A Comprehensive Fuzzy Method in Seismic Disaster Prediction of Urban Rail Transit Girder Bridges Based on Work Breakdown Structure (WBS)

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SUMMARY:

Based on the earthquake disaster investigation of 123 reinforced concrete girder bridges, introducing the philosophy of Work Breakdown Structure(WBS), altogether eight factors that were the building year, seismic fortification intensity, soil site category, failure extent of ground soil, superstructure of bridge, constructional measures for seismic resistance, heights of the piers and abutments, and the bridge spans, those affecting the seismic performance of bridges were considered in the seismic disaster prediction. According to the principle of maximum degree of membership, the fuzzy evaluation subsets for the different influential factors were determined by empirical statistic method. The corresponding weight coefficients were presented based on the statistical analysis of the seismic damage of 123 existing bridges. Relying on the developed prediction model, a Fortran based calculating program was developed to predicting the seismic disasters of the girder bridges in urban rail transit. It was shown that the method proposed in this paper was feasible through the comparing analysis of the actual seismic damages of the 123 existing bridges. The Fortran program could be planted to the existing GIS system to predict the arbitrary girder bridge in urban rail transit.

Key words: comprehensive fuzzy method; seismic disaster prediction; urban rail transit girder bridges

1. INTRODUCTION

As an important part of the lifeline engineering system, the urban rail transit line, taken as the “Blood Cycling System”, is playing the significant role in urban life. Once the line is destroyed after earthquake, the normal urban life would be significantly disturbed. It is necessary to analyse the seismic reliability (seismic disaster prediction) of the bridges in urban rail transit line so as to find the fragile sectors of bridges and reinforcing them. It is necessary to find out the behaviour of bridges in urban rail transit line under the different intensity of earthquakes through the seismic performance evaluation. According to the results of seismic disaster prediction, the corresponding reinforcement or maintenance methods could be work out to enhance their seismic performance, and the economic losses after the earthquake could be predicted.

Generally, the prediction or evaluation method for seismic performance of bridges are mainly including ①the code checking based method(Wang Dongsheng and Feng Qimin, 2001), ②the pushover analysis based method(Kilar V. and Fajfar P., 1997), ③the empirical parameters based statistical method (Zhu Meizhen, 1990), ④the probabilistic method based incremental dynamic analysis (IDA)(Dimitrios V., 2002) and ⑤ the neural network(including the fuzzy neural network method) based method(Liu Xingye et. al. 1996), and so on.

The methods of ①, ② and ④ were deterministic methods based on the detailed calculation of the single bridge. While the method of ③ was based on the empirical formula regressed through the statistical analysis after the investigations of seismic disaster for a great deal of bridges under earthquakes. The method ⑤ had the virtues of the above methods. So long as the training and rectifying of the neural network selected was performed successfully, the prediction precision of the seismic behaviour of bridges under earthquake could be reached to a satisfying level. In addition, Zhao Chenggang(1995) proposed the method which was based on artificial neural networks. Liu Chunguang(2008) proposed the method using genetic algorithms and BP neural network. The BP neural network based method was developed by Wu Xin, Ni Yongjun and Wu Hao(2010) as well. It was shown that the method could be used in the seismic disaster prediction of bridges for its availability and high precision. The BP neural network method was traditionally based on MATLAB software. It was difficult to plant the algorithm and the corresponding calculating program in the existing Geographic Information System (GIS) software platform.

Due to the fuzzy properties of the seismic damage extent and influencing factors of the bridges, a comprehensive fuzzy evaluation method could be applied to express the influencing factors of seismic disaster of bridges. A comprehensive evaluation matrix could be got through the fuzzy mathematic which was used to determine the certain seismic disaster degree of bridge.

