GIS-BASED EARTHQUAKE DISASTER PREDICTION AND OPTIMUM PATH ANALYSIS FOR THE URBAN ROAD TRANSIT SYSTEM

NI Yongjun[1], WANG Wanhong[1], HUANG Shimin[2], FU Shengcong[2] and OU Xianren[3]

1. Ph.D, Associate professor, School of Civil Engineering, Beijing Jiaotong University, Beijing, China
2. Institute of Earthquake Engineering, China Academy of Building Research, Beijing, Chiina
3. Beijing Jinkerong Scientific and Technologic Development Co. Ltd., Beijing, China

ABSTRACT:

In the earthquake disaster prediction of the urban road transit system (simplified as URTS), for bridge, 9 factors including the earthquake intensity, ground soil type failure extent of ground soil, superstructure type, the height, type and material of bridge pier, span length and span number of bridge were considered; for road, 7 factors including the primary earthquake intensity, soil type of the roadbed and ground, failure extent of ground soil, roadbed type, roadbed height and designed earthquake intensity were considered. The computer program for predicting the earthquake disaster of URTS was implanted in the GIS platform "Information System for Earthquake Resistance and Disaster Mitigation", which was developed based on SuperMap Objects. The prediction of earthquake disaster for the global or the arbitrary partial road sections within the URTS could be performed. Introducing the Warshall algorithm in Chart Theory, the connective reliability analysis for URTS was performed, and the connective probability matrix for road sections was provided. Considering the connective probability of URTS, adopting the method that each road section were designated a weight according its length, the optimum path between the arbitrary two points could be calculated and displayed in the interface. The calculation and analysis above mentioned were visually realized and demonstrated based on the GIS platform developed.

KEY WORDS: GIS, Earthquake Disaster, Prediction, Optimum Path, Road Transit

1 INTRODUCTION

As a prosperous developing technology, GIS (Geographic information System) has been widely used in the many engineering fields, especially in the prediction, loss assessment of earthquake disaster and the assistant decision after earthquake. The detailed review about the application of GIS in the seismic engineering and disaster mitigation was summarized by HUANG Shimin and NI yongjun in 2007. It is pity that most of the GIS platform only has simple functions such as the inquiry, modification and demonstration about the data information. Analyzing function and its convenience needs to be improved greatly. Based on the Objects of SuperMap, which was a native GIS platform developed, the "Information System for the Prediction of Earthquake Disaster in Urban City" was developed independently. On the developed GIS software, it was realized for the analysis and assessment of earthquake ground motion of engineering site, reliability and function analysis of supply pipeline network under earthquake, the prediction of earthquake disaster for buildings, the prediction of earthquake disaster for urban road transit system, the prediction of economic loss etc.

As an important part of the lifeline engineering system, the urban road transit system (simplified as URTS) is taken as the "Blood Cycling System", plays the significant role in urban life. Once the URTS is destroyed after earthquake, the normal urban life would be significantly disturbed. The control of the secondary disaster and the supply of the rescuing materials would be limited as well. It is necessary to analyze the seismic reliability (seismic disaster prediction) of the URTS so as to find the fragile sectors and rebuild them. Ensuring the safety, quickness and high efficiency of URTS is valuable and required.

The earthquake disaster prediction of URTS includes two pats, namely as the disaster prediction of bridges and roads.

2 Prediction of Earthquake Disaster of Bridge

The empirical formula for predicting the seismic disaster of bridges was introduced by the Regression Statistical Method proposed by ZHU Meizhen (1990) as:

$$y = \omega_0 \cdot \prod_{j=1}^{N} \prod_{k=1}^{j_n} \omega_{jk}^{\delta_{jk}} \tag{1}$$

in which, δ_{jk}=1, with k type within the disaster prediction j factor; else, δ_{jk} =0, without k type within the disaster prediction j factor. y is the index value of disaster prediction. N is the dimension of predicting factors set. j_n is the dimension of predicting factors set corresponding to the j factor. ω_0 and ω_{jk} are calculating coefficients seen in Table 1. Referring to the threshold value seen in Table 2, the earthquake disaster level could be predicted. Then the connective probability of the bridge could be estimated referring to Table 3.

