A Spatial Approach to Resource Allocation for Post-Earthquake Restoration of Urban Roadway Networks

Xingju Wang, Ph.D.¹
Associate Professor
Email: wangxingju@stdu.edu.cn

Yang Zhou, MS¹
Graduate Research Assistant
Email: zhouyang507@163.com

Zhe Han, MS²
Graduate Research Assistant
Email: hanzhe@utexas.edu

Zhanmin Zhang, Ph.D.²
Associate Professor and Fellow of the Clyde E. Lee Endowed Professorship in Transportation Engineering
Email: z.zhang@mail.utexas.edu

(1) Corresponding author: School of Traffic and Transportation, ShijiazhuangTiedao University, Shijiazhuang, Hebei, China, 50043

(2) Department of Civil, Architectural and Environmental Engineering, University of Texas at Austin, Austin, TX 78712.

Abstract = 216 words

Word Count: 7438

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Text</td>
<td>4188</td>
</tr>
<tr>
<td>Figures</td>
<td>12</td>
</tr>
<tr>
<td>Tables</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>7393</td>
</tr>
</tbody>
</table>

Paper Submitted for Presentation at the Transportation Research Board 95th Annual Meeting
ABSTRACT

Multiple violent earthquakes have occurred in the past decade. The reliability of post-earthquake urban roadway networks has attracted the attention of engineers and researchers. Since a post-earthquake urban roadway network is a large-scale complex system, the reliability of the roadway network cannot be easily determined by a traditional serial or parallel system, or even a combination of the two. The primary challenge for solving this problem is determining how to integrate the relative importance or weight of each roadway section in the restoration of a post-earthquake urban roadway network. This paper proposes an Edge-Betweenness centrality based model to incorporate the relative importance of roadway sections into the prioritization of post-earthquake urban roadway networks for restoration. The weight model is used to support the resource allocation for restoring a post-earthquake urban roadway network. An assessment system of the post-earthquake urban roadway network based on geography information system (GIS) was developed to implement the proposed model. The roadway network in the city of Shijiazhuang, China, composed of 699 valid sections and 5,705 valid buildings, was employed to validate this model. The results show that the proposed model has the potential of not only obtaining the weight of each roadway section of a large-scale roadway network, but also of conducting the resource allocation for restoring the post-earthquake urban roadway network.

Keywords: reliability, disaster relief, Edge-Betweenness centrality, weight, GIS, post-earthquake urban roadway network.
INTRODUCTION

Multiple violent earthquakes have occurred in the past decade. The most recent earthquake of magnitude 9.0 or larger was a 9.0-magnitude earthquake which occurred in Japan in 2011, and was the largest earthquake on record in Japan. Due to the disastrous earthquake, it was estimated that at least 15,703 people were killed, 4,647 were missing, 5,314 were injured, and 130,927 were displaced. Also, at least 332,395 buildings, 2,126 roadways, 56 bridges, and 26 railways were destroyed or damaged by the earthquake and subsequent tsunami along the entire east coast of Honshu from Chiba to Aomori [1]. China is also a very active seismic country with strong earthquakes occurring throughout the vast region and destructive earthquakes taking place in 23 provinces. The massive Tangshan Earthquake in 1976, which killed at least 250,000 people and injured an additional 790,000, was regarded as the most deadly earthquake in the 20th century [2]. In May 2008, the Wenchuan earthquake, the most destructive seismic event in the last three decades, devastated Sichuan, China. Reports indicated that almost 70,000 people were killed, about 374,000 were injured, more than 18,400 were missing and presumed dead, and an estimated 5.3 million buildings collapsed [3]. The Lushan (or Ya'an) earthquake which occurred in April 2013 led to several townships suffering major damage: many old buildings in Lushan collapsed, and the electricity service was interrupted [4]. Confused traffic controls and managements were factors complicating the rescue efforts, as some expressways had to be reserved exclusively for rescue vehicles and were closed to other vehicles. However, erroneous and ineffective transportation controls and managements delayed the rescue effort and resulted in unnecessary injuries and loss of life, which was deemed as a secondary seismic disaster. In light of the additional losses due to secondary seismic disasters following the major disasters noted above, many engineers and researchers are now focusing on post-earthquake emergency transportation controls and managements.

