Study on Earthquake Loss of Transportation Networks

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ABSTRACT :

Earthquake disaster, which exists in many parts around the world, is one of the natural ones that cause tremendous loss to our society and the economy. With the rapid development of China's national economy, transportation network system, which has become a necessary component in people's daily life, is an important part of the lifeline systems. It also plays a crucial role in the post-earthquake search and rescue as well as in reconstruction efforts. Earthquake damage to a transportation system not only causes direct loss to the system, but also incurs serious indirect damage due to its networking property. Therefore, the analysis of the transportation network stability and economic loss under the earthquakes is very important and bears practical application potential.
Based on previous studies, this paper proposes a framework for analyzing economic loss for a typical transportation system. Structural vulnerability curves for the transportation system, which are suitable for the rapid assessment after an earthquake, are also proposed. Based on the characteristics of the earthquake damage in China and the method of traffic distribution, the paper evaluates the loss assessment method of the transportation network.

KEYWORDS: Transportation network, seismic vulnerability, traffic distribution, earthquake loss estimation

1. INTRODUCTION

Earthquake disaster, which exists in many parts around the world, is one of the natural ones that cause tremendous loss to our society and the economy. With the rapid development of China's national economy, transportation network system, which has become a necessary component in people's daily life, is an important part of the lifeline systems. Transport system is an important part in modern production because it is in the material production sector and it is also an extension of the production process in the material circulation. The highway, as a major component of the transportation network, is not only the key component of material transport channel, but also essential in the post-earthquake evacuation, sending rescue personnel and project teams and the delivery of earthquake relief supplies channel, and it is also a part of lifeline which is vital for earthquake relief. In addition to strong ground motion, there will be fault, liquefaction on the site near a strong earthquake; therefore the transport system is vulnerable to strong earthquakes, resulting in damage which will have a vital influence on earthquake relief in disaster area. For example, the great Wenchuan earthquake, with a magnitude 8.0 on the Richter scale and took place on May 12, 2008, caused landslides along the roads, damage to the bridges and tunnels, so the roads that provided access to all the affected villages and counties were disrupted, and external aid could not be delivered in time and relief supplies could not be rushed to the disaster areas. Some enterprises' raw material supplies were also affected because of transport disruption, which caused indirect economic losses to the enterprises. Therefore, the analysis of the transportation network stability and economic loss under the earthquakes is very important and bears practical application potential.

2. VULNERABILITY MODEL OF BRIDGES

2.1 Quick Evaluation Model of Bridge Damage[1~5];Model 1

Five stages are used to describe the destruction of a bridge, namely no damage, minor damage, moderate damage, major damage, and collapse. It is assumed that the empirical fragility curves can be expressed in the form of two-parameter lognormal distribution functions, and developed as functions of intensity (MMI) representing the intensity of the seismic ground motion. It is assumed here for the ease of demonstration of analytical procedure that there are five states of damage including the state of no damage, minor damage, moderate damage, major damage, and collapse. Events E1, E2, E3, E4, E5 respectively indicate the state of no, at least minor, at least moderate, at least major damage, and collapse. $P_{ik}=P(I_i,E_k)$ in turn indicate the probability that a bridge i selected randomly from the sample will be in the damage state E_k when subjected to ground motion intensity expressed by $MMI = I_i$. All fragility curves are represented by two-parameter lognormal distribution functions. The formula is expressed as [1]

$$F_j(I_i; c_j, \varsigma_j) = \Phi\left[\frac{\ln(I_i / c_j)}{\varsigma_j}\right] \tag{1}$$

Where c_j and ζ_j are the median and log-standard deviation of the fragility curves for the damage state of "at least minor", "at least moderate" ,"at least major" and "collapse" identified by j=1,2,3,4.respectively. From this definition of fragility curves, and under the assumption that the log-standard deviation is equal to ζ common to all the fragility curves, one obtains[1]:

$$P_{i1} = P(I_i, E_1) = 1 - F_1(I_i; c_1, \varsigma) \tag{2}$$

$$P_{i2} = P(I_i, E_2) = F_1(I_i; c_1, \varsigma) - F_2(I_i; c_2, \varsigma) \tag{3}$$

$$P_{i3} = P(I_i, E_3) = F_2(I_i; c_2, \varsigma) - F_3(I_i; c_3, \varsigma) \tag{4}$$

$$P_{i4} = P(I_i, E_4) = F_3(I_i; c_3, \varsigma) - F_4(I_i; c_4, \varsigma) \tag{5}$$

$$P_{i5} = P(I_i, E_5) = F_4(I_i; c_4, \varsigma) \tag{6}$$

The likelihood function can then be introduced as[1]