2. SEISMIC DISASTER PREDICTION METHOD BASED ON THE COMPREHENSIVE FUZZY EVALUATION

2.1. Factor Set

According to the existing research results and characteristics of urban rail transit bridge, in this paper, introducing the philosophy of Work Breakdown Structure (WBS) altogether eight factors are chosen to evaluate the seismic performance of the urban rail transit bridge, including the building year, seismic fortification intensity, soil site category, failure extent of ground soil, superstructure type of bridge, constructional measures, heights of the piers and abutments, and the bridge spans. The foundation type has significant effect on the seismic disaster of bridges. As the foundation of the existing urban rail transit bridges in China are mainly pile foundation, this factor is not taken into consideration.

(1) The building year. In this paper, the building year is divided into three periods according to the critical development of the seismic design code in China: the years before 1987, the years between 1987 to 2006, and the years after 2006.

(2) The seismic fortification intensity. It has a significant and direct impact on the seismic disaster of bridges. The seismic fortification intensity of 7 to 10 is considered in this paper.

(3) Site category. In an earthquake, the seismic energy is transmitted from the foundation to the piers and superstructure of bridges. So site category has a direct effect on the seismic force imposed on the structure. According to GB50011-2006, site category was divided into 4 types: site I, site II, site III, and site IV.

(4) Failure extent of ground soil. Liquefaction of the ground soils always leads to a series of disaster. Appendix B of GB50011-2006 can be used to determine failure extent of ground soil. The failure extent of ground soil is described as without damage, minor damage, strong damage.

(5) Superstructure type of bridge. The superstructure type of the existing girder bridges in urban rail transit line are mainly simple supported beam and continuous beam.

(6) Constructional measures. It mainly contains bridge restrainers, energy dissipation supporters, etc. According to the actual conditions, it can be divided into three conditions, namely without construction, with but destroyed or unreasonable construction, and with reasonable construction.
(7) Heights of the piers and abutments. Generally, it can be classified into three ranges, namely less than 5m, between 5m to 10m, and greater than 10m.
(8) The bridge spans. The amount can be classified into two categories considering the bridge spans less or not more than 3 spans.
In summary, the factors set could be expressed as **U** (factor class)=｛the building year, earthquake intensity, site category, failure extent of ground soil, superstructure of bridge, constructional measures, heights of the piers and abutments , the bridge spans｝.

2.1. Evaluation Set

Under the designated earthquake, the bridge may be undamaged, slightly damaged, moderately damaged, significantly damaged, or collapsed. So the evaluation set $\boldsymbol{V}$ of the seismic disaster of bridges) is expressed as $\boldsymbol{V}=\{v_1, v_2, v_3, v_4, v_5\}$.

2.2. The Fuzzy Membership Degree *R*

Referring to the statistical analysis (Wu Xin, Ni Yongjun and Wu Hao, 2010), the fuzzy membership degree $\boldsymbol{R_i}$ could be determined as Table 1:

2.3. The Weight Values of The Influential Factors

Each influential factor has an independent effect on the target. It means that the different influential factor has a correspondent weight value. Suppose a_i is the weight value of a certain influential factor, So the weight set is expressed as $\boldsymbol{A}=\{a_1, a_2, \ldots, a_8\}$, and in which $a_i = \frac{\omega_i}{\sum_{i=1}^{8}\omega_i}$, $a_i \geq 0$, and $\sum_{i=1}^{8} a_i = 1$, and $\boldsymbol{i}$ is the reference value of a certain influencing factor. The quantified value for the influential factors was proposed by Wu Xin, Ni Yongjun and Wu Hao as Table 1.

2.4. Comprehensive Fuzzy Evaluation

$\boldsymbol{B}$ is the fuzzy subset of $\boldsymbol{V}$, and $B = A \circ R$ ($\circ$ is the fuzzy operator. In this paper, it means weighted average.). The final evaluation result can be obtained according to the principal of maximum membership degree.