The reliability of the post-earthquake urban roadway network plays a critical role in post-earthquake emergency transportation control and management. Since the post-earthquake urban roadway network is a large-scale complex system, the reliability of the roadway network cannot be easily determined by a traditional serial or parallel system, or even a combination of the two. The real root of the problem is how to present the relative importance or weight of each roadway section in a post-earthquake urban roadway network. In addition, what should be considered in defining the “relative importance” of a roadway section for repairing and restoration purpose after an earthquake? Also, the role of each section connectivity should be addressed. In other words, one must determine how to define and formulate the relative importance. The motivation of the proposed solution is to find a group of roadway sections that form a sub-network that could be used for the movement of goods and people to and from the sites of essential functions after an earthquake, and thus should be repaired or restored. The Edge-Betweenness centrality of a roadway network is an indicator of the relative importance of a roadway section. In this paper, the Edge-Betweenness centrality is utilized to present the relative importance or weight of each roadway section in the post-earthquake roadway network to ascertain a sub-network, to repaired or restored.
LITERATURE

Based on the findings from a comprehensive literature review, various models have been proposed to conduct research on lifeline networks including electric power networks, urban water networks, and transportation networks [5-13]. Hazard management models have been extended to assess transportation networks [14-18]. A recently published paper provides a comprehensive methodological approach to manage resources for post-disaster reconstruction [19]. Several information technology applications have been developed for resource allocation for disasters [20, 21]. Allocation issues, such as transportation network recovery, reconstruction financing for housing, cost-based resource policy, and optimal measurement for reduction of the seismic risk of highway networks [22-26]. However, most of current studies focus on scheduled resource allocation or bridge recovery for the post-earthquake infrastructure. The linked roadways make up a post-earthquake roadway network. Very few methodologies exist to conduct resource allocation for reconstructing roadway networks in terms of quantifying the importance of the linked roadways.

Betweenness centrality is a measure of a node's centrality in a network. It is equal to the number of the shortest paths from all vertices to all others that pass through that node [27]. Betweenness centrality network measure has been widely used in graph and complex network fields. Gago et al. used betweenness centrality to describe properties and constructions of graphs [28, 29]. Kourtellis et al. proposed an algorithm to compute the betweenness centrality in an evolving graph [30]. Chung et al. applied betweenness centrality to examine the efficacy of control strategies on the propagation of infectious diseases by removing the edges [31]. Buechel and Buskens reviewed betweenness and closeness measures to analyze their effectiveness [32]. Several researchers have applied betweenness centrality to transportation studies. Bankston presented a mechanism of roadway systems depending on a betweenness centrality [33]. Gao et al. explained the observed traffic-flow distribution based on a betweenness centrality of transportation networks [34]. Puzis et al. proposed a traffic assignment model on the basis of betweenness centrality measure [35]. The betweenness centrality is divided into Node-Betweenness and Edge-Betweenness. As stated above, the Edge-Betweenness is paid more concern in a transportation field.

METHODOLOGY

In post-earthquake emergency transportation managements, the primary attention is paid to the analysis of a roadway network that represents relationships among roadway sections. One such typical task is assessing the reliability of a post-earthquake roadway network. A post-earthquake urban roadway network is a large-scale complex system; the reliability of the roadway network cannot be easily determined by a traditional serial or parallel system, or even a combination of the two. The measure of the relative importance of each roadway section plays a key role in determining the reliability of such roadway networks. Edge-Betweenness centrality, borrowed from the domain of complex network analysis, is applied to address the measure of this relative importance in the reliability analysis of post-earthquake urban roadway networks.

Edge-Betweenness centrality is the relative score, which is a measure of an edge's centrality in a network. It is equal to the number of shortest paths from all vertices to all others that pass...
through that edge. Consider a roadway network $G$ which is composed of $m$ nodes and $n$ roadway sections with nodes $i, j \in N$ and section $e_{ij} \in E$, where $N$ is a set of nodes, and $E$ is a set of sections. Consequently, the Edge-Betweenness centrality $B(e_{ij})$ of section $e_{ij}$ between node $i$ and node $j$ is denoted by

$$B(e_{ij}) = \sum_{k,l,i,j} \left[ \frac{\sigma_{kl}(e_{ij})}{\sigma_{kl}} \right]$$

where

$$\sigma_{kl}(e_{ij}) = \text{the total number of shortest paths between node } k \text{ and node } l \text{ that pass through section } e_{ij}; \text{ and } \sigma_{kl} = \text{the total number of shortest paths between node } k \text{ and node } l.$$

