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EARTHQUAKE DAMAGE ESTIMATION FOR LIFELINE SYSTEMS USING FUZZY REASONING

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SUMMARY

In a large city, lifelines are especially vulnerable to an earthquake. In the case of a buried pipeline network, it is crucial to assess damage as soon as possible and shut off the supply if necessary. The system proposed in this paper uses measured ground motion characteristics and soil conditions to evaluate damage at each point of the considered area by fuzzy reasoning. Obtained results are then displayed as a map on computer. Results of example calculations are shown and compared to values measured during past earthquakes.

1. INTRODUCTION

For a pipeline network, especially for city-gas, the first reaction when an earthquake occurs would be to initiate an emergency shut-off because of the risk of leak. Nevertheless, an unnecessary shut-off would cause much inconvenience and the network may need time to recover.

Hence, a system to evaluate damage due to the earthquake and to enable the decision maker to make a quick judgement on whether to cut or maintain the supply seems essential.

By using the information obtained by accelerometers or SI (Spectral Intensity) sensors [1] laid in the service area it seems possible to build up a model assessing the potential damage due to the earthquake. Nevertheless it is difficult to obtain precise and reliable data to construct such a model. Despite considerable efforts which have been made lately, the number of seismometers can only be limited and the ground motion characteristics may still vary considerably within the area monitored by one instrument.

All these uncertainties are mainly due to our incomplete knowledge of the system studied (and not to an intrinsic randomness) and to take them into account fuzzy theory [2] seems appropriate.

2. OUTLINES OF THE DECISION ASSISTING SYSTEM

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

Several tens of SI sensors are laid in each supply block, as well as a few accelerometers. Their measurements are transmitted to the control room by a multiple radio telemeter system. The proposed system, shown on Figure 1, uses this information to estimate damage and motivate the shut-off decision.

This paper concentrates on the highlighted part of Figure 1. Two parameters are chosen to represent the state of the block in order to make the decision : damage to buildings (customers' houses) R_b and damage to pipes (buried pipelines of the network) R_p. These two damage indices are globally refered to as "damage" in Figure 1. The supply block being divided in square sub-zones (with sides of 500m for example), the damage indices will be evaluated in each sub-zone using SI and A_{max} (peak ground acceleration) values. The outlines of the subsequent procedure, which will lead to a global evaluation for the whole supply block, will be explained in section 4.

3. BUILDING AND PIPE DAMAGE ESTIMATION IN ONE SUB-ZONE

3.1 Outlines of the Model

To assess damage to buildings, peak ground acceleration A_{max} (which has a predominant influence for buildings of short period) and SI (which is a good

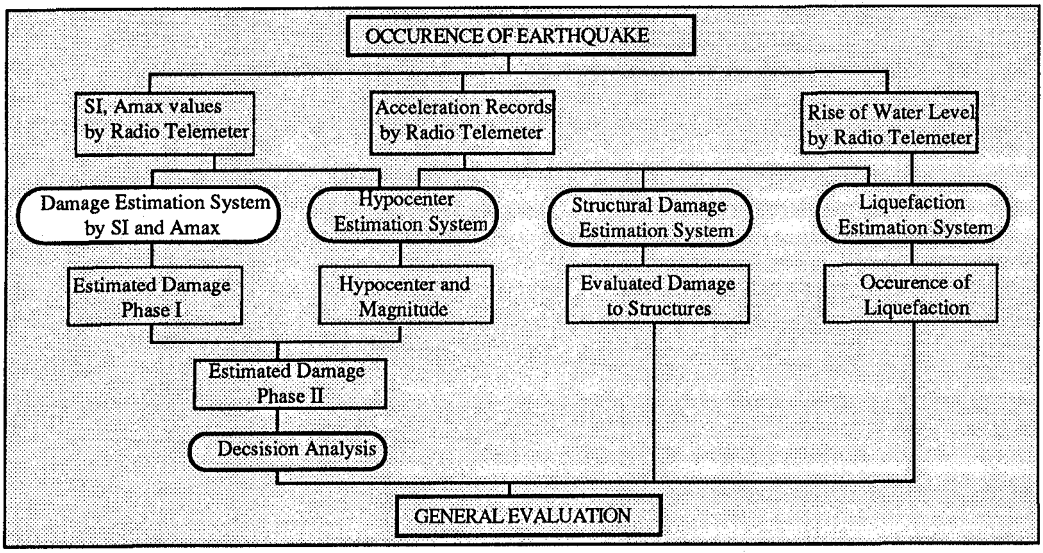


Figure 1 : Flowchart for damage assessment and decision making in a supply block

index for structures of medium period) are taken into account. The biggest difficulty is maybe to define a relevant damage index. In this paper, the following definition is adopted [1]: for each building, damage evaluation is taken as 1 if the building is completely destroyed (i.e needs to be rebuilt), 0.5 for moderate damage, 0.1 for minor damage, 0 for no damage. A ratio is then taken for all buildings giving a percentage as a damage index. This means that if the damage index is 100%, all buildings are destroyed in the considered sub-zone. This is a very extreme situation and thence usually the logarithm of the damage index (in percents) is taken as the meaningful variable.

