehran metropolis with around 10 million population, almost 1200 square km of transportation network coverage, 58 fire stations, around 160 hospitals, and about 180 highway bridges.

INTRODUCTION

After a major earthquake in a large and populated city the extent of damage and casualty are not uniform. The older parts of the city and those parts which are more populated are more likely to have extensive life losses. Obviously the traffic paths serving these areas are more important in the whole city transportation network. Because of the abrupt change in traffic demand just after the occurrence of a sever earthquake in a large vulnerable city the transportation network should be not only safe enough to offer its normal

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service to the city, but also it should be able to cope with this increased demand. This is while the transportation network in many large and populated cities in earthquake prone areas are highly vulnerable on the one hand, and there are financial limitations, time restriction and little number of retrofit experts, particularly in developing countries, on the other. Therefore, it is necessary to consider a prioritization scheme for the retrofit of city transportation system components.

In recent decades, particularly during 90s, many researchers have worked on the functionality of transportation systems subjected to earthquakes, and some models have been proposed for evaluation of the performance of these systems [1]. The reliability analysis of urban transportation systems has been also taken into consideration [2], and some fragility functions have been introduced for highway systems as well [3]. In recent years researchers have paid more attention to seismic risk assessment of transportation systems [4], and the concepts like demand and capacity have used [5]. However, based on the available literature the prioritization of transportation system components for seismic retrofit has not been addressed so far.

In this paper a method is presented in which the vulnerable components of transportation system are prioritized based on their service level to the rescue and relief traffic. In the proposed method at first, by considering the existing seismic sources in the area some scenarios are defined based on the occurrence time of the earthquake. Then, the damage and life loss distributions are obtained by considering the buildings vulnerability level and population density in different parts of the city. The available transportation network after the earthquake is simulated based on the fragility curves (HAZUS relationships) of the system components. The service level of the system components are determined and based on distribution and assignment of rescue and relief travels the main parameter for the network evaluation, which is called the Accessibility Index, is obtained. Simulation results are evaluated by @Risk computer program to find out which components have greater role in the improvement of the whole network. The proposed method is presently being applied to the case of Tehran metropolis with 10 million inhabitants, almost 1200 square km of transportation network coverage, 58 fire stations, around 160 hospitals, and about 180 highway bridges.

STATE OF THE PROBLEM

The importance of rescue and relief activities in the first few hours after the earthquake occurrence and dissemination of travels in a large area necessitate the employment of a preparedness and prevention program. In the first days after the event the travel pattern in the city is quite different from normal situation. Travels for job, entertainment, school, and shopping are not the same as before and are usually omitted. Instead, there are some new travels such as rescue and relief teams travels as well as travels for evacuation and temporal shelters and distribution of aids, of which the most important travels are the first group. In this group some origin-destination pairs can be defined as discussed by Hosseini et al [6] and Shariat Mohaymany et al [7]. The origins and/or destinations of rescue and relief travels are the centers of densely populated areas, which are called the population centers hereinafter for simplicity. Other ends of these travels are fire stations, red-crescent centers, and hospitals, among which hospitals have the most number of travels. So, the paths which provide access to and from hospitals to population centers can be considered as the basic network.

The reliable provision of accesses between population centers and hospitals is considered as the first criterion for the functionality assessment of the city transportation network. The second criterion is the number of casualties in each population center. The higher this number the more is the importance of that center and its accessibility. The third criterion is the importance of the relief center or the hospital. Although number of beds is not the only factor in the importance of a hospital, and other factors such as the capacity of the emergency, and orthopedics sections as well as the fame of the hospital and its potential capacity increase are also important, as stated by Shariat Mohaymany [8], this number has been considered as the main factor in this study for the capacity evaluation of hospitals. To apply these criteria to evaluation of transportation system and decision making on prioritization of the system components retrofit a somehow new concept call here the Accessibility Index (*AI*) can be defined as follows.

