研　究　速　報
UDC 550.34.04 : 621.644 : 681.3 : 164

Fuzzy Inference for Earthquake Damage Estimation in Buried Pipeline Networks

ファジィ推論を用いた埋設管路網の地震被害推定

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1. INTRODUCTION

Nowadays, in large cities, organization of social and economic life is increasingly dependent on telecommunication and lifeline networks. Hence, if an earthquake occurs, in addition to immediate damage and casualties, the disruption of lifelines can also have a great impact. In that situation, earthquake damage assessment for lifeline networks can be used to start repair work as quickly and effectively as possible where it is most needed. For gas networks, there is an additional problem due to the fact that secondary damage like leaks or explosions can occur. In that case, quick damage assessment immediately after the earthquake is necessary to decide whether or not an emergency shut-off of the gas supply is necessary. The present system assesses earthquake damage in the supply area using observed ground motion characteristics and soil conditions.

2. ORGANIZATION OF THE STUDIED NETWORK

The considered lifeline network comprises pipelines with minimum shut-off zones that we can call "control blocks" (or "blocks" for short). Such a block contains typically several main pipelines and several hundred thousands customers. This study concentrates on damage assessment for one block.

As soil conditions are known to be a major factor for earthquake damage estimation, each block is divided in zones by considering three soil types (see Figure 1) and each zone is divided into square sub-zones (with sides of 500m).

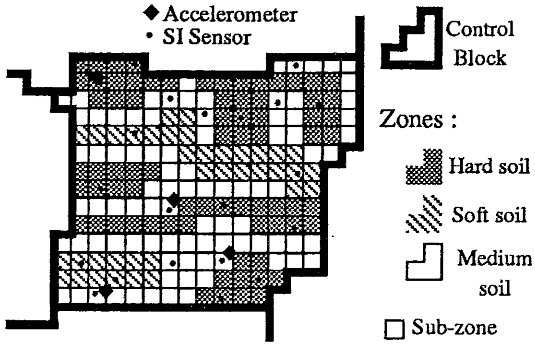

Figure 1　Layout of one control block

Several tens of SI (Spectrum Intensity) sensors (Katayama et al., 1988) are laid in each control block, as well as a few accelerometers. Their measurements are transmitted to the control room by a multiple radio telemeter system. The proposed system uses this information to estimate damage and motivate the shut-off decision.

Two parameters are chosen to represent the state of the block: damage to buildings (customers' houses) R_b, which is defined as the equivalent percentage of collapsed houses, and damage to pipes (buried pipelines of the network) R_p, which is defined as the number of leaks per km of pipeline.

3. OUTLINE OF THE MODEL

The general idea of the proposed system is to assess damage in each sub-zone, where soil conditions are reasonably homogeneous, and then take the weighted

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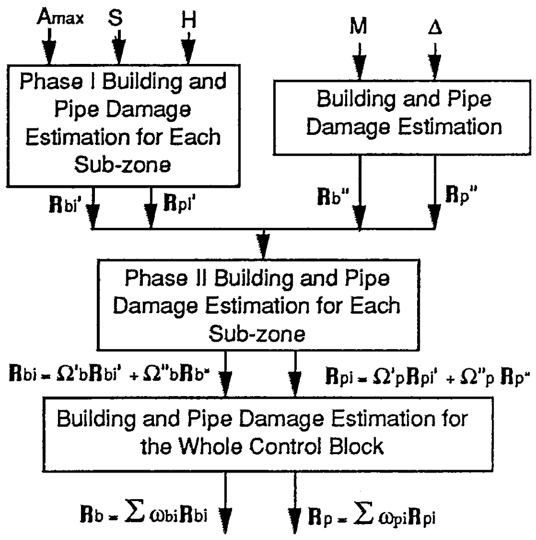

Figure 2 Flowchart of the study

average of the estimates in all sub-zones as the global damage estimate for the whole control block. As shown on Figure 2, damage assessment in each sub-zone is made in two phases. First, one estimate is calculated using observed ground motion characteristics and soil conditions and then this value is corrected with another estimate obtained from the magnitude and epicentral distance.

