On-line damage estimation for lifeline systems during earthquakes

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ABSTRACT: Large cities with extensive lifeline networks are especially vulnerable to earthquakes. In the case of gas networks, it is necessary to shut off the supply to heavily damaged areas to prevent possible secondary disasters. The system proposed in this study is meant to provide assistance for emergency shut-off decision in a given area of a gas network. Earthquake damage is estimated using measured ground motion characteristics and soil conditions. Fuzzy reasoning is used to model empirical knowledge of the relation between input data and output damage indices. The results are displayed by computer in a comprehensive and easy-to-use way.

1 INTRODUCTION

When an earthquake occurs in a large city, the disruption of lifelines may have a big impact on social and economic life. On-line earthquake damage estimation can be used to start repair works as smoothly as possible and to increase the speed of recovery of the network. In the case of gas networks, earthquake damage estimation is not easy because pipelines are buried, which makes field survey difficult. However it is crucial to assess damage rapidly because leaks may cause explosions and therefore the gas supply should be interrupted if the damage is extensive.

In this study, earthquake damage is estimated on-line by computer and the result will be used to assist the decision.

2 OUTLINE OF THE SYSTEM

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

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

Several tens of SI (Spectrum Intensity) sensors as well as a few accelerometers are laid in each control block. Their measurements are transmitted to the control room by a multiple radio telemeter system. The proposed system uses this information to estimate damage.

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
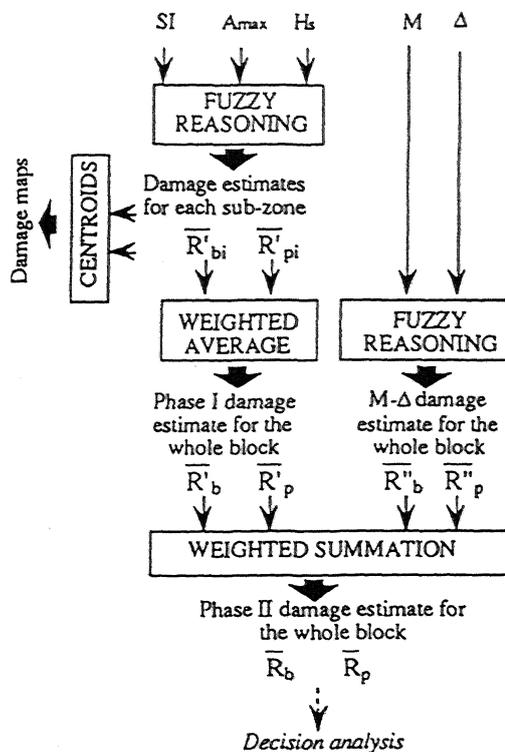

Figure 1. Flowchart of the study

collapsed houses, and damage to pipes (buried pipe lines of the network) R_p, which is defined as the number of leaks per kilometer of pipeline.

Damage estimation is performed first at a local level and then at the level of the whole block (see Figure 1). In each sub-zone, where soil conditions are relatively

homogeneous, observed ground motion characteristics (SI and A_{max}) are used to assess building damage (Ando et al. 1990) while the intensity of ground shaking (SI) and the thickness of the liquefiable sandy soil layer (H_s) are used to predict pipe damage. This information is then converted into the damage state of the whole block (phase I damage estimation) by weighted average. The weight of each sub-zone represents its relative "importance". If the number of points where SI and A_{max} are observed is small, the obtained phase I damage estimate will be very much biased by the soil conditions at these few points. To remedy this effect, a more primitive but more general damage ratio, calculated by using the magnitude of the earthquake and the epicentral distance, is used to correct the phase I damage estimate.

The proposed method has been used to develop a computer system for damage estimation during earthquakes. The outputs of this system are maps showing the damage state in all sub-zones and global damage indices for each control block which can be used in decision analysis.