Table 1 Parameters and Factors Influencing the Earthquake Disaster of Bridge

Items	Type	Weighting Coefficients	Adopted Coefficients
Earthquake Intensity	VII	1.00	1.00
	VIII	1.05	1.10
	IX	1.10	1.20
Site Type	Hard		0.80
	Medium	1.00	1.00
	Soft	1.78	1.80
Failure Extent of Ground	Without failure	1.00	1.00
	Minor failure	1.52	1.50
	Heavy failure	1.82	1.80
Supperstructure	Continuous Beam or Rigid Frame	1.00	1.00
	Slab Beam or Arch	1.13	1.10
	Simple-supported beam or Cantilever Beam	1.37	1.40
Bearing Type	With collapse-proof measures of bridges		0.70
	Isolation bearings	1.00	1.00
	Ordinary bearings	1.03	1.10
Height of Piers/Abutment	＜5m	1.00	1.00
	5～10m	1.02	1.10
	＞10m	1.05	1.20
Material type of Piers/Abutment	Reinforced concrete	1.00	1.05
	Masonry foundation	1.05	1.10
Foundation Type	Extended foundation	1.00	1.00
	Pile foundation	1.00	1.00

	Bent pile foundation	1.20	1.20
	Platform with high pile	1.20	1.20
Span Length of Bridge	Span length＜10m	1.00	1.00
	Span length＞10m	1.20	1.20
Comprehensive Weighting		0.98	0.85

Table 2 Threshold Values of Earthquake Disaster Level

y	<1.23	1.23~2.20	2.20~3.38	3.38~4.40	>4.40
earthquake disaster level	Without/slight damage	Minor damage	Medium damage	Heavy damage	Collapse

Table 3 Connective Probability of Bridge

Earthquake disaster of bridge	Without/slight damage	Minor damage	Medium damage	Heavy damage	Collapse
Connective probability	1.0	0.8	0.6	0.1	0

3 PREDICTION OF EARTHQUAKE DISASTER OF ROAD

3.1 Classification of Seismic Disaster Grade

Considering the coincidence of seismic disaster grade for bridges and roads, the disaster grade of roads was classified as three levels. The first level was without damage or slight damage. The second level was minor damage (only simple mend needed). The last level was mediate damage. Once the heavy damage of road after earthquake occurred, the road section would be rebuilt and out of service, which was not considered in this paper. The classification of the seismic disaster grades and their corresponding parameters were shown in Table 4 (BAI Yongzheng and ZHANG Yunyan, 2000).

Table 4 Description of Earthquake Disaster Grade for Road

Damage grade	Description of seismic disaster of roads	Average index of earthquake disaster
Without/slight damage	No damage or only little cracks of pavement, no influence on transportation	0.10
Minor damage	Minor damage on pavement or roadbed, such as cracks, knob, sinkage, collapse or slide of roadbed, spraying sand or water, have minor influence on transportation.	0.30
Mediate damage	Mediate damage on pavement or roadbed, such as cracks, knob, sinkage, collapse or slide of roadbed, spraying sand or water, have significant influence on transportation. Need to be repaired in time.	0.50

3.2 Selection of Seismic Disaster Factors and Their Quantification

Based on the existing lessons and experiences on earthquake disaster, 7 factors including the primary earthquake intensity, soil type of the roadbed and ground, failure extent of ground soil, roadbed type, roadbed height and designed earthquake intensity were considered in earthquake disaster prediction of roads. The classification and quantification of influencing factors are shown in Table 5.

Table 5 Parameters and Factors Influencing the Earthquake Disaster of Roads

Factors	1	2	3	4	5
Earthquake Intensity	VI 0.20	VII 1.00	VIII 1.05	IX 1.15	X 1.20
Soil Type of Roadbed	Stiff soil 0.9	Clay 1.0	Silty soil or Fine grained soil 1.1	Stage-constructed Roadbed 1.2	/
Site Type	I 0.9	II 1.00	III 1.10	IV 1.30	/
Failure Extent of Ground	Without failure 1.00	Minor failure 1.05	Medium failure 1.15	Heavy failure 1.40	/
Roadbed Type	Low roadbed 1.00	Embankment or Road cutting 1.10	Combined roadbed by cutting or filling 1.30	Roadbed along river 1.35	/
Roadbed Height	$H \le 1$ 1.00	$1 < H \le 2$ 1.05	$2 < H \le 3$ 1.10	$3 < H$ 1.40	/
Design Earthquake Intensity	With fortification 0.90	Without fortification 1.00	Damaged 1.20	/	/

