Estimation of Reconstruction Cost and Traffic Functionality Relating to Roadway Transportation Lifelines after Natural Disasters

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Abstract

Earthquakes are among those natural hazards which may lead to disruption in the function of arterial traffic routes. Road networks are particularly vulnerable, due to their geographical dispersion, extensive functions and structural reliance on favourable geophysical conditions. Traffic functionality after a natural disaster and the repair/rehabilitation cost of roads are crucial considerations in planning the best priority recovery scenario. In the current paper, the primary focus is placed on the method for evaluating the costs of damage to the roadway network following an earthquake. Bridges, pavements, tunnels and base layers are assumed to be the main elements of a roadway structure. Through this approach, the level of damage can be specified for each component of the roadway. The repair/rehabilitation cost pattern can then be generated according to the level of damage, and the entire reconstruction costs can be calculated according to the total damaged surface area of each route. Finally, the total damage cost of roadways can be provided by considering the likely duration of the rehabilitation period, and determining the performance reduction in traffic flow caused by the damaged components. Secondly this paper demonstrates a method of measuring roadways' functional performance. This method, based on path dividing and consideration of the attachment of sections leads to more precise feedback on roadways' functionality. This is calculated by computing the width of sections in a route that remain undamaged and which retain the ability to sustain traffic flow. In this way, traffic flow and the linkage of sections can be determined as functions of road capacity.

Keywords: Natural disasters, reconstruction cost, Traffic functionality

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1. Introduction

Transportation networks constitute one class of major civil infrastructure system that is a critical backbone of modern societies. To date, the true prevention of a natural disaster has only rarely been achieved; such events continue to pose a threat to life and property. Especially following earthquakes - events typically unheralded and associated with widespread destruction and high mortality - there is a need for rapid, accurate and reliable damage information to guide response activities during the critical first few hours. Transportation and utility networks (e.g., water delivery, power, and oil systems) are essential in the support of all economic and social activities in an industrialized region. The functional loss of this urban infrastructure component - due to internal or external perturbations, such as earthquakes - can severely impact commercial and industrial activities on regional, national, and international scales. It is crucial that authorities meet such disasters with rapid, effective emergency responses and with appropriate repair operations following the event. Therefore, an understanding of the influence of hazards to these infrastructure systems and a careful allocation of limited resources for the seismic retrofitting of infrastructure systems components are critical to mitigating damage and to effective response and recovery efforts.

On one hand, estimating the likely cost of damage to a transportation network after a disaster is an important process in enhancing the effectiveness of decision making. Naturally, greater knowledge surrounding the repair/rehabilitation of transportation components helps transportation agencies and planners assign budgets and resources optimally. Accurate cost estimates for reconstruction depend on damage state evaluation procedures, which may be assess in the pre-planning stage, or survey phase after the event. A reliable method is required to survey damaged components after a disaster.

On the other hand, physical damage and functional loss to transportation infrastructure systems not only hinder everyday societal and commercial activities; they also impair post disaster responses and recovery procedures, leading to substantial socio-economic consequences. Therefore, it is vital that emergency managers and government agencies understand and model the possible impact of a disaster on the various components of the transportation infrastructure. These agencies should implement changes to travel patterns under extreme events, so as to mitigate, prepare for, respond to, and recover from the potential impacts [Chang et al. 2010].This paper therefore sets out not only to present a cost pattern for repair to road components, but also to present an accurate model for formulating the effect on traffic of the total demolition of a road in the ‘post-disaster’ phase.