Edge-Betweenness centrality is a global exogenous variable which is addressed by a shortest path between two nodes. In order to obtain a shortest path, the weight $W(e_{ij})$ of section $e_{ij}$ is defined by

$$W(e_{ij}) = \frac{1}{F(e_{ij})}$$

where

$$F(e_{ij}) = \text{a traditional comprehensive importance index surrounding section } e_{ij}.$$

Since Edge-Betweenness relies on shortest path approach, an inverse function $\frac{1}{F(e_{ij})}$ is treated as the weight of sections instead of $F(e_{ij})$. $F(e_{ij})$ is denoted by

$$F(e_{ij}) = \sum_{p \in Z, q \in Q_p} \alpha_p x_{pq}^{e_{ij}}$$

where

$$\alpha_p = \text{the weight of building category } p \text{ in building category set } Z, \text{ where } \sum_{p \in Z} \alpha_p = 1;$$

$$x_{pq}^{e_{ij}} = \text{a standardized importance score of building } q \text{ of category } p \text{ surrounding section } e_{ij} ;$$

and

$$Q_p^{e_{ij}} = \text{the set of all } q \text{ in category } p \text{ surrounding section } e_{ij}.$$

Furthermore, $x_{pq}^{e_{ij}}$ is computed by a standardized equation:
where

\[ x_{pq}^{e_i} = \frac{\sum_{p \in Z, q \in Q_p} y_{pq}^{e_i}}{\sum_{p \in Z, q \in Q_p} y_{pq}} \]  \tag{4}

\[ y_{pq} = \text{an importance score of building } q \text{ in building category } p ; \]

\[ Q_p = \text{the set of building category } p ; \text{ and} \]

\[ y_{pq}^{e_i} = \text{an importance score of building } q \text{ in category } p \text{ surrounding section } e_i. \]

The quantifying importance model of links of the roadway network is proposed. The corresponding resource allocation diagram, as shown in Figure 1, is illustrated as following:

Step 1: Obtained GIS data of urban including roadway network and building surrounding roadway section.

Step 2: Categories and importance scores of each building. Moreover, standardize the importance scores of each building.

Step 3: The general weight of each roadway section in terms of standardized importance scores of corresponding surrounding buildings using spatial query. Furthermore, standardize general weight of each section.

Step 4: Edge-Betweeness of each roadway section in light of topological structure of roadway network and corresponding standardized general weight.

Step 5: Standardize the Edge-Betweeness of each section. In addition, the standardized Edge-Betweeness of each section is considered as the relative importance of each section.

Step 6: Conduct resource allocation based on relative importance of each roadway section.
Urban GIS data

GIS data of roadway network

Building GIS data of surrounding roadway section

Categories and importance scores of each building

Standardize the importance scores of each building

Spatial query

The general weight of each roadway section

Standardize general weight of each section

Edge-betweenness of each roadway section

Address relative importance of each section by standardize the Edge-betweenness

Conduct resource allocation based on relative importance of each roadway section

FIGURE 1. Diagram of resource allocation
CASE STUDY

Psurn-GIS

As shown in Figure 2, an assessment geography information system of the post-earthquake urban roadway network (PSURN-GIS) was developed based on geography information system (GIS). PSURN-GIS can conduct spatial query, deal data fusion and data integration, compute Edge-Betweenness of sections, save computing processes, and represent GIS data. SQL Server was used to manage GIS data; computing processes were conducted by Python where networkx, matplotlib, numpy and pyodbc packages were applied to cover Edge-Betweenness of sections, save results, and output figures. SQL store processes were coded to deploy data fusion and data integration. PSURN-GIS was developed by C# and SuperMap Objects (COM). SuperMap Objects, based on Microsoft’s COM technology, is a full-component platform for developing professional GIS.