Liquefaction may be considered to be most damaging to buried structures. Hence to evaluate damage to pipes, not only the intensity of ground motion (expressed by SI) is taken into account, but also the thickness of liquefiable sandy layer H_s. In the following, damage to pipes has been expressed as the number of leaks per unit pipe length (1 km) and considered to be directly related to the thickness of the layer actually liquefied.

Definitions of both damage indices are not very precise but this can be handled by fuzzy theory.

3.2 Use of Fuzzy Reasoning

Fuzzy theory enables modelling of human vocabulary and its imprecision. In our case, we define the fuzzy sets representing the values "Small", "Medium", "Big" ... for each universe of discourse (i.e. for each variable). This comes to define a membership function $\mu(x)$ for each of these fuzzy subsets (see Figure 2 and 3). For example in Figure 2 a), SI = 15 cm/s has a membership of 0.5 in the fuzzy set Small : it means that the value 15 cm/s can be said to be "small" to the extent 0.5 (in a classical set, the membership could be only 0 or 1).

With these definitions as a basis, we can now use fuzzy reasoning [3]. The idea of fuzzy reasoning is to express the modelling of the system in simple natural-language-like form. Instead of usual equations, fuzzy inference rules are used. 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.

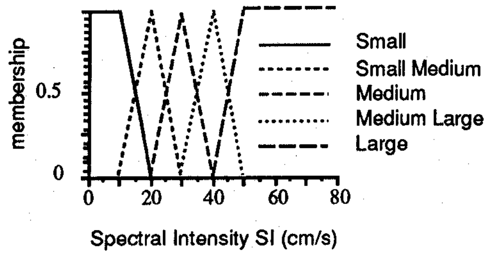
The general form of a fuzzy inference rule is :

$$\text{IF } x_1 \text{ is } \mathbf{A}_{i,1} \text{ AND } x_2 \text{ is } \mathbf{A}_{i,2} \text{ AND } \dots \text{ AND } x_n \text{ is } \mathbf{A}_{i,n} \text{ THEN } y \text{ is } \mathbf{B}_i \qquad i = 1 \dots m \qquad (1)$$

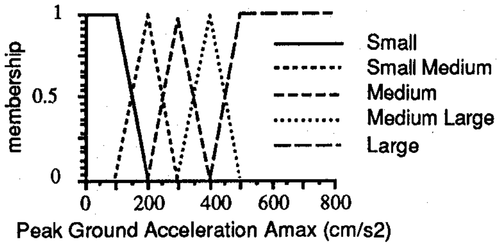
where n is the number of conditions, m is the numbers of rules, $\mathbf{A}_{i,j}$ are fuzzy subsets (such as Small, Medium ...) representing the conditions of the rules and $\mathbf{B}_i$ are the fuzzy subsets representing the consequences of the rules.

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

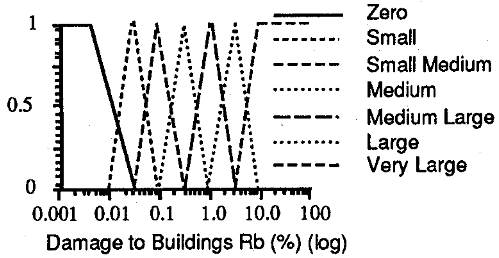
The result of fuzzy inference is predicted y, which is represented by the fuzzy set $\mathbf{B}'$ defined by the membership function (Mamdani method):