THE ACCESSIBILITY INDEX

If I_i is the number of injured peopled in a population center, the relative importance or weighting factor of that center can be defined as:

$$W_i = \frac{I_i}{\sum_{i=1}^{p} I_i} \tag{1}$$

in which p is the total number of population center with casualties. A capacity factor C_j can be also defined for each hospital j, by which the relative importance factor can be defined as:

$$\gamma_j = \frac{C_j}{\sum_{j=1}^{q} C_j} \tag{2}$$

where q is the number of available hospitals. To have an estimation of the accessibility between origin-destination pairs Equation (3) can be used.

$$A_i = \sum_j [\sum_l P_{ij}^{\ l}] \times \gamma_j \qquad l \in \{R_{ij}\} \tag{3}$$

in which $\{R_{ij}\}$ is the set of all possible paths (routes) between origin-destination pair of i and j. In Equation (3) l is the indicator of any existing path between i and j, and $P_{ij}^{\ l}$ is the stability probability of path l, varying between 0.0 for the totally failed path and 1.0 for the fully functional path. This probability itself can be calculated as the product of stability probabilities of all components in path l, namely:

$$P_{ij}^{\ l} = \prod_{k=1}^{n} P_{ij}^{lk} \tag{4}$$

In this evaluation each path like l is considered to have n components, and P_{ij}^{lk} is the stability probability of the k^{th} component. It should be noted the without a powerful crisis management, even without heavy damage to the transportation network components, the functionality of the network will decrease to a great extent because of the unpredicted public reaction [9]. By suing the concepts presented by Equations (1) to (4), the Accessibility Index can now be defined as:

$$AI_i = A_i \times w_i \tag{5}$$

and the Total Accessibility Index for the whole network can then be given by:

$$TAI = \sum_{i=1}^{p} AI_i \tag{6}$$

in which p is again the total number of population centers in the city. Obviously, higher value of *TAI* means the better condition of the whole network. By simulation of any transportation network and by using some appropriate earthquake scenarios and calculating the values of Total Accessibility Index for various combinations or sets of paths, the set which gives the highest value of *TAI* can be considered as the optimum network for rescue and relief activities, and accordingly, the vulnerable components in this optimum network have the highest priority for retrofitting. This procedure is explained in detail in the following section of the paper.

THE PRIORITIZATION PROCEDURE

The aforementioned formulas can be used for introducing the optimum transportation network for rescue and relief activities and prioritization of components retrofit in the following nine steps:

1. Identifying the location of population centers and hospitals in the city – this is suggested to be done by using a GIS, as it has been in this study.
2. Considering the appropriate areas around all population centers for rescue and relief services – in fact, regarding the public reaction and in the very first hours after the occurrence of earthquake and the people-initiated emergency help process, just the mostly known hospitals around every population center will be referred by the people. Furthermore, it is basically more reasonable to refer to the closer hospitals to every population center. Therefore, it is suggested that for every population center a rescue and relief service area is considered.
3. Identifying all existing paths between population centers and hospitals – this is an essential part of the procedure as every selected set of paths will result is a different *AI* value, which are the main parameter for network evaluation.
4. Identifying the number and the situation of vulnerable components in various paths as well as their stability conditions – this step is thoroughly engaged with the use of fragility functions of the network components. Obviously, different fragility curves will result in different values of *AI*, and consequently will affect the final result about the optimum network and the prioritization decision making.
5. Defining earthquake scenarios – To define an earthquake scenario the seismic hazard in the area as well as geotechnical and topographical data are required. The occurrence time of earthquake is the key parameter in defining scenario, because it affects extensively both the number of casualties and the traffic condition, as explained in detail by Hosseini et al [6].
6. Estimating the number of casualties in all population centers and obtaining their relative importance factors by Equation (1) – this can be considered as a part of information presented in the earthquake scenarios, but because of its crucial role in the evaluation process it has been considered separately here.
7. Obtaining the capacity factor of hospitals and their relative importance factors by Equation (2) – this is also a very important part of the procedure as these capacity factors have the main role in the calculation of accessibility values by Equation (3), which should be calculated separately for any service area mentioned in step 2 above in a simulation process as explained in the next setp.
8. Simulating the network and calculating the Accessibility Indices of various possible paths and the corresponding Total Accessibility Indices for different sets of selected path by Equations (4) and (5) – this step is the main part of calculations which can be performed by various techniques. In this study the Monte Carlo technique has been employed.

9. Obtaining the optimum rescue and relief network and which shows which components in which routes should be prioritized for retrofitting works.

The application of the aforementioned steps is shown by a numerical example in the next section of the paper.

THE NUMERICAL EXAMPLE

A very simple numerical example is presented here for illustrating the prioritization procedure, explained in the previous section. In this example a set of three population centers I_1 to I_3 as well as four relief centers or hospitals J_1 to J_4 are considered as shown in Figure 1.