To assess damage to buildings in phase I, peak ground acceleration A_{max}, which has a predominant influence for buildings of short period, and SI, which is a good index for structures of medium period, are taken into account (Ando et al., 1990). For damage to pipes, soil liquefaction is known to be an important factor and thence the thickness of the liquefiable sandy layer H_s is used in addition to the intensity of ground shaking represented by SI. On the other hand, another damage estimate is calculated using the earthquake magnitude M and the epicentral distance Δ. As this estimation method is not very precise, it is not applied to each sub-zone individually, and the epicentral distance of the center of the control block is used for all sub-zones.

Phase II damage estimation of each sub-zone is performed by weighted summation of the estimates obtained by the two methods. The damage estimates for the whole control block are then obtained by taking the weighted average. The weights ω_{bi} and ω_{pi} in the summation represent the relative importance of each sub-zone.

4. USE OF FUZZY INFERENCE

As the definition of the damage indices R_b and R_p are not very precise and because their relations with the input parameters (SI, A_{max}, H_s, M, Δ) are not well known, fuzzy reasoning is used to express mathematically the imprecise knowledge that was acquired from experience.

The idea of fuzzy inference (Mizumoto, 1988) is to express the modelling of the system in simple natural-language-like form. Instead of usual equations, fuzzy inference rules are used. To construct a model for fuzzy reasoning, we first divide the range of each variable into linguistic values, for example from Small to Large (see Figure 3). Each of these linguistic values is represented by a fuzzy set and its membership function $\mu(X)$, which can take values between 0 and 1. For example in the case of the fuzzy set "Small" and the variable SI, for each value of SI, $\mu(SI)$ represents the extent to which this value can be said to be small. As the fuzzy sets used in the 3 different fuzzy inferences have a similar form, they have been represented simultaneously in Figure 3: for each inference one should read the corresponding graduated axis.

In addition to the fuzzy sets, we also define inference rules as shown in Tables 1 to 3. For example, Table 1 reads:

IF SI is Small and A_{max} is Small THEN R_b is Zero
IF SI is Small Med. and A_{max} is Small THEN R_b is Small
... ...

Once such a model is constructed, it is mathematically combined with observed values of the variables to give the predicted damage, which will be a fuzzy set.

The general form of a fuzzy inference rule is:

IF x_1 is $A_{i,1}$ AND x_2 is $A_{i,2}$ AND……AND x_n is $A_{i,n}$ THEN y is B_i i = 1……m (1)

where n is the number of conditions, m is the number of rules, $A_{i,j}$ are fuzzy subsets (such as Small, Medium…) representing the conditions of the rules and B_i are the fuzzy subsets representing the consequences of the rules.

Table 1 Fuzzy inference rules for building damage estimation using SI and A_{max}

		IF SI is ...				
		Small	Small Med.	Med.	Med. Large	Large
and	Small	Zero	Small	Small Med.	Med.	Med. Large
A_{max}	Small Med.	Zero	Small	Small Med.	Med.	Med. Large
is	Med.	Small	Small Med.	Med.	Med. Large	Large
...	Med. Large	Small	Small Med.	Med.	Med. Large	Large
	Large	Small Med.	Med.	Med. Large	Large	Very Large

Table 2 Fuzzy inference rules for pipe damage estimation using SI and H_s

		IF SI is ...				
		Small	Small Med.	Med.	Med. Large	Large
and	Small	Zero	Zero	Zero	Small	Small Med.
H_s	Small Med.	Zero	Zero	Small	Small Med.	Med.
is	Med.	Zero	Small	Small Med.	Med.	Med. Large
...	Med. Large	Small	Small Med.	Med.	Med. Large	Large
	Large	Small Med.	Med.	Med. Large	Large	Very Large