2. Literature Review

An experts’-opinion-based approach has been employed throughout this research because it is easy to implement and captures the necessarily subjective nature of bridge functionality as assessed in closure and repair decisions. This approach was used in the ATC-13 [ATC-13, 1985] to evaluate the loss of functionality and to estimate the restoration time for lifeline facilities including the transportation infrastructure [Hwang et al. 2000]. Conducted a survey to collect expert opinions on stepwise restoration curves, in which only nine responses were recorded. More recently, Padgett [Padgett and DesRoches 2007] performed a web-based survey to collect expert opinions from experienced staff members in the departments of the Central and South eastern United States relating to bridge engineering maintenance and operations (CSUS) [Chang et al. 2010]. The findings from the experience of Loma Prieta, Northridge, Hyogoken-Nabnbu and the Chi-Chi earthquakes show that the seismic damage to highway systems caused heavy damage to transportation networks including highways and bridges [Feng and Wang, 2009]. Despite exist of many studies into road damage resulting from seismic activity, limited research measures the conditions and performance of roads in a post-earthquake scenario. Furthermore, the existing research fails to present an exact method for collecting data and analyzing the real situation of roads. By contrast, the rail system and bridges are the elements receiving researchers' greatest focus, resulting in the neglect of the road system and pavements. The research of Chang and Nojima should not be overlooked; as part of their methodological approach, they suggest several measures to evaluate system deterioration and performance restoration in the immediate aftermath of an earthquake and over the course of the reconstruction period [Chang and Nojima, 2000]. It should be noted that Nojima also proposed road traffic capacity as a basic post-earthquake performance measure for highway systems, where 'capacity' consists of the aggregate flow capacity of links connecting a specific 'origin-destination' pair of nodes [Nojima, 1998].

3. Cost Estimation

3.1 Definition of Patterns and Related Parameters

The patterns introduced in this research are based on characteristics of contractor systems and their usual expenses in the areas under study. It is therefore necessary to develop expense-reconstruction procedures for each country, based on the repair and maintenance systems of that area.

This paper presents a model for the estimation of cost pertaining to post-disaster reconstruction, building upon modifications to the methods employed in the previously mentioned studies. In this way, reconstruction periods are defined, along with the repair costs relevant to each traffic structure, together with the construction period - estimated according to interviews with executives, taking into consideration the criticality of the conditions for reconstruction and the availability of repair machinery and equipment.

It should be acknowledged that the time periods mentioned here have been estimated by neglecting the time required for cleansing debris from the roads. In other words, the reconstruction phase is considered to begin just after the initiation of emergency relief and road cleaning. The percentile of disturbance has been estimated based on the area of destruction and on surveys from experts in transportation crisis management. 94 percent of the questionnaires were returned. It should be noted that the experts had already been familiarized with elements and the aims of the questionnaires before filling them.

In order to record the impact of destruction on traffic structures most accurately, this research presents three factors, pertaining to: the reconstruction duration; the costs of the reconstruction of each road element and, finally; the rate of disturbance to traffic function in the destruction areas. Each of these factors is addressed in the following tables.

3.2 Pattern Generation

Since the complete reconstruction of any system is considered as a costly and rarely a justifiable option, arrangements should be made to fully exploit the remaining elements. That is to say, the reconstruction of the network - even in the event of mass destruction - is not a reasonable aspiration. It is provided that, only in case of the full failure of the structure should renewal of the structure being conducted. In other cases, repair / reconstruction is the favored option. Accordingly, reconstruction costs are estimated individually for each road element. This method is also applied to the degree of deterioration for each element; the final cost will be estimated according to the degree of deterioration and the vulnerability levels expressed across a range of 5 integers, according to the HAZUS scale [Hazus, 2011]. The range is expressed by scores of 1 to 5 in proportion with the extent of the damage. The integers are defined thus: PGD DS =1: not considerable; PGD DS = 2: medium; PGD DS = 3: High; PGD DS = 4; PGD DS = 5: fully destroyed.

Although the classification system used here has been presented for discussion of traffic bridges, the intervals between deterioration levels are considered as consistent qualitative measures for estimating the extent of vulnerability.

In order to make precise qualitative values, it is necessary to define individually the types of damage affecting the traffic structures. In this way, the damage survey team can easily define the vulnerability level of traffic coordinates based on the observations made. Table 2, based on 4 levels of damage classification, shows the damage to urban tunnels. The reconstruction cost is represented by values per meter and per lane of road. Table 3 shows the

Table 1. Quantitative and qualitative classification of bridge damage classification

Damage type	Damage level	Damage Classification
Not considerable	1	Not considerable
Limited cracks	2	Negligible
Cracks, spall, roller bearing fault, joint damage	3	Moderate
Damage to structural pillars without collapse	4	High
Bridge deck settlement, Collapse of structural pillars	5	Complete

Table 2. Tunnel damage classification, as defined by cost, reconstruction duration and disturbance percentile

Damage Classification	Missed Days	Disturbance Percent	Cost($)/ln/m
Negligible	25	25	50
Moderate	90	50	110
High	210	90	260
Complete	360	100	380

data for urban bridges. For the bridge, the reconstruction cost is represented by values per meter and per lane of road. Table 4 also includes data for the base and the sub-base. Reconstruction costs have been estimated for a unit area with a thickness of 1 meter.