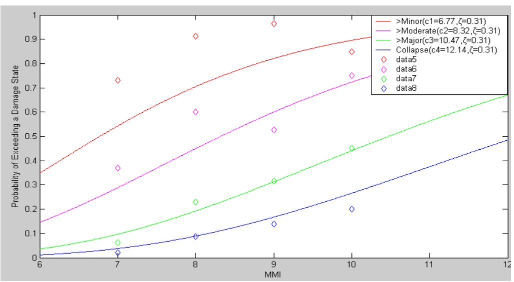
$$L(c_1、c_2、c_3、c_4, \varsigma) = \prod_{i=1}^{n} \prod_{k=1}^{5} P_k(I_i; E_k)^{x_{ik}} \tag{7}$$

$$\text{Where} \begin{cases} x_{ik} = 1 & \text{If the damage state } E_k \text{ occurs for the i-th bridge subjected to } I=I_i \\ x_{ik} = 0 & \text{Otherwise} \end{cases} \tag{8}$$

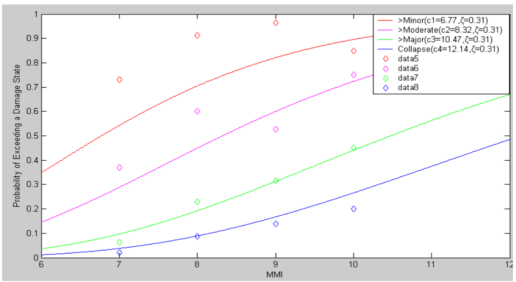
Otherwise, the maximum likelihood estimates c_{0j} for c_j and ζ_0 for ζ are obtained by solving the following equations,

$$\frac{\partial \ln L(c_1, c_2, c_3, c_4, \varsigma)}{\partial c_j} = \frac{\partial \ln L(c_1, c_2, c_3, c_4, \varsigma)}{\partial \varsigma} = 0 \quad (j = 1, 2, 3, 4) \tag{9}$$

The arch bridges are separated from the beam bridges. According to damage data of Tangshan, Haicheng, and Tonghai [6][7][8], and from the formulation (1) ~ (9), the fragility curve of bridges is shown in Figure 1.



(a)Beam bridges



(b)Arch bridges

Figure 1: The fragility curve of bridges

2.2 Quick Evaluation Model of Bridge Damage ;Model 2

Two groups of vulnerability curves of the above are under normal circumstances, and it does not take into account the specific circumstances of each bridge. Since each bridge's geographical location, structure type, the construction year and soil type are not the same, every bridge is destroyed by different reasons. If the earthquake emergency database can provide the datum which are greater impact on the destruction of the bridges, the correction factor η can be used to amend the vulnerability of the above to make it more in line with each of the specific characteristics of a bridge. The formula of the η is described as:

$$\eta = \Delta b1 + \Delta b2 + \Delta b3 + \Delta b4 \qquad (10)$$

Where, for Beam Bridges,

$\Delta b1$ is the number of span of Beam Bridge on the impact of the fragility.
$\Delta b2$ is the construction of the year on the impact of the fragility.
$\Delta b3$ is the soil types on the impact of the fragility.
$\Delta b4$ is the fortify intensity on the impact of the fragility.

Table 1: The value of $\Delta b1$

The Number of Span	<=3	>3
$\Delta b1$	-0.5	0.5

Table 2：The value of $\Delta b2$

Construction	Before 77	77~85	86~99	After 1999
$\Delta b2$	1.0	0	-0.5	-1

Table 3：The Value of $\Delta b3$

Soil Types	I	II	III	Ⅳ
$\Delta b3$	-1	0	2	3

Table 4：The Value of $\Delta b4$

Fortify Intensity	Lower	Equal	Higher
$\Delta b4$	1	0	-1

For arch bridges,

$\Delta b1$ =the soil types on the impact of the fragility.
$\Delta b2$ =the span of Arch Bridge on the impact of the fragility.
$\Delta b3$ =the material of Arch Bridge on the impact of the fragility.