Table 1. Influential factors and their quantification

Influential factors		reference value □*i*	evaluation set $\{v_1, v_2, v_3, v_4, v_5\}$
Building year	before 1987	1.1	(0.30, 0.40, 0.20, 0.10, 0.00）
	1987 to 2006	1	(0.15, 0.25, 0.30, 0.20, 0.10）
	after 2006	0.9	(0.55, 0.35, 0.10, 0.00, 0.00)
Seismic fortification intensity	7	1	(0.45, 0.30, 0.15, 0.10, 0.00)
	8	1.1	(0.15, 0.25, 0.30, 0.20, 0.10)
	9	1.2	(0.00, 0.10, 0.30, 0.40, 0.20)
	10	1.5	(0.00, 0.00, 0.30, 0.40, 0.30)
Soil site category	Ⅰ	0.8	(0.50, 0.40, 0.10, 0.00, 0.00)
	Ⅱ、Ⅲ	1	(0.30, 0.35, 0.15, 0.10, 0.10)
	Ⅳ	1.2	(0.10, 0.15, 0.30, 0.25, 0.20)
Failure extent of ground soil	Without damage	1	(0.30, 0.35, 0.25, 0.10, 0.00)
	Minor damage	1.5	(0.00,0.10, 0.20, 0.35, 0.35)
	Strong damage	1.8	(0.00,0.00, 0.10, 0.40, 0.50)
Superstructure type	Continuous beam	1	(0.15, 0.35, 0.25, 0.15, 0.10)
	Simple supported beam	1.4	(0.15, 0.15, 0.20, 0.25, 0.25)
Detailed construction	with reasonable construction	1	(0.35,0.40, 0.15, 0.10, 0.00)
	with but destroyed or unreasonable construction	1.2	(0.00,0.20, 0.35, 0.40, 0.05)
	without construction	1.4	(0.00,0.15, 0.20, 0.35, 0.30)
Height of pier or abutment	Less than 5m	1	(0.35,0.25, 0.20, 0.10, 0.10)
	5m-10m	1.1	(0.05, 0.30, 0.25, 0.20, 0.20)
	Greater than 10m	1.2	(0.00,0.15, 0.25, 0.30, 0.30)
Span amount	Less than 3 spans	1	(0.40,0.25, 0.15, 0.10, 0.10)
	More than 3 spans	1.2	(0.00,0.15, 0.25, 0.35, 0.25)

Table 2. Damage state of bridge and its seismic disaster level

Damage State	S1	S2	S3	S4	S5
Seismic disaster level	Without/slight damage	Minor damage	Medium damage	Heavy damage	Collapse

3. EXAMPLES

Based on the disaster investigation of bridges damaged in the earthquakes occurred in Wenchuan (Sichuan province, 2008, M=8.0), Chichi (Taiwan province, 1999, M=7.6), Lijiang (Yunnan province, 1996, M=7.0), Tangshan (Hebei province, 1976, M=7.8), Tonghai (Yunnan province, 1970, M=7.7), Haicheng (Liaoning province, 1975, M=7.3), altogether 123 reinforced concrete girder bridges with pile foundation were taken as samples. The actual seismic disaster(column B) and the prediction results from the empirical formula method(column C) and the comprehensive fuzzy evaluation(column A) are shown in Table 3.

Table 3. Seismic disaster results from investigation and prediction

Number	Influencing factors								Results		
	1	2	3	4	5	6	7	8	A	B	C
1	1.1	1.5	1.2	1.5	1.4	1.2	1	1.2	S4	S5	S5
2	1.1	1.5	1	1.5	1.4	1.2	1.2	1.2	S4	S5	S5
3	1.1	1.5	1	1.5	1.4	1.2	1.2	1	S4	S4	S4
4	1.1	1.5	1	1	1.4	1.2	1.2	1.2	S4	S4	S4
5	1.1	1.5	1.2	1	1.4	1.2	1.2	1.2	S4	S4	S4
6	1.1	1.5	1.2	1	1.4	1	1	1	S3	S3	S3
7	1.1	1.5	1.2	1	1.4	1	1	1	S3	S3	S3