Furthermore, the duration of the reconstruction of road sub layers has been estimated regardless of the time required for pavement construction. Hence, the final duration used for the whole track is equal to the time required for the construction of the sub-layers plus that of the superior layer .Table 5 shows the reconstruction cost per square meter of asphalt pavement layers.

Retrofitting the existing bridges of the transportation infrastructure systems has proven a very effective and relatively economical way to enhance the performance of transportation systems and to mitigate potentially catastrophic losses [Chang et al. 2000; Shinozuka et al. 2003; Zhou et al. 2004; Kim et al. 2008]. However, it is neither practical nor economical to invest very substantial resources into retrofitting all existing bridges. Hence, it is vital to make priorities among candidate bridges for seismic retrofitting, with a strategy that is mindful of funding and aging challenges [ASCE, 2009; Basőz and Kiremidjian, 1996].

Table 3. Bridge damage classification, as defined by cost, reconstruction duration, and disturbance percentile

Damage Classification	Missed Days	Disturbance Percent	Cost($)/ln/m
Negligible	35	25	55
Moderate	70	60	125
High	180	90	300
Complete	450	100	450

Table 4. Base Layer damage classification, as defined by cost, reconstruction duration, and disturbance percentile

Damage Classification	Missed Days	Disturbance Percent	Cost($)/m^2
Negligible	12	30	50
Moderate	21	60	85
High	35	85	150
Complete	45	100	175

Table 5. Pavement damage classification, as defined by cost, reconstruction duration, and disturbance percentile

Damage Classification	Missed Days	Disturbance Percent	Cost($)//m^2
Negligible	4	20	10
Moderate	11	50	50
High	14	70	85
Complete	21	100	120

4. Traffic Functionality

4.1 Overview

Based on the limited existing studies made into the subject of road functionality after a natural disaster like earthquake, several uncertain correlations have been identified. These studies are usually founded on the physical deterioration of a road, following the assumption of an indirect relationship between the extent of deterioration and traffic functionality. But, experience shows that, under real conditions, this presumption is incorrect; serviceability and full disruption of traffic flow depends on the shape of the road in the region of destruction. For example, even in the case of medium-scale physical deterioration, provided that the deterioration of transversal road elements has occurred, it can be assumed that path will become fully blocked. Therefore, consideration of the mere deterioration of an area results in a false interpretation of the functional performance of the area's roads. The current approach - as well as defining the connectivity conditions for each section - involves calculating the width of those sections of the route that remain undamaged and which are still able to sustain traffic flow.

4.2 Concept

Several approaches have been developed to examine the reliability and serviceability of systems subjected to an earthquake, but most of them deals only with the probability of physical or functional failure, and do not provide any information on the post-disaster role of each structure to the system as a whole. This kind of information is important in determining not only the seismic design of each structure in the system but also the most appropriate network configuration [Kawakami, 2000].

The method described is to be implemented at the 'post-disaster' phase -when information concerning the type and extent of damage to roads is gathered for the consultation of decision makers. It is assumed that evacuation, debris removal/clean-up has already been accomplished- as part of the 'response phase'. Figure 1 is a flowchart describing the methodology for calculating the traffic functionality of roads after an earthquake:

4.2.1 Segment and Net width

The method commences with dividing the road into segments of between 50 and 200 meters. The undamaged width of any segments that still capable of sustaining traffic flow is then measured. This width is called the 'net width'. The net width should not be less than 2.2 meters in order to have passing ability of at least one vehicle at a time through the segment. However, in ideal situations, the net width will be equal to standard road lane width [Zamanifar, 2012].

4.2.2 Connectivity of Segments

As part of efforts to ensure continuous traffic flow through a route in a road system, con-