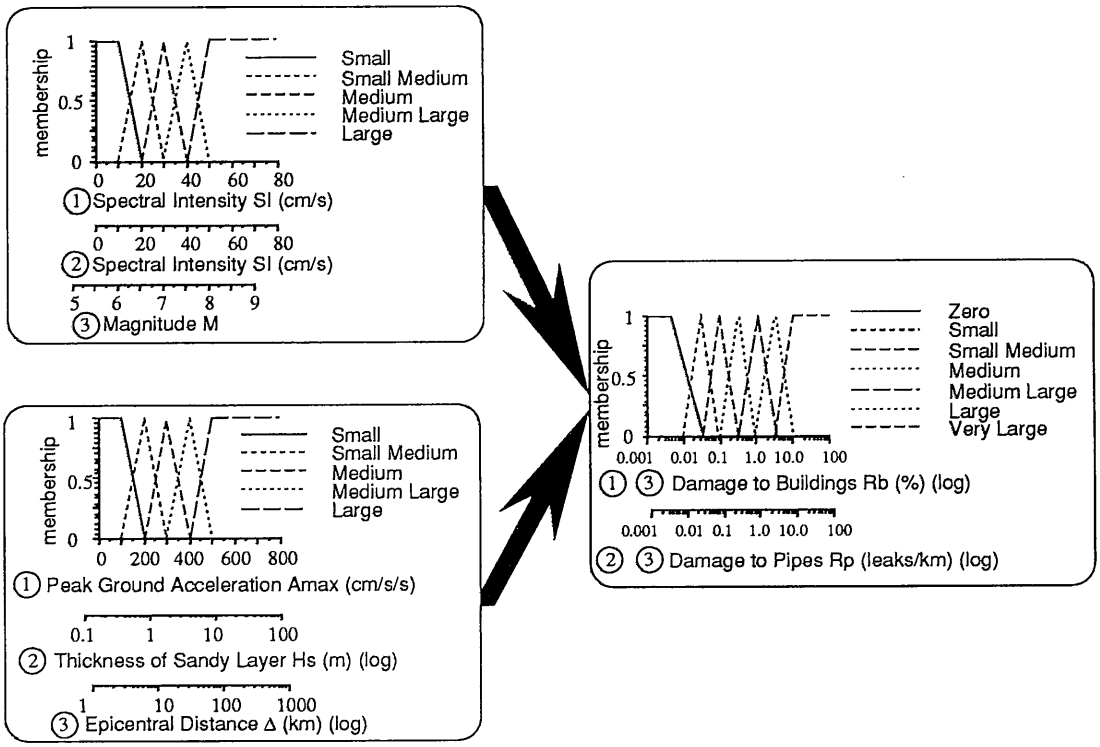

Figure 3 Fuzzy sets used for fuzzy inference: three fuzzy inferences are performed and the variables used in each one of them are indicated by the symbols ①, ②, ③ respectively.

This type of set of rules being adopted as a model, values for x_1, $x_2 \cdots\cdots x_n$ are measured and represented by the fuzzy subsets A_1', $A_2' \cdots\cdots A_n'$ (for example "around 20 cm/s", "approximately 100 cm/s²" etc ……).

The result of fuzzy inference is the predicted value for y, which is represented by the fuzzy set B′ defined by the membership function $\mu_B'(y)$ (Mamdani method):