Table 5：The Value of $\Delta b1$

Soil Types	I	II	III	Ⅳ
$\Delta b1$	-1	-0.5	1.5	3.5

Table 6：The Value of $\Delta b2$

Span(m)	<=20	20~30	>30
$\Delta b2$	-1	-0.5	0

Table 7：The Value of $\Delta b3$

Material	Brick Arch	Stone Arch	RC Arch
$\Delta b3$	1.5	0	-0.5

The value of $\Delta b4$ is 0。

After it gets the value of η, the value of $F_j(I_i; C_j, \zeta_j)$ can be amended as described below

$$F_j(I_i; c_j, \varsigma_j) = \Phi\left[\frac{\ln((I_i+\eta)/c_j)}{\varsigma_j}\right] \qquad (11)$$

Where, if $Ii+\eta > 12$, then $Ii+\eta = 12$; if $I_i+\eta < 6$, then $I_i+\eta = 6$. From formulation (11), the value of $P_{i1} \sim P_{i5}$ can also be updated.

3. TRAFFIC ASSIGNMENT OF THE TRANSPORTATION NETWORK

3.1 Traffic Assignment Model

There are many traffic assignment methods, such as Incremental Assignment Method, All-or-Nothing Method, the shortest distance traffic assignment method, and so on. In this paper, the Modified Capacity constraint-Incremental Assignment Method [9] is utilized. In this method, the total O-D trip matrix OD(bij) is divided into 10 fractional matrix, and the assignment proportion is respectively 0.30, 0.2 0.05, 0.05, 0.05, 0.05, 0.1, 0.1, 0.05, 0.05. The steps are as follows:

Step 1: Divide the total O-D trip matrix OD(bij) into 10 fractional matrix, △**OD= OD**(b_{ij})* assignment proportion; select an initial set of free-flow link travel times t_k^0, and the link travel times including the travel times and the times changed from the charge; initialize all flows $h_k^0 = 0$; set l=0.

Step 2: Build the set of shortest distance trees (one for each origin) using Dijkstra algorithm based on the current link travel times; set l=l+1;

Step 3: If no available route is found for O-D ij, set △b_{ij}=0; if all △b_{ij}=0, proceed to Step 8.

Step 4: Load △OD all-or-nothing to the shortest distance trees, obtaining a set of auxiliary flows Fk; accumulate flows on each link: $h_k^l = h_k^{l-1} + F_k$.

Step 5: Calculate a new set of current link travel time t_k^l based on the flows h_k^l.

Step 6: If the flow reaches the link capacity C_k, set $t_k^l = \infty$.

Step 7: If l=10, proceed to Step 8; otherwise proceed to Step 2.

Step 8: Terminate the incremental assignment; calculate performance measures.

3.2 Road Traffic Impedance Function

Based on the function developed by the United States Bureau of Public Roads, many researchers in China have mended the function to suit to the Chinese actual situation, and the traffic speed and traffic relationship was modeled as follows[10]:

$$U = \frac{\alpha U_s}{1+\gamma\left(V/C\right)^{\beta}} \tag{12}$$

Where

U= traffic speed on the highway
Us=design traffic speed on all highway levels
V=current traffic on the highway
C=capacity of the highway
α , β , γ =the correction coefficient

The correction coefficients α 、β 、γ are obtained from the measured data using regression analysis or determined though fitting the measured mode and the corresponding curve. The formula of β is[10]:

$$\beta = \alpha_2 + \alpha_3 (V/C)^3 \tag{13}$$

Where, α_2 , α_3 is the parameter. Therefore, the traffic speed and traffic relationship was modeled as below[10]:

$$\begin{cases} U = \dfrac{\alpha_1 \bullet U_s}{1+(V/C)^{\beta}} \\ \beta = \alpha_2 + \alpha_3\left(V/C\right)^3 \end{cases} \tag{14}$$

The value of the $\alpha_1, \alpha_2, \alpha_3$ is listed in the table 8 on all highway levels.
From above, the time traveling on the highway can be calculated as,

$$\begin{cases} t = t_0 \bullet \dfrac{1}{\alpha_1}\left(1+\left(\dfrac{V}{C}\right)^{\beta}\right) \\ \beta = \alpha_2 + \alpha_3\left(\dfrac{V}{C}\right)^3 \end{cases} \tag{15}$$

Where

t_0=travel time at zero flow on the link (this is simply the link's length divided by the speed limit plus the times transformed from the toll on the highway)

t=travel time at actual state on the link

Table 8: the universal model parameters of the speed-capacity of all highway levels[10]

Road Type	Design traffic speed(Km/h)	Capacity [cars/(hours • car lanes)]	α_1	α_2	α_3
Four-lane Highway	120	2200	0.93	1.88	4.85
	100	2200	0.95	1.88	4.86
	80	2000	1.00	1.88	4.90
Six-lane Highway	120	2150	0.93	1.89	4.86
	100	2100	0.95	1.88	4.93
	80	2000	1.00	1.88	4.90
State Road	100	2100	0.93	1.88	4.93
	80	1950	0.98	1.88	4.88
	60	1650	1.10	1.89	4.85