3 USE OF FUZZY SET THEORY

3.1 Fuzzy reasoning

As the definitions 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 reasoning (Mizumoto 1988) is to express the modelling of the system in a simple natural-language-like form. Instead of ordinary functional relationships, fuzzy inference rules are used. To construct a model for fuzzy reasoning, the range of each variable is divided into k linguistic values, for example from "Small" to "Large" (see Figure 2 for variable SI). 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, $\mu(SI)$ represents, for a given value of SI, the extent to which this value can be said to be "small" (Dubois and Prade 1980). For each of the variables, the shape of the membership functions has been chosen to be very simple i.e., triangular or trapezoidal as shown in Figure 2. Table 1 shows the values for which the membership functions cross the axis $\mu = 0$ for the different variables.
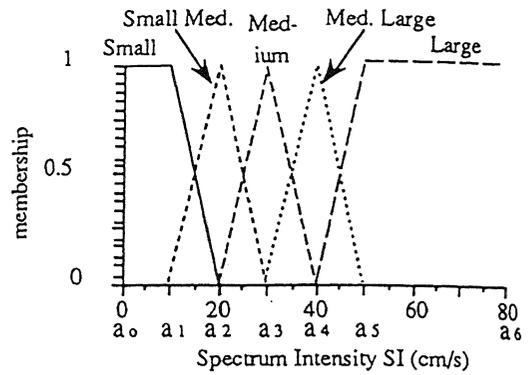

Figure 2. Basic membership functions for variable SI.

In addition to the fuzzy sets, inference rules are also defined. The general form of a fuzzy inference rule is:

IF x_1 is $\overline{A}_{i,1}$ and x_2 is $\overline{A}_{i,2}$ and ... and x_n is $\overline{A}_{i,n}$

THEN y is $\overline{B}_i$ i = 1 ... m   (1)

where n is the number of conditions, m is the number of rules, $\overline{A}_{i,j}$ are fuzzy subsets (such as Small, Medium, etc.) representing the conditions of the rules, and $\overline{B}_i$ are the fuzzy subsets representing the consequences of the rules.

In this study, n = 2 (2 conditions), m = 25 (25 rules). x_1 = SI, x_2 = A_{max} and y = R_b for the first set of rules (Table 2); x_1 = SI , x_2 = H_s and y = R_p for the second set of rules (Table 3); x_1 = M , x_2 = Δ and y = R_b or R_p for the third and fourth set of rules (Table 4).

This type of set of rules being adopted as a model, values for x_1, x_2, ..., x_n are measured and represented by the fuzzy subsets $\overline{A}_1'$, $\overline{A}_2'$, ..., $\overline{A}_n'$ (for example, "around 20 cm/s", "approximately 100 cm/s^2", etc.).

The result of fuzzy inference is the predicted value for y (damage in this study), which is represented by the fuzzy set $\overline{B}'$ defined by the membership function $\mu_{\overline{B}'}(y)$ (Mamdani method):

$$\mu_{\overline{B}'}(y) = \underset{i}{Max}\ min\left(M_i\ ,\ \mu_{\overline{B}_i}(y)\right) \quad (2)$$

where

$$M_i = \underset{j}{Min}\ M_{i,j} \quad (3)$$

Table 1. Parameters of the basic membership functions for each variable.

variable	unit	k	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
SI	cm/s	5	0	10	20	30	40	50	80	-	-
A_{max}	cm/s^2	5	0	100	200	300	400	500	800	-	-
Hs	m (log)	5	0.1	0.316	1	3.16	10	36.1	100	-	-
M	-	5	5	6	6.5	7	7.5	8	9	-	-
Δ	km (log)	5	1	10	17.8	31.6	52.6	100	1000	-	-
Rb	% (log)	7	0.001	0.00316	0.01	0.0316	0.1	0.316	1.0	3.16	100
Rp	leaks/km (log)	7	0.001	0.00316	0.01	0.0316	0.1	0.316	1.0	3.16	100

and $\quad M_{i,j} = \underset{x_j}{\text{Max}} \min\left(\mu_{\overline{A}_j}(x_j), \mu_{\overline{A}_{i,j}}(x_j)\right)$ (4)

The fuzzy reasoning models proposed here have been tested on past earthquakes for which damage survey was available (Cret et al. 1991). Although the amount of available data is small, the results were generally satisfactory.