3.3 Prediction of Earthquake Disaster of Road

Prediction of earthquake disaster of road was described by earthquake disaster degree (simplified as EDD). Relying on the history experience of earthquake disasters, considering the convenience of analyzing and calculating, the parameter of EDD was supposed to be normally distributed (BAI Yongzheng and ZHANG Yunyan, 2000), namely as:

$$u_{B_i}(ind) = \left[e^{-\frac{(ind - \overline{ind}_i)^2}{2\sigma_i^2}} \right] \tag{2}$$

in which, σ_i is the dispersion coefficients respecting to the earthquake disaster under the different earthquake intensities, can be found in Table 6. $\overline{ind}_i$ is the average index of earthquake disaster, can be obtained by eq. (3):

$$\overline{ind}_i = \left[\prod_{j=1} X_{ij} \right] \times 0.2 - 0.1 \tag{3}$$

in which, X_{ij} is the quantified value corresponding to j factor of i road section, can be found in Table 5.

If $\overline{ind}_i \ge 0.6$, then designating $\overline{ind}_i = 0.6$.

With the EDD values corresponding to the different earthquake intensities, the percentage of the road damage can be calculated. The approximation of the road damage can be determined finally referring to Table 7.

Table 6 Proposed Dispersion Coefficients σ_i

Earthquake intensity	VI	VII	VIII	IX	X
Proposed σ_i	0.1	0.2	0.2	0.3	0.3

Table 7 Feasibility of the Road Damage

Damage Level	Earthquake intensity				
	VI	VII	VIII	IX	X
Without/slight damage	100	95	90	84	70
Minor damage	0	3.5	7	10	18
Mediate damage	0	1.5	3	6	12

Correspondingly, the proposed connective probability of the road under the different EDD level can be obtained referring to Table 8.

Table 8 Proposed Connective Probability of Road

EDD	Without/slight damage	Minor damage	Mediate damage
Connective Probability	1.0	0.8	0.6

4 CONNECTIVE RELIABILITY ANALYSIS

Once the connective probabilities of the bridges and road sections were determined, the connective reliability analysis for the global URTS could be carried out. Within the many analyzing methods, Monte-Carlo method (LI Jie, 2005) was a method in common use. The damage probability of the URTS was simulated based on the production of the random number. The simulated damage probability would be compared with the actually calculated probability. The damage matrix of URTS was constructed using the connective matrix of URTS. Then the connectivity of URTS would be analyzed considering the connective matrix. The simulation test would be repeated many times. The connective frequencies between the arbitrary two nodes could be summed up respectively and be taken for the reliability probability of URTS.

The process of analyzing the connectivity of road sections is essential for solving the connective matrix of the reachable matrix. Since the reachable matrix is a Boolean matrix, which is consisted of elements with their value of 0 or 1, the calculating can be implemented by Boolean operation. Owing to the complexity of the calculation, the alterative Warshall algorithm (XIAO Weishu, 1993) with more efficiency was introduced in this paper.
The calculating procedures of Monte-Carlo method are as following:

(1) Calculating the failure probability $P_f(i)$ of each road sections through the reliability analysis of roads.
(2) Producing the random number $r(i)$ with even distribution within the interval of [0, 1] for each road sections. Having the comparison the random number $r(i)$ and the failure probability $P_f(i)$, TB(i)=1 while $r(i)> P_f(i)$, else $TB(i)$=0.
(3) Constructing the damaged probability matrix $AB(i,j)$ through $TB(i)$ and the connective matrix.
(4) Calculating the reachable matrix C through matrix $AB(i,j)$ using Warshall algorithm.
(5) $t_{ij}= t_{ij} +1$, while $C_{ij} =1$ (namely connective); else $t_{ij} = t_{ij} +0$, while $C_{ij} =0$ (namely not connective).
(6) Repeating the procedure (2) to (5) until to the required precision. If the simulated times was k, the connective frequency between nodes was taken for the connective probability P, namely that