$$\mu_B'(y) = \bigvee_i M_{i} \vee \mu_{Bi}(y) \qquad (2)$$

where

Table 4 Damage prediction for some past earthquakes

Data Set Number	Earthquake Event, Place of Observation	SI (cm/s)	A_{max} (cm/s^2)	M	Δ (km)	Observed Building Damage (%)	Predicted Damage by SI and A_{max}(%)	Predicted Damage by M and Δ (%)
1	1964.6.16 Niigata Earthquake, Niigata	32.0	159.0	7.5	54	Heavy Damage due to liquefaction	0.04	0.38
2	1966.4.5 Matsushiro Earthquake, Hoshina	26.7	601.9	5.1	4.4	0.19	0.21	0.32
3	1966.4.17 Matsushiro Earthquake, Hoshina	10.1	331.2	5.0	3.6	0.0	0.03	0.32
4	1968.5.16 Tokachi-oki Earthquake, Aomori	39.7	252.0	7.9	237	0.96	0.18	0.24
5	1968.5.16 Tokachi-oki Earthquake, Hachinohe	37.6	224.4	7.9	176	5.16	0.10	0.24
6	1978.6.12 Miyagi-ken-oki Earthquake, Shiogama	59.1	316.7	7.4	113	0.43	2.70	0.07
7	1978.6.12 Miyagi-ken-oki Earthquake, Sendai	48.8	258.1	7.4	130	0.4	0.51	0.07
8	1983.5.26 Nihonkai-chubu Earthquake, Akita	34.0	205.2	7.7	107	0.2	0.06	0.16
9	1987.12.17 Chiba-ken-toho-oki Earthquake, Chiba	15.2	322.3	6.7	55	No damage	0.03	0.01
10	1987.12.17 Chiba-ken-toho-oki Earthquake, Kisarazu	35.0	384.5	6.7	52	Almost no damage. Displaced sea walls	0.18	0.01
11	1989.7.9 Izu-hanto-toho-oki-gunpatsu Earthquake, Ito	41.8	233.4	5.5	6.2	No damage to buildings. Damage to gas pipes in 10 places	0.21	0.32
12	1989.10.17 Loma Prieta Earthquake, Corralitos	59.0	617.7	7.1	5	Heavy damage	20.4	6.5
13	1989.10.17 Loma Prieta Earthquake, Watsonville	55.1	352.3	7.1	11	Heavy damage	1.78	4.9
14	1989.10.17 Loma Prieta Earthquake, Menlo Park VA	26.9	288.0	7.1	54	No damage	0.05	0.17

Table 3 Fuzzy inference rules for damage estimation using M and Δ

		IF M is ...				
		Small	Small Med.	Med.	Med. Large	Large
and Δ is ...	Small	Med.	Med. Large	Large	Very Large	Very Large
	Small Med.	Small Med.	Med.	Med. Large	Large	Very Large
	Med.	Small	Small Med.	Med.	Med. Large	Large
	Med. Large	Zero	Small	Small Med.	Med.	Med. Large
	Large	Zero	Zero	Small	Small Med.	Med.

$$M_I = \bigwedge_j M_{I,j} \text{ and } M_{I,j} = \bigvee_{x_j} \mu_{A'j}(x_j) \wedge \mu_{AI,j}(x_j) \quad (3)$$

In the above equations usual notations ∨ for maximum and ∧ for minimum are used.

In our case, n=2 (2 conditions), m=25 (25 rules). x_1=SI (respectively SI, M), $x_2=A_{max}$ (resp. H_s, D) $y=R_b$ (resp. R_p, R_b or R_p).

Examples of application of the proposed method are shown in the next section.

5. RESULTS AND ASSESSMENT OF THE METHOD

The present method has been applied to past earthquakes in order to test its validity. Because of the lack of precise data concerning earthquake damage distribution, only a few events have been taken into account. Table 4 shows the results obtained by the SI-A_{max} method and the M-Δ method. The columns corresponding to predicted damage contain the centroid of the obtained fuzzy damage indices. Results are not always perfect, but most of the time