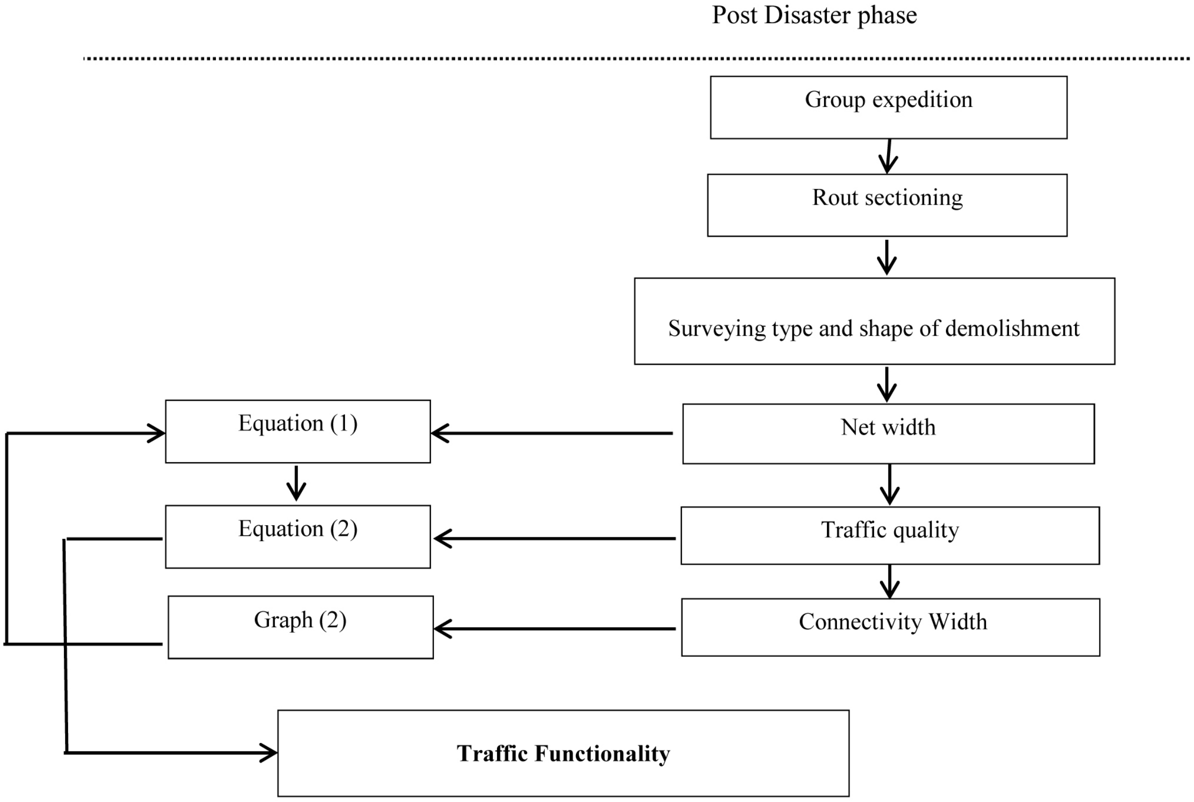

Figure 1. Flowchart of the methodology for computing traffic functionality

nectivity is one of the most frequently used measures. Connectivity between segments makes the passage 'stable'. The transmission ability of roads depends on the existence of proper connections between any given segment and those segments which come before and after it. The next section of this research is therefore concerned with the 'continuity' of sections - an indicator of the ability of traffic to travel by road between two sections. This parameter is indicated by the term Wji, and calculated by Eq. 2.

4.2.3 Quality of Traffic Flow

The functional performance of a road after damage caused by natural disasters can actually be considered as the capacity of that road in a 'critical condition'. So, in order to evaluate the performance of any such road, it is necessary to consider the pattern of traffic flow after an earthquake. While there are no generally accepted measures of turbulence in the traffic stream, the basic distinguishing characteristic of weaving, merging and diverging segments is the additional lane–changing these manoeuvres cause [McShane and Roger, 1990]. Road demolition is another aspect of this disruption – one which calls for greater vigilance on the part of drivers and which poses an on-going risk as part of the generally-uncertain post-earthquake conditions. It is clear that the lane-changing necessitated by the destruction of part of a road may lead to considerable frequent changes in speed, rendering the average speed of vehicles somewhat lower than in pre earthquake conditions. Consequently, it is necessary for those assessing the performance of the road network to record the number of lane changes required of a driver as a result of the physical destruction of the road. Therefore, in the calculation of a traffic closure equation, this parameter has been emphasized by number of damaged locations in the section of the road causing deviation from the straight line – all of which is cumulatively considered. Although, ideally, the precise assessment of weaving required by traffic should take into account the length of the weaving area, as well as its width, owing to the urgent requirements of such analysis, a width-based approach – such as is provided in this article - is fast and easy to calculate. The amount of this reduction can be found according graph 1. This amount varies from 2 - for the segment with the minimal lane-changing area to 5 - for the segment with the maximum compulsory deviation for drivers (regarding the length of each segment). The maximum acceptable deviation in each segment is equal to 1 compulsory lane-change in every 50 meters of road. This amount reduces the capacity of a road to its lower value. For instance, not more than 4 dictated deviations are acceptable for a segment of road 200 meters in length.