Number	Influencing factors								Results		
	1	2	3	4	5	6	7	8	A	B	C
8	1.1	1.5	1.2	1	1.4	1	1	1	S3	S3	S3
9	1.1	1.5	1.2	1	1.4	1.2	1.2	1.2	S4	S4	S4
10	1.1	1.5	1	1	1.4	1	1.2	1	S3	S3	S3
11	1.1	1.5	1.2	1.5	1.4	1	1	1	S4	S4	S4
12	1.1	1.2	1.2	1.5	1.4	1.2	1	1.2	S4	S4	S4
13	1.1	1.2	1.2	1.8	1.4	1.2	1	1.2	S4	S5	S5
14	1.1	1.2	1.2	1.5	1.4	1.2	1.2	1.2	S4	S5	S5
15	1.1	1.2	1.2	1	1.4	1.2	1	1	S3	S3	S3
16	1.1	1.1	1.2	1.8	1.4	1.2	1	1	S4	S4	S4
17	1.1	1.1	1.2	1	1.4	1.2	1	1	S3	S3	S2
18	1.1	1.1	1.2	1	1.4	1.2	1	1	S3	S3	S2
19	1.1	1.1	1.2	1	1.4	1.2	1	1	S3	S3	S2
20	1.1	1.1	1.2	1	1.4	1	1.2	1.2	S3	S3	S3
21	1.1	1.1	1.2	1	1.4	1.2	1	1.2	S3	S3	S3
22	1.1	1.1	1	1	1.4	1	1	1.2	S2	S2	S2
23	1.1	1.1	1.2	1	1.4	1.2	1	1.2	S3	S3	S3
24	1.1	1.1	1.2	1.5	1.4	1.2	1	1.2	S4	S4	S4
25	1.1	1.1	1.2	1.5	1.4	1.2	1	1	S3	S4	S4
26	1.1	1.1	1.2	1.5	1.4	1.2	1	1.2	S4	S4	S4
27	1.1	1.1	1.2	1.5	1.4	1.2	1	1.2	S4	S4	S4
28	1.1	1.1	1.2	1	1.4	1.2	1	1.2	S3	S3	S3
29	1.1	1.1	1.2	1.5	1.4	1.2	1	1.2	S4	S4	S4
30	1.1	1.1	1.2	1.5	1.4	1.2	1	1.2	S4	S4	S4
31	1.1	1.1	1.2	1.5	1.4	1.2	1	1	S3	S3	S3
32	1.1	1.1	1.2	1	1.4	1.2	1	1	S3	S2	S2
33	1.1	1.1	1.2	1.5	1.4	1.2	1	1.2	S4	S4	S4
34	1.1	1.1	1.2	1	1.4	1.4	1	1	S3	S3	S3
35	1.1	1.1	1	1	1.4	1.4	1	1.2	S3	S3	S3
36	1.1	1.1	1.2	1	1.4	1.4	1	1	S3	S3	S3
37	1.1	1.1	1	1	1.4	1.4	1	1.2	S3	S3	S3
38	1.1	1.1	1.2	1	1.4	1.4	1	1.2	S3	S3	S3
39	1.1	1.1	1	1	1.4	1.2	1	1	S2	S2	S2
40	1.1	1.1	1	1	1.4	1	1	1.2	S2	S2	S2
41	1.1	1	1.2	1	1.4	1	1	1.2	S2	S2	S2
42	1.1	1	1	1	1.4	1	1	1.2	S2	S2	S2
43	1.1	1	1.2	1	1.4	1.2	1	1.2	S3	S3	S3
44	1.1	1	1.2	1	1.4	1.4	1	1.2	S3	S3	S3
45	1.1	1	1.2	1	1.4	1.2	1	1.2	S3	S3	S3
46	1.1	1	1	1	1.4	1	1	1.2	S2	S2	S2
47	1.1	1	1.2	1	1.4	1	1.1	1.2	S2	S2	S2
48	1.1	1	1	1	1.4	1.2	1.2	1.2	S3	S3	S3
49	1.1	1	1	1	1.4	1.2	1.2	1.2	S3	S3	S3
50	1.1	1	1.2	1	1.4	1	1.2	1.2	S3	S3	S3
51	1.1	1	1	1	1.4	1	1.1	1.2	S2	S2	S2
52	1.1	1	1	1	1.4	1	1	1.2	S2	S2	S2
53	1.1	1	1	1	1.4	1	1	1	S1	S2	S2
54	1.1	1	1	1	1.4	1	1.1	1.2	S2	S2	S2
55	1.1	1	1	1	1.4	1	1	1.2	S2	S2	S2
56	1.1	1	1	1	1.4	1.2	1.2	1.2	S3	S3	S3
57	1.1	1	1	1	1.4	1.2	1	1.2	S2	S2	S2
58	1.1	1	1	1	1.4	1.2	1	1.2	S2	S2	S2
59	1.1	1	1	1	1.4	1	1	1.2	S2	S2	S2
60	1.1	1	1.2	1	1.4	1.2	1	1.2	S3	S3	S3
61	1.1	1	1	1	1.4	1	1	1	S1	S1	S2
62	1.1	1	1	1	1.4	1	1	1	S1	S1	S2
63	1.1	1	1	1	1.4	1	1	1	S1	S1	S2
64	1.1	1.2	1	1.5	1.4	1.2	1.1	1.2	S4	S4	S4
65	1.1	1.2	1	1.5	1.4	1.2	1	1.2	S4	S4	S4
66	1.1	1.1	1	1.5	1	1.2	1	1	S2	S2	S2
67	1.1	1.1	1	1.8	1.4	1.2	1.1	1.2	S4	S4	S4