3.3 Toll Effect on the Road Traffic Impedance Function

The impact on the road traffic impedance function of Charging on the highway is divided into two aspects[10] [11] one is that the travel time become longer due to the process of the toll, the other is the change of the choice of the road due to the fees charged on the highway, because some people will select the free road, thus the travel time including the conventional travel time and the time transformed from the toll. It can be called generalized time, namely[11]

$$t' = t_r + t_f \tag{16}$$

Where, t' =generalized time, t_r=the conventional travel time, t_f=the time transformed from the toll. In this paper, the time due to the process of the toll couldn't be considered.

In the paper [11], the concept of time value is introduced, thus the different circumstances in different regions are better reflected. The conclusion is described as below:

For bus transportation[11],

$$tf_k = \sum_{i=1}^{n} \frac{P_i F_i}{M_{ki} E_{tk}} \tag{17}$$

Where, tf_k=the time weight of the charge of the bus, P_i=the proportion of the bus type i in the total bus types (%), F_i=the charge of the bus type i, E_{tk}=the average time value in the region (Yuan/person/h), M_{ki}=the average carrying coefficient of the buses (person), n=the number of the bus types on the highway.

For truck transportation[11],

$$tf_h = \sum_{i=1}^{n} \frac{P_i F_i}{M_{hi} E_{th}} \tag{18}$$

Where, tf_h=the time weight of the charge of the truck, P_i=the proportion of the truck type i in the total truck types (%), F_i=the charge of the truck type i, E_{tk}=the average time value in the region (Yuan/t/h), M_{ki}=the average carrying coefficient of the trucks (t), n=the number of the truck types on the highway.

Therefore, the time weight of the charge is shown [11]:

$$t_f = p \cdot tf_k + (1-p) \cdot tf_h \tag{19}$$

Where, p=the proportion of the bus in the total cars on the highway.

4. EARTHQUAKE ECONOMIC LOSS EVALUATION METHOD OF HIGHWAY

4.1 Roadway Repair Cost Estimation in an Earthquake

In the past earthquake, the economic losses of the roadway are relatively small. The formula of the direct loss of a roadway under an earthquake is described as below [5] [12] [13]:

$$RC_j = \sum_{k=1}^{4} P\left(Ds = k / I_j\right) \cdot l \cdot C \cdot r_k \tag{20}$$

Where

$P(D_s = k / I_j)$ =probability of roadway sustaining damage state k under ground motion I_j; this is a fragility curve of roadway for damage state k evaluated at I_j

k=damage state of bridge (1: minor damage, 2: moderate damage, 3: major damage, 4: collapse)
l=the length of the roadway (Km).
C=the cost of the roadway in a kilometer (Yuan/Km).
r_k=damage ratio corresponding to damage state k (1: 0.15; 2: 0.3; 3: 0.6; 4: 1)

Therefore, the evaluation of roadway repair cost can be expressed as

$$DL1 = \sum_{i=1}^{N} RC(i) = \sum_{i=1}^{N}\sum_{k=1}^{4} P_i\left(Ds = k / I_{ij}\right) \cdot l \cdot C_i \cdot r_k \tag{21}$$

Where, N=the total number of the roadways in the transportation network.

4.2 Bridge Repair Cost Estimation in an Earthquake

The evaluation of a bridge repair cost resulting from event j can be expressed as [5] [12] [13]

$$RC_j = \sum_{k=1}^{4} P\left(Ds = k / I_j\right) \cdot C \cdot r_k \tag{22}$$

Where

RC_j=expected bridge restoration (repair or replacement) cost due to earthquake

k=damage state of bridge (1: minor damage, 2: moderate damage, 3: major damage, 4: collapse)

I_j=ground motion at the site of bridge i due to event j

$P(D_s = k / I_j)$ =probability of bridge sustaining damage state k under ground motion Ij; this is a fragility curve of bridge for damage state k evaluated at Ij

C=replacement value of bridge

r_k=damage ratio corresponding to damage state k (1: 0.1~0.2; 2: 0.2~0.4; 3: 0.4~0.7; 4: 0.7~1.0) [13] [14]

Therefore, the evaluation of bridge repair cost of the transportation network resulting from event j can be expressed as

$$DL2 = \sum_{i=1}^{N} RC(i) = \sum_{i=1}^{N}\sum_{k=1}^{4} P_i\left(Ds = k / I_{ij}\right) \cdot C_i \cdot r_k \tag{23}$$