$$P= t_{ij} /k \tag{4}$$

5 OPTIMUM PATH ANALYSIS

The Dijkstra algorithm was introduced in the analysis of optimum path. The input of the Dijkstra algorithm includes a weighted chart G with directions and an origin peak point S. V represents the set of all peak points in G. An arbitrary side line was formed by an order elements couple composed of two peak points. (u,v) represents that it has a connective path from peak point u to v. Designating that E is a set of all side lines. The weights of side lines are defined as a weight function w: E→[0,∞]. So $w(u,v)$ is the cost from peak point u to v. The whole cost of all paths connecting arbitrary two points is a summation of every costs of all side line sections. Known as the peak point s and t, the minimum cost path (i.e. shortest path) can be found using Dijkstra algorithm. Applying the algorithm the shortest path from the peak point s to the arbitrary other points within the chart can be found. The sketch map of Dijkstra algorithm is shown in Figure 1. The detailed description of Dijkstra algorithm can be found in the reference (by XIAO Weishu, 1993).

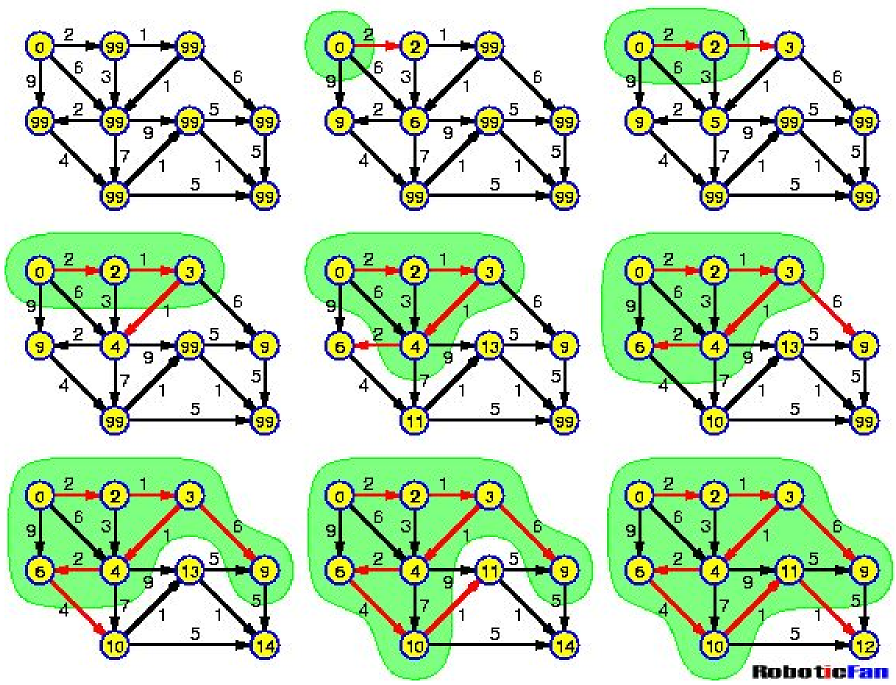

Figure1 Sketch map of Dijkstra algorithm

The connectivity of all road sections can be judged according to the corresponding connective probabilities. Generally, it is taken for being reliable for the connective probability P_{tr}≥0.8, mediate reliable for 0.4≤ P_{tr} <0.8 and unreliable for P_{tr} <0.4 (i.e. not connective). For the road section between two adjacent points with its length Li, the calculating length of the road section is taken as:

$$L_{cal} = L_i + (1 - P_{tr})L_i \quad (5)$$

Finally, the minimum of the cumulated calculating length of road sections between arbitrary two points is the optimum path.

Both the connective probability of the single road section and the influence of road section length on the traveling time were considered in the optimum path analysis using the algorithm above mentioned. It was validated that the algorithm was convenient and efficient.

6 ILLUSTRATION

On the GIS platform, "Information System for the Prediction of Earthquake Disaster in Urban City" (seen Figure 2), which was developed independently based on the SuperMap Objects, the prediction of earthquake disaster of the URTS of Huaian city in Jiangsu province under the different earthquake intensities was carried out. The connective ability and optimum rescuing path between two arbitrary points were analyzed. Limited to the paper, only the prediction of earthquake disaster and analysis result of URTS under designed earthquake intensity VII are listed below.