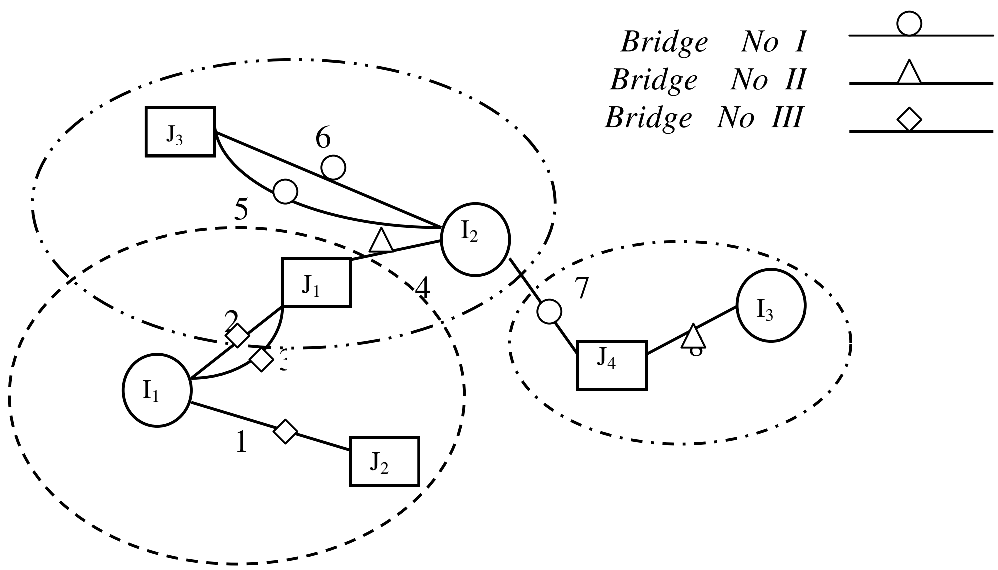

Figure 1- The sample network for numerical example

It is seen that 8 paths in total have been considered which connect the population centers to hospitals. It has been also assumed that there are three types of bridges in the network. The assumed service areas for the three population centers are shown in closed curves with dash line. The assumed numbers of injured people in the population centers are shown in Table 1, and the assumed capacities of hospitals are shown in Table 2.

Table 1- The assumed numbers of casualties in three vulnerable population centers

Population Center (*i*)	**1**	**2**	**3**
Number of casualties (I_i)	200	100	70

Table 2- Hospitals and their assumed capacities

Relief Center (*j*)	**1**	**2**	**3**	**4**
Capacity (C_i)	50	30	40	20

The considered bridges have been assumed to be in three different categories based on Hazus-97 classification [10]. Bridge *I* have been assumed to be highly vulnerable, bridge *II* to be moderately vulnerable, and bridge *III* to be seismically resistant. On this basis every bridge can have various damage probabilities depending on the PGA value in its site. For example Figure 2 shows the damage probability of bridge *I* for a PGA value of 0.6g.

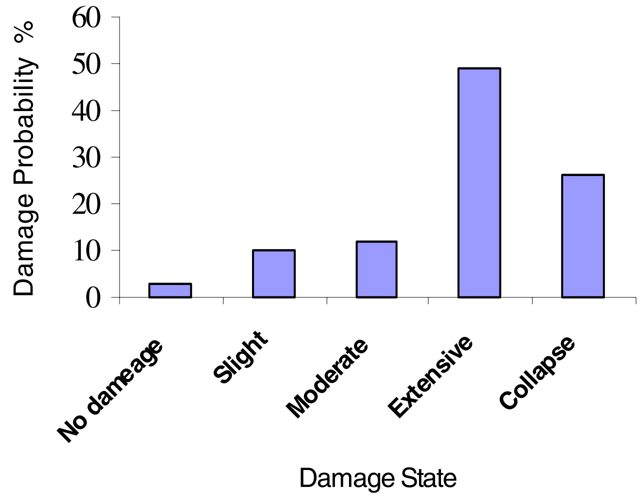

Figure 2- Damage probabilities vs damage states for bridge category *I*, assuming a PGA value of 0.6g at bridge site (based on Hazus-97 [10])

Table 3 shows the damage probability levels for the considered bridges for various values of PGA based on Hazus-97 for three assumed scenarios with 0.2g, 0.4g, and 0.6g values of PGA respectively.