Where, N=total number of bridges in the transportation network

In past earthquake, the seismic performance of the tunnels and culverts is relatively better, and this kind of research o

f those is relatively little, so in this paper, it doesn't include the loss due to the tunnels and culverts' damage.
From above, the total loss of the highway system is described as below

$$DL = DL1 + DL2 \tag{24}$$

4.3 Part of Earthquake Indirect Economic Loss Evaluation of Transportation Networks

Earthquake indirect economic loss is one of the losses which due to the malfunction of economic operation system because of the damage of economic system under earthquake. Comparing with the direct economic loss, it has a longer period of time effect.
It is difficult to estimate the earthquake indirect economic loss correctly because there is much factor which is effect on the loss. Until now, there is still not a complete assessment model, so in general, the input-output model and statistical regression methods are used. In this paper, it only lists a very small part of the earthquake economic loss. More researches must be done later.

4.3.1Drivers' delay cost

In order to define the network performance as a whole after an earthquake, a comprehensive index of performance is quoted. The index used here is the "Drivers' Delay" [2] [4]. This is defined as the increase in total daily travel time for all travelers including commuters and commercial vehicles caused by earthquake induced delays [2] [4], and the formula of it is described as below

$$T = \sum_i x_i t_i(x_i) \tag{25}$$

$$Delay = \sum_i x_i' t_i'(x_i') - \sum_i x_i t_i(x_i) \tag{26}$$

Where,

x_i is the flow on link a (in Passenger Car Unit), and t_i is the travel time on link a (in hours per Passenger Car Unit).

$\sum_i x_i t_i(x_i)$ represents the total daily travel time for all network users before earthquake, in hours per day;

$\sum_i x'_i t'_i(x'_i)$ represents the total travel time for all network users after earthquake.

Therefore, the indirect losses due to drivers' delay are calculated as below

$$IL1 = \sum_{i=1}^{M} Delay(i) \bullet S \tag{27}$$

Where, Delay (i) is the increment of the i days' travel time; S is the value of time per hour, and M is the time that the network restore to normal state from earthquake (day).

4.3.2The loss due to the cancel of the trip of the tourists

When the earthquake happened in a certain region, the region's tourism industry will have a big impact. Scheduled tours will be cancelled or postponed, and the income of the tourism industry will be reduced. This kind of loss can be described as:

$$IL2 = \sum_{i=1}^{N} OD(i) \bullet p \bullet g \bullet f \bullet consume \tag{28}$$

Where, OD(i)=the i O-D matrix to the earthquake-affected regions, p=the proportion of tourism in the i O-D matrix, g=the average numbers of the tourists per car, f=the probability of the cancel (f=0 or f=1, f relates to the seismic intensity), and consume=the consume of per people.

In this paper, the two losses above have been considered, but there are many other kinds of indirect loss. In the future research, the other kind of the indirect loss must be evaluated through the appropriate approach. Therefore, in this paper, the indirect loss due to the earthquake is:

$$IL = IL1 + IL2 \tag{29}$$

5 CONCLUSIONS

This study concentrates on the evaluation of the socio-economic impact of the transportation system under the earthquake. A series of studies, including the development of empirical fragility curves for the Beam Bridges and the Arch Bridges, traffic assignment, freeway network seismic performance evaluation, road repair cost, bridge repair cost, and the indirect loss estimation, are carried out to evaluate the earthquake loss of the transportation networks. While the authors are hopeful that the conceptual and theoretical treatment dealt in this paper can provide theoretical basis and analytical tools of practical usefulness for the evaluation the loss in China due to the earthquake, this paper is only the framework of the evaluation of the loss, and there are many analytical and implementation aspects that require further study including:

(1) This paper don't include the practical examples, so in subsequent applications, it should be further improved to test the accuracy of the model above.
(2) Whether the economic loss is evaluated accurately or not, a large extent, it depends on the reliableness of the vulnerability model of the bridges. At present, the data of the damage of the bridges is less, so in the future study, the reliableness of the vulnerability model of the bridges needs to be improved and perfected.
(3) In general, the OD matrix doesn't change before and after the earthquake in all kinds of studies for simpleness, but it doesn't accord with the actual situation, so the OD matrix after the earthquake needs to be further study.
(4) Earthquake indirect economic loss is a very complex problem, and it is very difficult to study because many of the specialties are involved. In the previous earthquake, the indirect loss due to the earthquake is huge, and as the economy develops, it increases very quickly. Thus, the further study is necessary through using the economic tools like input-output model.

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