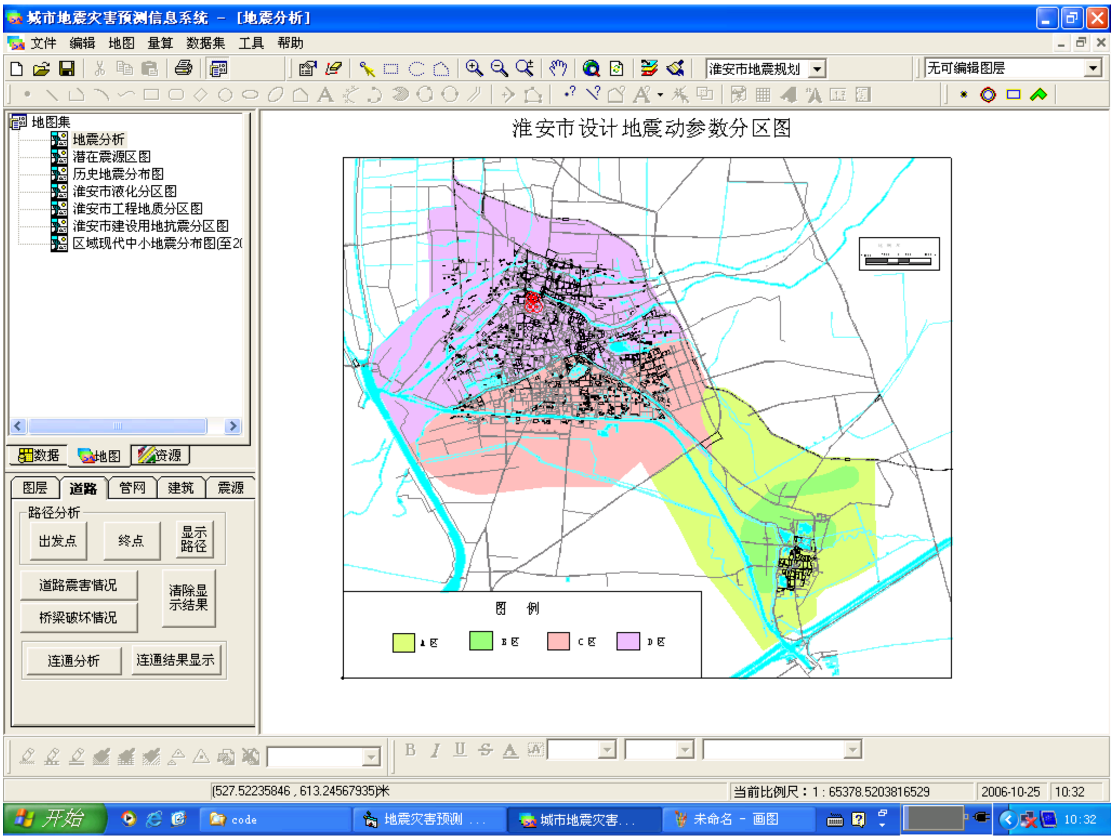

Figure2 Interface of "Information System for the Prediction of Earthquake Disaster in Urban City" —Road Transit System for Huaian City

The bridge was considered to be a key node in the GIS system. Under the designed earthquake intensity VII, the earthquake disaster prediction of bridges and roads is shown in Figure 3 and Figure 4. The connective ability between nodes is also shown in Figure 4. The reachable matrix from a specified origin point to the arbitrary points is shown in Figure 5. It is noted that the green color for without/slight damage, the yellow color for minor damage and the orange color for mediate damage. The optimum path from a specified origin point to an arbitrary end point is shown in Figure 6. All the calculated results above mentioned can be exported as EXCEL tables.

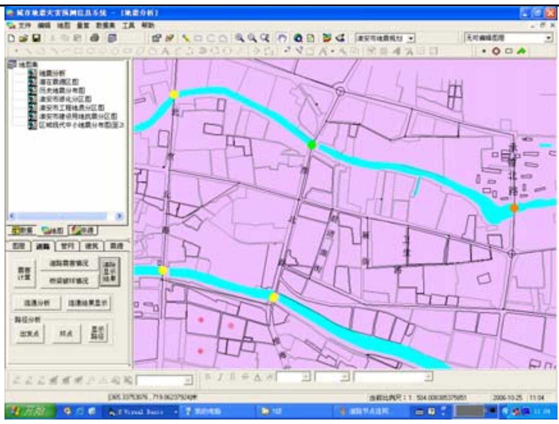

Figure 3 Earthquake disaster prediction and connective ability for bridges (Solid circle with different colors)