FIGURE 2. An assessment geography information system of the post-earthquake urban roadway network

GIS Data Collection and Description

For demonstration purposes, GIS data (699 valid sections and 5,705 valid buildings) was
Wang, Zhou, Han and Zhang

preparing information on the city of Shijiazhuang in China. The roadway network in Shijiazhuang is illustrated in Figure 3. Building importance scores, indicating the relative importance of building categories surrounding roadway sections, were assigned according to Table 1. Importance scores of buildings were 1 (unimportant), 3 (fair), or 5 (important), representing the relative importance of building categories. The general weight of each roadway section is given depending on the buildings surrounding the corresponding roadway section. A generally-weighted roadway network is able to be constructed by this way. On the top of that weighted roadway network, an Edge-Betweenness of each roadway section is computed based on its definition. A detailed computed process is presented in Figure 4. A range of section influence was set to conduct a spatial query to obtain the affected buildings as shown in Figure 4. Moreover, the relative importance score of a section was obtained by standardizing its importance score. Figure 4 describes the data fusion process to achieve the relative importance score of a section based on relative scores of the buildings surrounding that section. There were 28 buildings, composed of 8 restaurants, 4 shopping centers, 3 stores, 2 schools, 4 hospitals, 1 government building, and 6 hotels, in a certain range of that section. Relative scores of each category were calculated, respectively. According to Equations (2) and (3), the weight of that section was addressed in terms of that section’s relative score (0.11228208). In addition, an SQL store process was coded to perform data integration. Finally, a Python program was applied to obtain the Edge-Betweenness of sections, and the results were saved into a section table of the roadway network in Shijiazhuang.

FIGURE 3. Illustration of GIS data for roads and buildings in Shijiazhuang
**Table 1. Importance scores of building categories**

<table>
<thead>
<tr>
<th>Name of building category</th>
<th>Level</th>
<th>Importance score</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Restaurant</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fast food or casual</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Casual dining restaurant</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Fine restaurant</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td><strong>Shopping center</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Community Center</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Regional Mall</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Super-Regional Mall</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td><strong>Police</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>District Level</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>City Level</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Provincial Level</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td><strong>Store</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grocery store</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Supermarket</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Hypermarket</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td><strong>School</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary School</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Middle School</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>University</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td><strong>Hospital</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>District Level</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>City Level</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Provincial Level</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td><strong>Government</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>District Level</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>City Level</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Provincial Level</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td><strong>Hotel</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Economy hotel</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Mid-Range hotel</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>World class hotel</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

**FIGURE 4. Data fusion processes**
Results and Discussion

In this case study, the relative importance (or weight) of roadway sections was defined by five categories: “Very Important,” “Important,” “Fair,” “Unimportant,” and “Very Unimportant.” Two approaches were used to represent the results. One was the equal difference method, which divided sections into 5 categories by equal difference of data value. By employing this method, weight distribution of the sections could be clearly found out. The other approach was equivalent quantity method, which classified the roadway sections by equal quantity of data. With this method, different weight indexes were utilized to present the comparison results of the 5 categories.

Edge-Betweenness, which describes the relationships among sections in the road network, was applied to present the importance of the sections graphically. Since sections were treated as independent units, a relative score was used to show the discrete importance of sections. Regarding the equal difference method, the results were as shown in Figure 5 and Figure 6. Figure 5 shows the importance categories using relative score by color coding, where red, pink, blue, green and black lines present “Very Important,” “Important,” “Fair,” “Unimportant,” and “Very Unimportant” category, respectively; the number of sections in each category is 2, 4, 5, 31, and 657, respectively. There were only 0.86% of the sections in the “Important” category. For post-emergency transportation managements, only those 0.86% important sections were required to be focused on. On the other hand, there were about 98.42% in the “Unimportant” category. Figure 6 shows the importance categories using Edge-Betweenness. There were 12 sections in “Very Important” category, 8 sections in “Important” category, 25 sections in “Fair” category, 33 sections in “Unimportant” category, and 621 sections in the “Very Unimportant” category. Moreover, important sections were about 2.86%, and unimportant sections were around 93.56%. For post-emergency transportation managements, only those 2.86% important sections were required to be focused on.