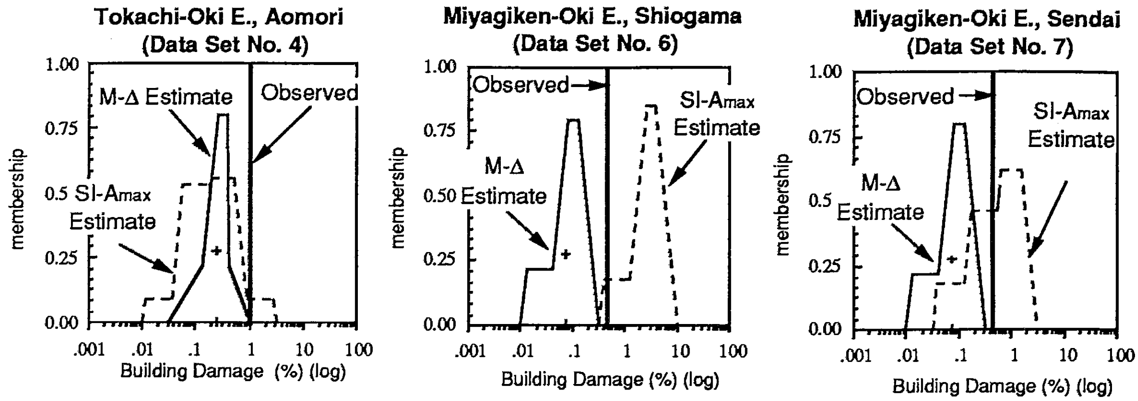

Figure 4 Predicted fuzzy damage for few data sets of Table 4

satisfactory. Table 4 shows only the centroid of the obtained results, but by looking at the full results (examples are given in Figure 4) one can see that the observed value is almost always within the range where the membership function of the predicted value is non zero (except for data sets No. 1, 5 and 11).

The estimate using SI and A_{max} takes soil conditions implicitly into account because it uses ground motion characteristics actually observed at the site and thence should be better than the M-Δ estimate, which does not depend at all on soil conditions. Nevertheless, the results show that it is not always so. As a matter of fact, in these examples only one value of SI and A_{max} is known for an entire city. The damage estimate we obtain by using these values might be satisfactory in the immediate surroundings of the measurement point, but not necessarily for a larger area. In that situation the M-Δ estimate, which is rougher but more general, is used to mitigate the effects of the particularities of the soil conditions at the measurement point.

A linear combination of these two estimates is used as the phase II damage estimate in the sub-zone:

$$R_{bi}=\Omega_b' R_{bi}'+\Omega_b'' R_b'' \ ; \ R_{pi}=\Omega_p' R_{pi}'+\Omega_p'' R_p'' \quad (4)$$

The weights Ω_b', Ω_b'' Ω_p' and Ω_p'' are not easy to determine for optimum damage estimation. They depend on the number of measurement points and the precision of soil zoning. In the case of the present examples where measurement points are scarce, the M-Δ method should be given a big importance whereas in the case of the gas supply area, where we can hope to have a dense monitoring system, its weight should be considerably reduced.

6. FINAL DAMAGE ESTIMATION AND FURTHER DEVELOPMENT OF THE SYSTEM

Once damage assessment has been made in each sub-zone by the method described in Sections 4 and 5, yielding the damage indices R_{bi} and R_{pi}, the global damage estimates R_b and R_p for the control block are calculated by weighted average:

$$R_b=\sum_i \omega_{bi} R_{bi} \ ; \ R_p=\sum_i \omega_{pi} R_{pi} \quad (5)$$

The weights ω_{bi} and ω_{pi} represent the relative importance of sub-zone i, that is to say, the relative number of buildings in the sub-zone for ω_{bi} and the relative pipe length in the sub-zone for ω_{pi}.

The summation of the fuzzy sets is made by using arithmetics of fuzzy numbers (see Kaufmann and Gupta, 1985).

The damage estimation procedure described here is used in the case of a gas supply network as a part of a computer system aimed at decision assisting in case of emergency. The system uses the values of the parameters observed in the supply area in order to estimate damage and displays the results as maps in which the centroid of the obtained fuzzy damage indices are plotted.

Once the procedure described in the flowchart of Figure 2 is performed, the damage state of the considered control block is known through the two fuzzy sets R_b and R_p. Fuzzy decision analysis with two variables is then applied to decide whether it is preferable to cut or maintain the gas supply in the block. The results of the decision analysis are also displayed graphically in order to guide the decision maker in his choice.

7. CONCLUSION

In a large city, lifelines are especially vulnerable to an earthquake. In that situation, earthquake damage estimation can be useful to start efficient repair work as soon as possible. In the case of a gas supply network, quick damage assessment is even more important because it is necessary to shut off the supply in the relevant areas in order to prevent leaks or explosions.

The system proposed in this paper estimates earthquake damage in each sub-zone of a buried pipeline network by fuzzy reasoning from observed ground motion characteristics and soil conditions. The obtained estimate is then corrected considering the earthquake magnitude and the epicentral distance. Results of example calculations are shown and compared to values measured during past earthquakes. A global damage estimate for each block of the network is obtained by taking the weighted average of the estimates in all sub-zones of the block.

(Manuscript received, October 1, 1991)

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