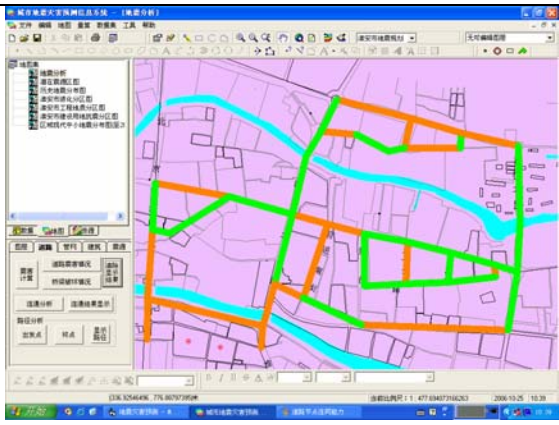

Figure 4 Earthquake disaster prediction and connective ability for roads

道路节点连通能力显示

连通能力 显示设置 选择节点编号 1 定位 清除显示 图形显示

编号	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1	.86	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.86	1	.86	.86	.64	1	1	.72
2	.86	.93	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.86	.86	.73	.86	.67	.86	.86	.67
3	.8	.83	1	1	1	1	1	1	1	1	1	1	.82	.8	.67	.82	.79	.8	.8	.68
4	.8	.83	1	1	1	1	1	1	1	1	1	1	.82	.8	.67	.82	.79	.8	.8	.68
5	.8	.83	1	1	1	1	1	1	1	1	1	1	.82	.8	.67	.82	.79	.8	.8	.68
6	.8	.83	1	1	1	1	1	1	1	1	1	1	.82	.8	.67	.82	.79	.8	.8	.68
7	.8	.83	1	1	1	1	1	1	1	1	1	1	.82	.8	.67	.82	.79	.8	.8	.68
8	.8	.83	1	1	1	1	1	1	1	1	1	1	.82	.8	.67	.82	.79	.8	.8	.68
9	.8	.83	1	1	1	1	1	1	1	1	1	1	.82	.8	.67	.82	.79	.8	.8	.68
10	.8	.83	1	1	1	1	1	1	1	1	1	1	.82	.8	.67	.82	.79	.8	.8	.68
11	.8	.83	1	1	1	1	1	1	1	1	1	1	.82	.8	.67	.82	.79	.8	.8	.68
12	.8	.83	1	1	1	1	1	1	1	1	1	1	.82	.8	.67	.82	.79	.8	.8	.68
13	.86	.86	.82	.82	.82	.82	.82	.82	.82	.82	.82	.82	1	.86	.74	1	.67	.86	.86	.66
14	1	.86	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.86	1	.86	.86	.64	1	1	.72
15	.86	.73	.67	.67	.67	.67	.67	.67	.67	.67	.67	.67	.74	.86	.9	.74	.54	.86	.86	.62
16	.86	.86	.82	.82	.82	.82	.82	.82	.82	.82	.82	.82	1	.86	.74	1	.67	.86	.86	.66
17	.64	.67	.79	.79	.79	.79	.79	.79	.79	.79	.79	.79	.67	.64	.54	.67	.88	.64	.64	.54
18	1	.86	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.86	1	.86	.86	.64	1	1	.72
19	1	.86	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.86	1	.86	.86	.64	1	1	.72
20	.72	.67	.68	.68	.68	.68	.68	.68	.68	.68	.68	.68	.66	.72	.62	.66	.54	.72	.72	.95
21	.61	.57	.59	.59	.59	.59	.59	.59	.59	.59	.59	.59	.57	.61	.52	.57	.47	.61	.61	.8
22	.7	.69	.76	.76	.76	.76	.76	.76	.76	.76	.76	.76	.68	.7	.6	.68	.57	.7	.7	.81
23	.7	.69	.76	.76	.76	.76	.76	.76	.76	.76	.76	.76	.68	.7	.6	.68	.57	.7	.7	.81
24	.8	.83	1	1	1	1	1	1	1	1	1	1	.82	.8	.67	.82	.79	.8	.8	.68
25	.6	.64	.77	.77	.77	.77	.77	.77	.77	.77	.77	.77	.63	.6	.5	.63	.8	.6	.6	.52
26	.39	.35	.34	.34	.34	.34	.34	.34	.34	.34	.34	.34	.36	.39	.41	.36	.29	.39	.39	.29
27	.44	.33	.34	.34	.34	.34	.34	.34	.34	.34	.34	.34	.34	.44	.42	.34	.26	.44	.44	.31
28	.72	.6	.56	.56	.56	.56	.56	.56	.56	.56	.56	.56	.63	.72	.73	.63	.46	.72	.72	.52
29	.75	.61	.59	.59	.59	.59	.59	.59	.59	.59	.59	.59	.62	.75	.7	.62	.47	.75	.75	.56