FIGURE 5. View of importance categories using relative score based on the equal
FIGURE 6. View of importance categories using Edge-Betweenness based on the equal difference method

Figure 7 presents the distribution of category change using relative score and Edge-Betweenness-based categories, and the vertical axis is relative-score-based categories. Light gray squares represent the sections with no changes. Gray squares represent sections that change a little. Heavy gray squares indicate sections which change a lot. According to the Figure 7, 611 sections (87.41%) remained in the no-change state; 70 sections (10.01%) changed a little; and the other 18 sections (2.58%) changed a lot. Figure 8 describes the spatial information of sections that change greatly based on the equal difference method. Red and pink lines are “Very Important” and “Important” sections using Edge-Betweenness. Red-black, pink-black, and red-green lines represent sections changing from relative-score-based “Very Unimportant” or “Unimportant” sections to “Very Important” or “Important” sections using different indices. As seen in Figure 8, sections that change greatly were not only adjacent to “Very Important” sections, but also the optimal links connecting “Very Important” sections with other sections.
FIGURE 7. Category change distribution using relative score and Edge-Betweenness based on the equal difference method
FIGURE 8. Map of sections changed greatly based on the equal difference method

The results of the equivalent quantity method are presented in Figure 9 and Figure 10. The same numbers for each category were selected. 69 “Very Important” sections, 70 “Important” sections, 140 “Fair” sections, 140 “Unimportant” sections, and 280 “Very Unimportant” sections were assigned. Red, pink, blue, green, and black lines represent “Very Important,” “Important,” “Fair,” “Unimportant,” and “Very Unimportant” categories, respectively. Figure 9 shows a view of importance categories based on relative score. Figure 10 indicates a view of importance categories according to Edge-Betweenness. As can be seen from Figure 9, the importance distribution of the roadway network was discrete lines; while as shown in Figure 10, a sub-network was approximately connected.
FIGURE 9. View of importance categories using relative score based on the equivalent quantity method

FIGURE 10. View of importance categories using Edge-Betweenness based on the equivalent quantity method

Figure 11 presents the distribution of category change using relative score and
Edge-Betweenness based on the equivalent quantity method. The horizontal and vertical axes are categories obtained from Edge-Betweenness and relative score, respectively. According to Figure 11, 296 sections (42.35%) remained in no-change state; 369 sections (52.79%) changed a little; and 34 sections (4.86%) changed a lot. Figure 12 describes the growth trends of “Important” sections from top 10 to top 100. According to the relative score, the views from top 10 to top 100 described a haphazard discrete spatial distribution. The views from top 10 to top 100 based on Edge-Betweenness presented a trend that “Important” sections grow up from a root (original “Important” sections) to an approximately connected sub-network in terms of the optimal Edge-Betweenness. This approximately connected sub-network played a key role in seismic disaster relief: allowing agencies to re-open roadways, assign rescue resource efficiently, and create other policies in emergency transportation control and management field.

FIGURE 11. Category change distribution using relative score and Edge-Betweenness based on the equivalent quantity method
FIGURE 12. Growth trends of important sections based on the equivalent quantity method.
CONCLUSION

Strong earthquakes have occurred in both China and the rest of the world during recent decades. The reliability of the roadway network following a seismic event cannot be easily determined by a traditional serial or parallel system, or even a combination of the two. The weight of each roadway section plays a critical role in the post-earthquake restoration of urban roadway networks. This paper proposes a model to present the relative importance or weight of roadway sections in the post-earthquake restoration of urban roadway networks. The Edge-Betweenness is applied to obtain the relative importance of the roadway sections. The roadway network in Shijiazhuang is employed to validate the model. Results show that according to Edge-Betweenness, “Important” sections grow up from their original “root” to an approximately connected sub-network; while the results of the traditional method show a haphazard discrete spatial distribution. In this paper, one of the most important findings is to borrow Edge-Betweenness to define and model the relative importance or weight of a roadway section in support of the restoration of a post-earthquake roadway network. On the top of these models, we found out the approximately connected sub-network in terms of the Edge-Betweenness. This finding plays a key role in seismic disaster relief: allowing agencies to re-open roadways, assign rescue resource efficiently, and create other policies in emergency transportation control and management field.

ACKNOWLEDGMENTS

This research was funded by the National Natural Science Foundation of China (Grant No: 51008201), Natural Science Foundation of Hebei Province in China (Grant No: E2012210016 and E2014210152), Science Program of Hebei Province in China (Grant No: 13455408D and 13456236D), and the Scientific Research Foundation of Education Department of Hebei Province for Outstanding Young Teachers in University in China (Grant No. Y2012033 and ZD2014084). This research is further sponsored by the Outstanding Young Talent Foundation of Hebei Province in China, Talent Program of Hebei Province in China (Grant No. A201400212) and the Outstanding Young Talent Foundation of Shijiazhuang Tiedao University in China.

REFERENCES