Number	Influencing factors								Results		
	1	2	3	4	5	6	7	8	A	B	C
68	1.1	1.1	1	1	1.4	1.2	1	1.2	S3	S2	S2
69	1.1	1	1	1	1.4	1.2	1	1.2	S2	S2	S2
70	1.1	1.1	1	1.5	1	1.4	1	1.2	S4	S3	S3
71	1.1	1	1	1.8	1	1.2	1.1	1.2	S4	S5	S3
72	1.1	1.1	1	1	1.4	1.2	1	1.2	S3	S2	S2
73	1.1	1.2	1	1.5	1	1.2	1	1.2	S4	S3	S3
74	1.1	1.2	1.2	1.5	1.4	1.2	1	1.2	S4	S3	S4
75	1.1	1.2	1	1.8	1.4	1.2	1	1.2	S4	S4	S4
76	1.1	1.2	1	1.8	1.4	1.2	1	1.2	S4	S4	S4
77	1.1	1	1	1	1.4	1.2	1	1.2	S2	S2	S2
78	1.1	1.1	1	1.5	1	1.2	1	1	S2	S2	S2
79	1.1	1.1	1	1.8	1	1.2	1	1	S4	S4	S2
80	1.1	1	1	1.5	1	1.2	1	1	S2	S2	S2
81	1.1	1.1	1	1.8	1	1.2	1	1.2	S4	S3	S3
82	1	1	1.2	1.5	1.4	1	1.2	1	S2	S5	S3
83	1	1	1.2	1.8	1.4	1	1	1.2	S4	S4	S4
84	1	1	1.2	1.5	1	1	1.1	1.2	S2	S3	S3
85	1.1	1	1	1	1	1.4	1.2	1.2	S2	S2	S2
86	1.1	1	1	1	1.4	1.4	1.2	1	S2	S3	S3
87	1.1	1	1	1	1.4	1.4	1	1.2	S2	S3	S3
88	1.1	1	1	1	1.4	1.2	1	1	S2	S4	S2
89	1.1	1	1	1	1.4	1.4	1	1	S2	S5	S2
90	1.1	1	1	1	1	1.2	1.2	1.2	S2	S4	S2
91	1.1	1	1	1	1.4	1.2	1.1	1.2	S2	S4	S2
92	1.1	1	1	1	1	1	1.2	1.2	S2	S3	S2
93	1	1	1	1	1.4	1	1.1	1.2	S2	S2	S2
94	1	1	1	1	1.4	1	1	1.2	S2	S2	S2
95	1	1	1	1	1.4	1	1.1	1.2	S2	S2	S2
96	1	1	1	1	1.4	1	1.1	1.2	S2	S2	S2
97	1	1	1	1	1.4	1	1	1.2	S2	S2	S2
98	1	1	1	1	1.4	1	1	1.2	S2	S2	S2
99	1	1	1	1	1.4	1	1	1.2	S2	S2	S2
100	1	1	1	1	1.4	1	1	1.2	S2	S2	S2
101	1	1	1	1	1.4	1.2	1.2	1.2	S2	S1	S2
102	1	1.1	1	1	1.4	1.2	1.2	1.2	S3	S1	S3
103	1.1	1	1	1	1	1	1	1.2	S2	S1	S1
104	1	1	1	1	1.4	1	1	1	S1	S1	S1
105	1	1	1	1	1.4	1	1	1	S1	S1	S1
106	1.1	1	1	1	1	1.4	1.2	1.2	S2	S2	S2
107	1.1	1	1	1	1.4	1	1	1.2	S2	S2	S2
108	1.1	1.2	1.2	1	1.4	1	1.2	1.2	S3	S3	S3
109	1.1	1.2	1.2	1	1.4	1	1.2	1.2	S3	S3	S3
110	1.1	1.2	1.2	1	1	1	1.2	1.2	S3	S2	S2
111	1.1	1	1	1	1.4	1	1	1	S1	S2	S2
112	1.1	1	1	1	1.4	1.2	1	1	S2	S3	S2
113	1.1	1	1	1	1	1.2	1.2	1.2	S2	S2	S2
114	1.1	1	1	1	1.4	1.2	1	1	S2	S2	S2
115	1.1	1	1	1	1.4	1.4	1	1	S2	S2	S2
116	1.1	1	1	1	1.4	1	1.2	1.2	S2	S2	S2
117	1.1	1	1	1	1.4	1	1.2	1.2	S2	S2	S2
118	1.1	1	1	1	1.4	1	1.1	1.2	S2	S2	S2
119	1.1	1	1	1	1.4	1	1	1.2	S2	S2	S2
120	1.1	1	1	1	1.4	1	1	1.2	S2	S1	S2
121	1.1	1	1	1	1.4	1	1	1.2	S2	S2	S2
122	1.1	1	1	1	1.4	1	1	1.2	S2	S1	S2
123	1.1	1	1	1	1.4	1	1	1.2	S2	S2	S2