Figure 5 The reachable matrix from a specified origin point to the arbitrary points

7 SUMMARY

Based on the "Information System for the Prediction of Earthquake Disaster in Urban City", which was developed independently based on the SuperMap Objects, the earthquake disaster of URTS was carried out. Introducing the Warshall algorithm, the connective reliability for URTS was analyzed using Monte-Carlo simulation method. The connective probability matrix of road network was also provided. Considering the connective probability of road sections and the influence of road section length on traveling time, the optimum path analysis was fulfilled applying Dijkstra algorithm. The calculation and analysis above mentioned could be explicitly illustrated by graphs and tables. It was validated that the GIS platform developed was convenient and efficient for predicting the earthquake disaster and analyzing the connective ability of URTS.

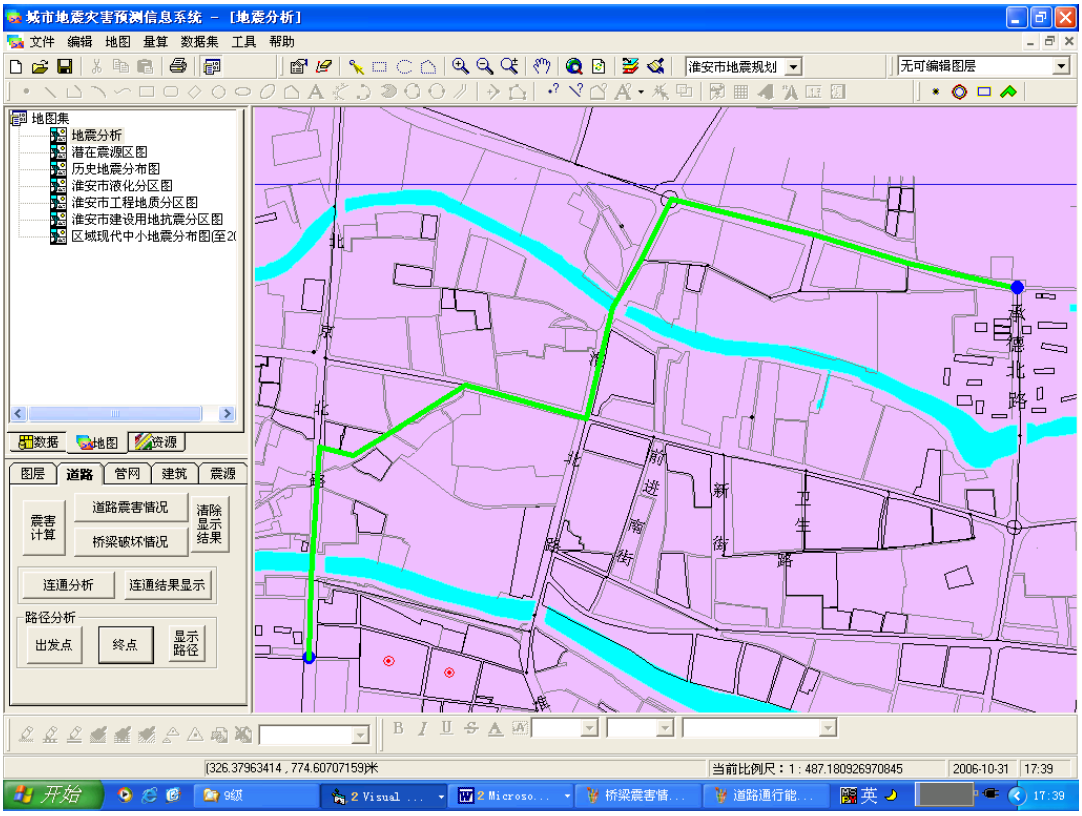

Figure 6 The optimum path from a specified origin to an arbitrary end point

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