The following equations are used to evaluate the percentage of roads closure:

$$\mathrm{TDi} = \left(\left(1 - \frac{(\sum_{i=1}^{n} \frac{w_{efi}}{w_{Total}})}{N}\right)^{\log(7-nx)}\right)^{\log(7-nx)}$$

Eq.1.

*(0) if a bridg collaps and blocked the route)

F(log(7-nx))=(1) If there is no deviation or less than 2

$$TD_T = \sum_{i=1}^{n}\left(TD_i * \frac{\min(wj_{i+1}, wj_{i-1})}{w_{total}}\right) \quad (1)$$

(2)

Where:

TD_i: the percentage of segments closed to traffic

W_{efi}: the measured net width of each segment in the road

WTotal : the total width of the road section

N: the number of segments

N_x: The number of lane changes made by a driver as a result of damage to parts of the road

TD_T: the total percentage of roads closed to traffic

W_{ji} : the width of the connection to the previous and next segments

By this equation, both the closure of, and the connectivity between, segments are evaluated. Figure 2 shows the amount for various nx values from 2 to 5.

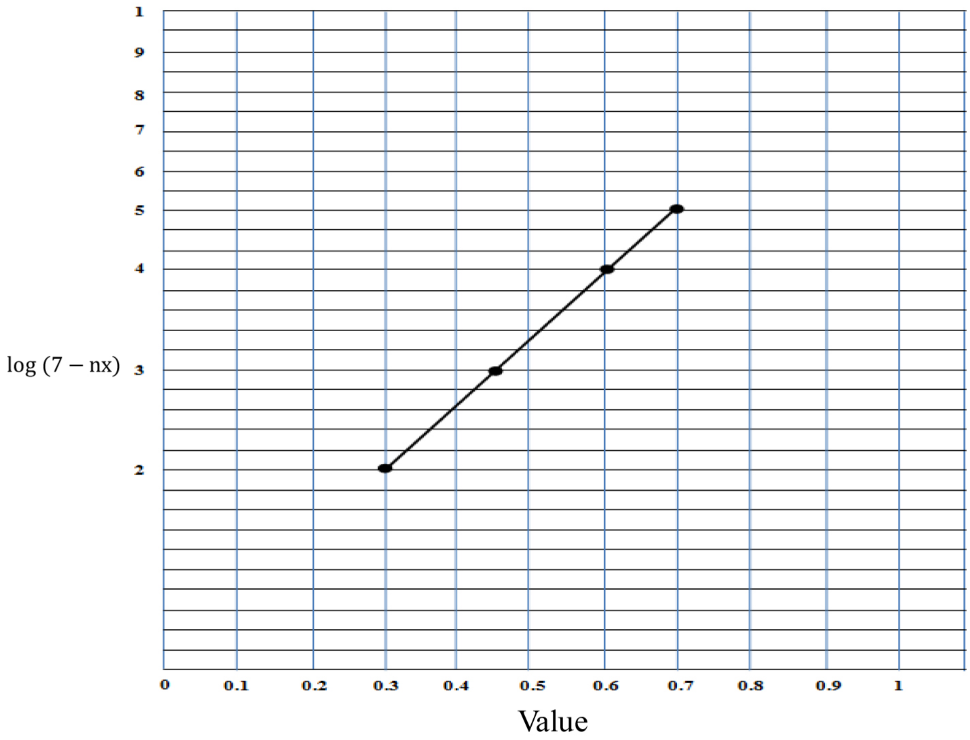

Figure 2. Computation of log(7-nx) for various values of nx [Zamanifar,2012]