3.2 Averaging of fuzzy sets

Fuzzy reasoning, as described in the previous section, is used to estimate damage in each sub-zone considering ground motion characteristics and soil conditions, yielding the damage indices $\overline{R}_{bi}'$ and $\overline{R}_{pi}'$.

The global phase I damage estimates $\overline{R}_b'$ and $\overline{R}_p'$ for the control block are calculated by taking the weighted averages:

$$\overline{R}_b' = \sum_i \omega_{bi} \overline{R}_{bi}' \qquad \overline{R}_p' = \sum_i \omega_{pi} \overline{R}_{pi}' \quad (5)$$

The weights ω_{bi} and ω_{pi} represent the relative importance of sub-zone i, that is, 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 (Kaufmann and Gupta 1985). If $\overline{A}$ and $\overline{B}$ are two fuzzy numbers and α and β are two constants then the fuzzy set $\alpha\overline{A}+\beta\overline{B}$ is defined by:

$$\mu_{\alpha\overline{A}+\beta\overline{B}}(z) = \underset{(x,y) \mid \alpha x+\beta y = z}{\text{Max}} \min\left(\mu_{\overline{A}}(x), \mu_{\overline{B}}(y)\right) \quad (6)$$

The obtained phase I estimate is then corrected by linear combination with the M-Δ estimate to obtain the phase II damage estimate for the considered block :

$$\overline{R}_b = \Omega_b' \overline{R}_b' + \Omega_b'' \overline{R}_b'' \;\; ; \;\; \overline{R}_p = \Omega_p' \overline{R}_p' + \Omega_p'' \overline{R}_p'' \quad (7)$$

The weights Ω_b', Ω_b'' Ω_p' and Ω_p'' are not easy to determine for optimum damage estimation. The larger the number of measurement points and the better the precision of soil zoning, the smaller should Ω_b'' and Ω_p'' be. The values $\Omega_b' = \Omega_p' = 0.66$ and $\Omega_b'' = \Omega_p'' = 0.33$ have been chosen for the application in Section 4.

4 APPLICATION TO A REAL CASE

The damage estimation procedure described above is used in the case of a gas supply network as part of a computer system aimed at assisting decision making in an 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.

As an example, the system was tested for the Chiba-ken Toho Oki earthquake (December 17th 1987, JMA

Table 2. Fuzzy inference rules for building damage estimation using SI and A_{max}.

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

Table 3. Fuzzy inference rules for pipe damage estimation using SI and H_S.

		IF SI is ...				
		Small	Small Med.	Med-ium	Med. Large	Large
and	Small	Zero	Zero	Zero	Small	Small Med.
H_S	Small Med.	Zero	Zero	Small	Small Med.	Med.
is	Med-ium	Zero	Small	Small Med.	Med-ium	Med. Large
...	Med. Large	Small	Small Med.	Med.	Med. Large	Large
	Large	Small Med.	Med.	Med. Large	Large	Very Large

Table 4. Fuzzy inference rules for building and pipe damage estimation using M and Δ.

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

magnitude 6.7) in Tokyo area. Figures 3 and 4 show recorded SI and A_{max} values during the quake: maximum values in the block near the epicenter were 34.6 cm/s for SI and 549 cm/s^2 for A_{max}. Figure 5 shows predicted (phase I) building damage: maximum values are between 0.1 and 1 %, which means that between 1 and 10 houses out of 1000 collapsed, or equivalently that between 1 and 10 houses out of 100 were slightly damaged in the most affected area. These figures are rather low but still far from negligible, which is consistent with what was observed in reality.