In table 3, the factors column of 1 to 8 represent the building year, earthquake intensity, site category, failure extent of ground soil, superstructure of bridge, constructional measures, heights of the piers and abutments and the bridge spans, respectively. And S1 to S5 represent the earthquake damage level.

In summary, the prediction results of 31 bridges are inconsistent with the actual seismic damage, and the results of 19 bridges are inconsistent with the results based on empirical equation. The difference of predicted result may be as follows:
(1) The weight values of this method are based on the traditional values of seismic disaster influence coefficient proposed by Zhu Meizhen. In addition, it is inaccurate to predict seismic disaster with the statistical analysis method.
(2) The information about the seismic damage of bridges was incomplete. As the description of the statistical data was not clear and detailed, the missing data could only be estimated by the corresponding bridges. The lack of the damage information will lead to the deviation of the predicted results.

4. CONCLUSION

(1) The fuzzy subsets for different influential factors respecting on the seismic damage of bridges are constructed using the fuzzy theory. Subsequently, the seismic disaster of bridges could be predicted according to the principle of the maximum degree of membership. The predicting results were compared with the real seismic damage of bridges under the different earthquakes. It was convinced that the proposed method in this paper was convenient and effective. This comprehensive method based on fuzzy evaluation was realized through the calculating program based on Fortran language. It could be planted in the existing GIS platform for predicting the seismic damage of girder bridges in urban rail transit line.

(2) To improve the accuracy of the evaluation, the detailed information of seismic damage of bridges need to be investigated and accumulated. Based on the statistical analysis, the weight values for the different influential factors could be determined exactly, then the membership degree of seismic damage of bridges could be described more properly.

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