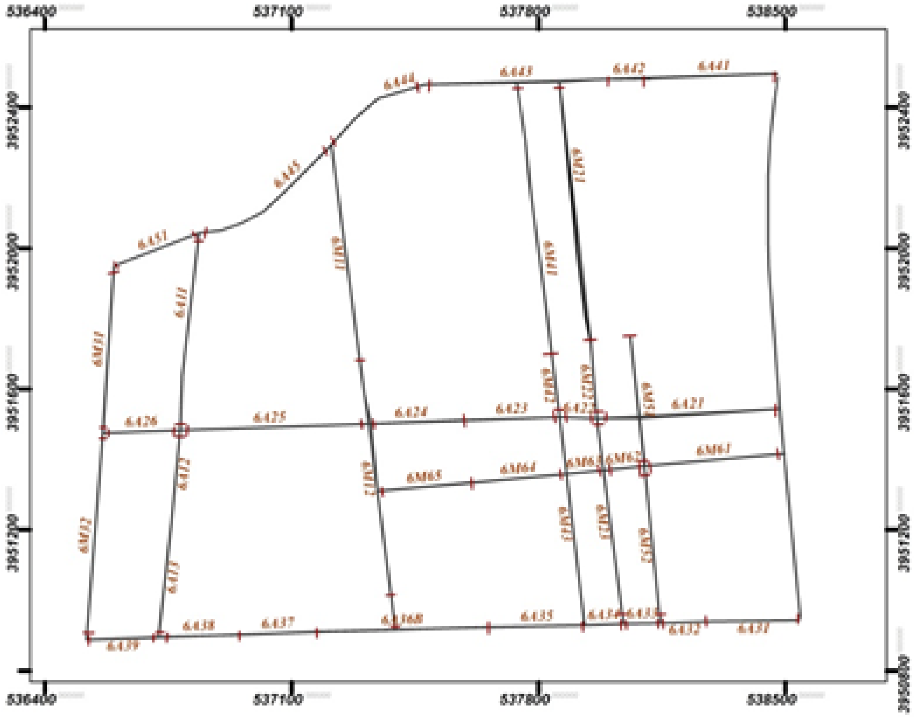

Figure 3: Map of coded paths in studied zone

To demonstrate the use of the model it was applied to a roadway as an example, which paths shown by codes. The suffix letter B indicates bridge in the path. Figure 2 represents the map shows coded paths of studied zone.

The demonstration follows the planning phase illustrated in Figure 1 along with hypothetical damage accrued by earthquake. A summary of the data used and results are given in the table 6

5. Conclusion

Presented methods are of remarkable benefit to authorities and decision makers; it represents a quantitative approach for estimating the direct cost of repairs to road elements.The estimated reconstruction cost of any route after an earthquake is considered one of the key decision making criteria. It is used for prioritizing all activities pertaining to road reconstruction. Although estimates of cost are important for rapid analysis in post-disaster situations, should not leave behind the fact that accuracy and efficaciousness are two vital parameters when considering the quality of road performance evaluation. Accuracy in estimations is strongly associated with effective reconstruction planning .Surveying the post-earthquake function of road network is a recommended approach for quick and efficient reactions. Therefore rapid recovering of the systems such that they can provide services with acceptable safety through optimal resource allocation needs appropriate planning

Taking into consideration the impact of an earthquake on the transportation network, to-

Table 6. Computed data and result regard to traffic functionality of paths

Path code	**Length**	**Width (W_{total})**	**No. Segment**	**No. Dictated Deviation (NX)**	**Mid net width (W_{efi})**	**Connectivity width (Wj_i)**	**Traffic Functionality (TD_i)**
6M11	0. 6km	12. 9	3	2+2	6.4	10	76%
6M12B	0. 55km		3	Collapse	-	0	0%
6M13	0. 16km	15. 9	1	0	12	15.9	75%
6A21	0. 53km	6. 6	3	0	3.4	3.4	49%
6A22	0. 24km	6. 6	1	4	2.7	3	86%
6A23	0. 32km	10. 4	2	closed	-	0	0%
6A31	0. 53km	12. 9	3	3+2	9	7.5	23%
6A32	0. 11km	13	1	0	13	13	100%
6A33	27km .	13	2	0	13	13	100%
6A34	0. 29km	13	2	5	6.2	5	88%
6A35	0. 35m	13. 3	2	2+3	3.2	6	11%
6A36	0. 2km	17. 1	2	0	16	17	94%

gether with prioritization models for decision making, three factors emerge: the direct cost of reconstruction, the duration of repairs and finally the percentage of disruption to such elements' function. Each of these factors can be considered crucial components in assessing the condition of each traffic structure at times of vulnerability. Moreover, studying the method that combines these 3 factors will require a methodology that encompasses specific decision making models and the subjective nature of decision making which is encouraged to be studied in future research. Finally, It should also be stated that the data in the tables provided here have been estimated according to surveys made by experts that have focused on the local characteristics of repair and maintenance systems, which is related to existed experience of crisis situation and costs in Iran.