Table 3- Damage probability levels for the considered bridges

Damage State		***Bridge No***	***Earthquake Acceleration***
Extensive Damage , Collapse	*No, Minor, or Moderate Damage*		
95	*5*	*No. 1*	***PGA = 0.6g***
65	*35*	*No. 2*	
48	*52*	*No. 3*	
80	*20*	*No. 1*	***PGA = 0.4g***
37	*63*	*No. 2*	
22	*78*	*No. 3*	
62	*38*	*No. 1*	***PGA = 0.2g***
20	*80*	*No. 2*	
2	*98*	*No. 3*	

The network sensitivity analyses have been performed in @Risk environment [11], and as a sample of final results the Tornado Graph obtained for the second scenario (PGA = 0.4g) is shown in Figure 3.

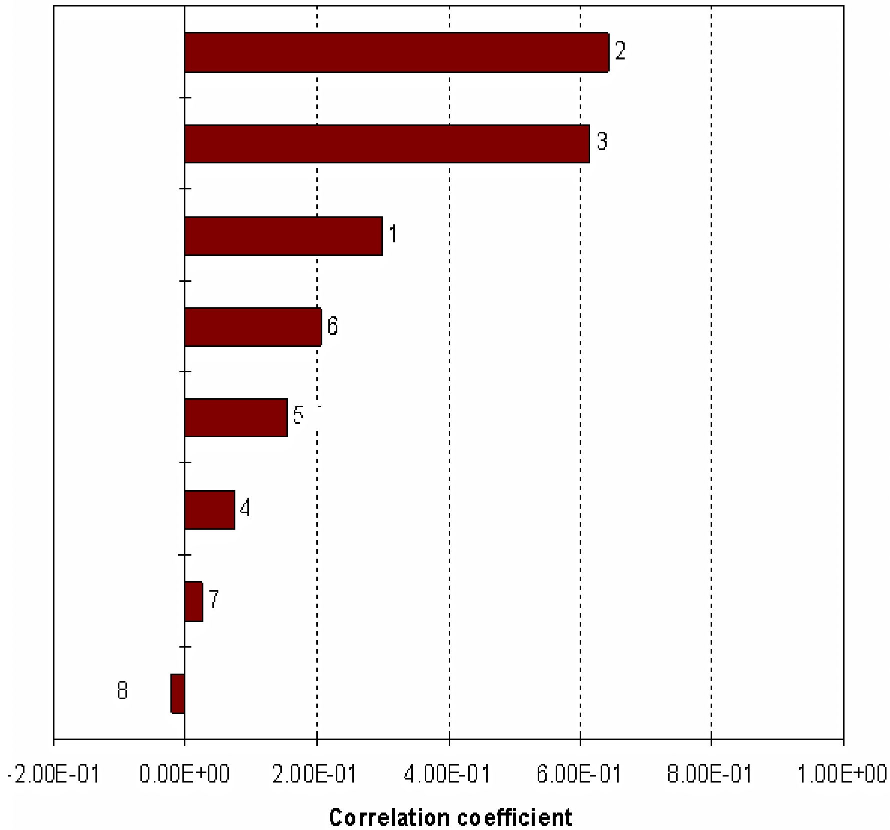

Figure 3- The Tornado Graph of the assumed network sensitivity analyses for second scenario

It is seen that the path number 2 has been the most effective path in the assumed network. This means that the components of this path have the highest priority for seismic retrofitting. The hierarchy of prioritization for other paths can be seen in the figure as well. Finally Table 4 shows the most significant paths based on the calculated *TAI* values for three assumed scenarios.

Table 4- The most significant paths based on the calculated *TAI* values in the considered network for three assumed scenarios

Scenario No.	PGA	Most Significant Path
1	0.2	4
2	0.4	2
3	0.6	3

It is seen in Table 4 that for different scenarios different path can be the most significant one. Therefore, the final decision on the prioritization is also dependent on the most probable scenario in the city.

CONCLUSION

Based on the presented numerical example it can be concluded that the propose formulation and procedure are suitable tools for prioritization of seismic retrofit of various components in a transportation system in large cities. It should be pointed out, however, that the fragility curves used for the vulnerable components has significant effect on the final result. The dependency of the final prioritization pattern on the assumed earthquake scenario is also an important point which should be taken into consideration in actual cases, in which various earthquake scenarios are possible.

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