Figure 6 shows phase I and phase II damage estimates for Block B_o in Figure 5. The obtained fuzzy
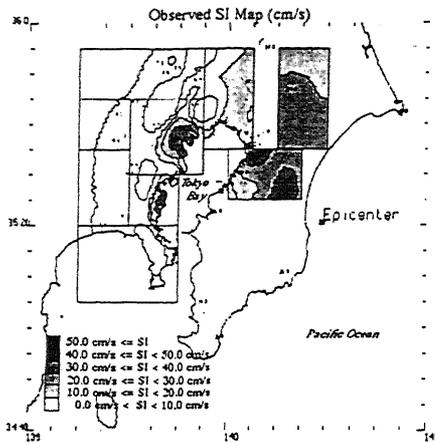
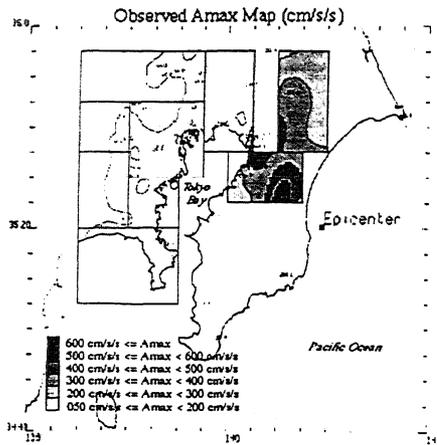Figure 3. Observed SI values in Tokyo area during Chiba-ken Toho Oki earthquake of 1987.

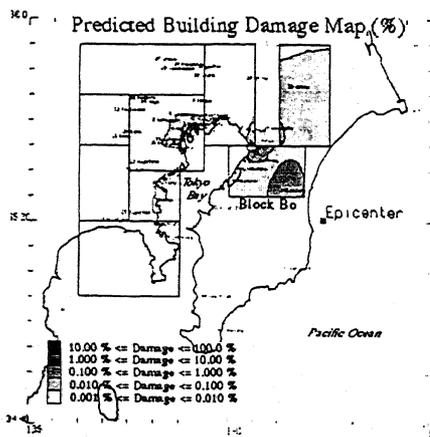Figure 4. Observed A_{max} values in Tokyo area during Chiba-ken Toho Oki earthquake of 1987.

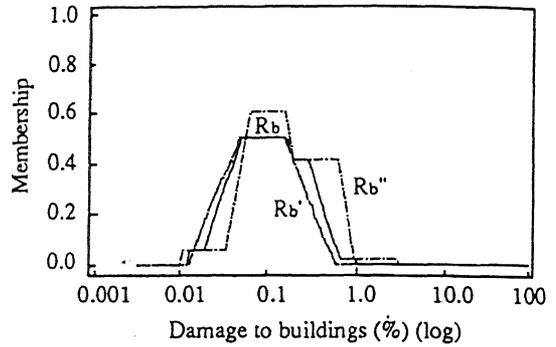Figure 5. Predicted building damage during Chiba-ken Toho Oki earthquake of 1987

Figure 6. Predicted fuzzy damage for Block B_0.

damage indices can be interpreted as possibility distributions and show that damage is between 0.01 and 1.0 % with a greater possibility around 0.1%.

5 CONCLUSION

For large city gas networks, quick damage estimation after an earthquake may be effectively utilized to decide whether or not to shut-off the gas supply in order to avoid secondary disasters.

The system proposed in this paper estimates earthquake damage in each sub-zone of a buried pipeline network from observed ground motion characteristics and soil conditions by fuzzy reasoning. A global damage estimate for each block in the network is calclulated by taking the weighted average of the estimates in all sub-zones of the block. The obtained estimate is then corrected considering the earthquake magnitude and the epicentral distance. The results are displayed graphically so that they can be readily used by a decision-maker in times of emergency. The damage indices calculated by the system can be used in fuzzy decision analysis to provide further assistance for decision-making.

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