6. References

- Applied Technology Council (ATC) (1985) "Earthquake damage evaluation data for California (ATC-13)", ATC, Redwood City, CA. pp 85-86, 235-245

- American Society of Civil Engineers (2009) "Report card for America's infrastructure", <http://www.infrastructurereportcard.org/fact-sheet/bridges> (June 5, 2009).

- Basőz, N. and Kiremidjian, A. S. (1996) "Risk assessment for highway systems", Report No. 118, John A. Blume Earthquake Engineering Center, Department of Civil Engineering, Stanford University, CA.

- Chang, Stephanie. E; Nojima, Nobouto; (2000) "Measuring post-disaster transportation system performance":The 1995 Kobe Earthquake in Comparative Perspective, Transportation Research Part A 35: pp. 475-494.

- Feng, Cheng-Min and Wang, Tsai-Chu (2009) "Highway emergency rehabilitation scheduling in post-earthquake 72 hours", Journal of the Eastern Asia Society for Transportation Studies, Vol.5, No 3281, pp. 20-28.

- Hazus®–MH MR5, (2011) "Technical manual, Department of Homeland Security", Federal Emergency Management Agency Mitigation Division, Washington, D. C.

- Ui, Hideji (2000) "Earthquake performance of highways in Tokyo", Proceedings of the 12th World Conference on Earthquake Engineering, New Zealand Earthquake Commission, New Zealand, pp. 8-26

- Kim, Y., Spencer, B. F., and Elnashai, A. S. (2008) "Seismic loss assessment and mitigation for critical urban infrastructure systems". Report No. NSEL-007, Newmark Structural Engineering Laboratory, Department of Civil and Environmental Engineering, University of Illinois, Urbana, IL.

- Liang Chang Amr, S., Elnashai, Billie F. Spencer, Jun, Ho, Song and Yanfeng, Ouyang (2010) Ttransportations Systems Modeling and Applications, In Earthquake Engineering", Report No. 10-03, Mid-America earthquake center

-McShane, William R; Roess Roger P; (2004) "Traffic engineering,. Chapter 13th, Prentice-Hall, Inc. Englewood Cliff, New Jersey. pp. 485-486

-Nojima, Nobouto (1998) "Prioritization in upgrading seismic performance of road network based on system reliability analysis", The 3rd China-Japan-US Trilateral Symposium on Lifeline Earthquake Engineering, Kunming, China.

-Padgett, J. E. and DesRoches, R. (2007) "Retrofitted bridge fragility analysis for typical classes of multi-span bridges." Earthquake Spectra, 23 (1), pp.115-130.

-Shinozuka, M., Murachi, Y., Dong, X., Zhou, Y. and Orlikowski, M. J. (2003) "Effect of seismic retrofit of bridges on transportation networks." Research Progress and Accomplishments (2001-2003), Report No. MCEER-03-SP-01, Multidisciplinary Center for Earthquake Engineering Research (MCEER), University of Buffalo, Buffalo, NY

- Wakabayashi, Hiroshi and Kameda, Hiroyuk (1992) "Network performance of highway systems under earthquake effects: A case study of the 1989 Loma Prieta earthquake". The 5th US-Japan Workshop in Earthquake Disaster Prevention for Lifeline Systems, Tsukuba Science City, Japan, 12.

-Werner, S. D., Lavoie, J. P., Eitzel, C., Cho, S., Huyck, C., Ghosh, S., Eguchi, R.T., Taylor, C.E. and Moore, J (2004) "New development in seismic risk analysis of highway systems, 13th World Conference on Earthquake Engineering", B.C., Canada, Paper No. 2189 pp 96-104

-Zamanifar, Milad (2012)"prioritization plan of urban roadways for recovery after earthquake", Master Thesis in transportation planning, Islamic Azad University, South Tehran Branch, Tehran, Iran.

-Zhou Y., Murachi, Y., Kim, S., and Shinozuka, M. (2004) "Seismic risk assessment of retrofitted transportation systems", Proceedings of the 13th World Conference on Earthquake Engineering, Canadian Association for Earthquake Engineering, Ottawa, Canada, pp. 234-246