a) First condition

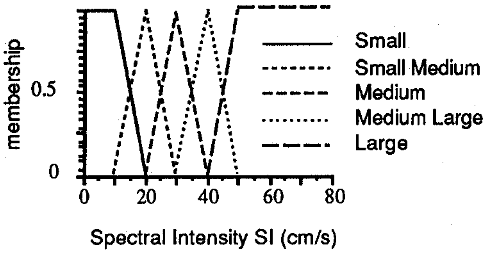


b) Second condition

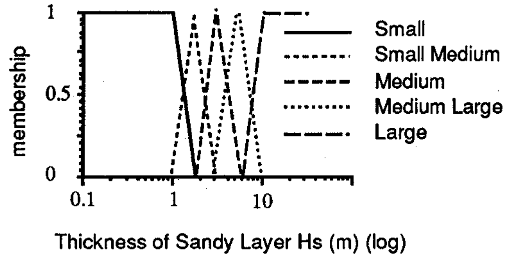


c) Consequence

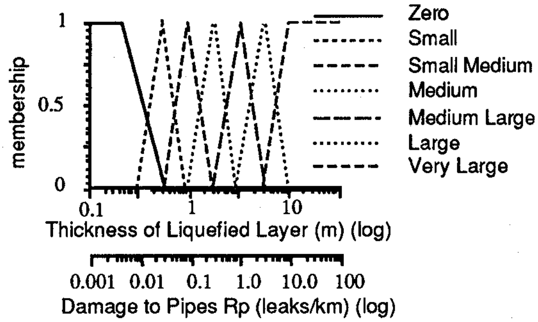
Figure 2 : Fuzzy Sets used to evaluate damage to buildings



a) First condition



b) Second condition



c) Consequence

Figure 3 : Fuzzy sets used to evaluate pipe damage

$$\mu_{B'}(y) = \bigvee_{i} M_i \wedge \mu_{B_i}(y) \qquad \text{where } M_i = \bigwedge_{j} M_{i,j} \text{ and } M_{i,j} = \bigvee_{x_j} \mu_{A'_j}(x_j) \wedge \mu_{A_{i,j}}(x_j) \qquad (2)$$

(usual notations $\vee$ for maximum and $\wedge$ for minimum are used).

In our case, n = 2 (2 conditions), m = 25 (25 rules), x_1 = SI, x_2 = A_{max}, y = damage to buildings (for one set of rules) or x_1 = SI, x_2 = H_s, y = damage to pipes (for the other set of rules). Tables 1 and 2 show the fuzzy inference rules, it is to say the 25 different possibilities for damage depending on the values of SI and A_{max} or SI and H_s. For example, Table 1 reads :

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

Table 1 : Fuzzy inference rules for building damage estimation

		IF SI is ...				
		Small	Small Med.	Med.	Med. Large	Large
and Amax is ...	Small	Zero	Small	Small Med.	Med.	Med. Large
	Small Med.	Zero	Small	Small Med.	Med.	Med. Large
	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

		IF SI is ...				
		Small	Small Med.	Med.	Med. Large	Large
and Hs is ...	Small	Zero	Zero	Zero	Small	Small Med.
	Small Med.	Zero	Zero	Small	Small Med.	Med.
	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

To assess damage to buildings, SI has been given a greater weight than A_{max} in the rules because it is considered to be a better index.

3.3 Results and Assessment of the Method

In practice, the values of SI, A_{max} and H_s are measured and damage is evaluated as described using fuzzy reasoning.

To fit in the pattern described in the previous section, we must define the fuzzy subsets $\mathbf{A}_j'$ representing observation of the variables. To make things simpler, it was chosen to use delta function for their membership function :

$$\mu_{\mathbf{A}_j'}(x) = \begin{cases} 1 & \text{if } x = \text{measured value for variable } j \\ 0 & \text{otherwise} \end{cases} \qquad (3)$$

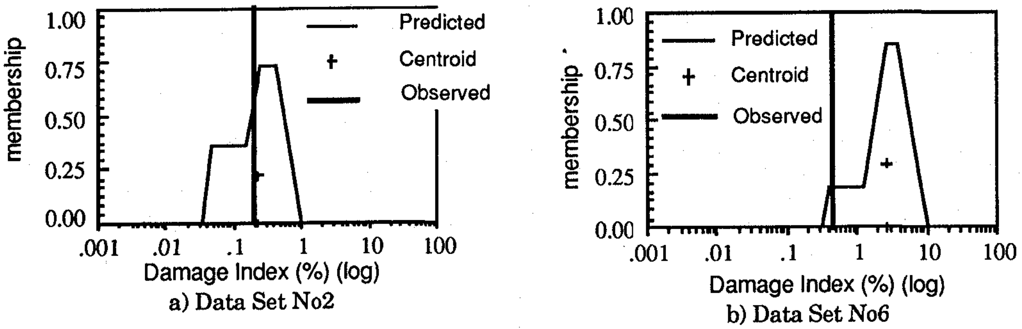
As shown on Table 3, the results for building damage given by fuzzy inference are compared to values measured during past earthquakes [1]. To obtain a crisp (non-fuzzy) value corresponding to the fuzzy estimated damage, it has been chosen to calculate the centroid of the graph of the membership function [3]. It is interesting to note that data sets 9 to 14 do not give a precise value of observed damage but can still be used in the context of fuzzy theory.

Figures 4 a) to 4 d) show the full results. Agreement between predicted and observed damage is not always perfect, but it should be noted that, for almost all data sets of Table 3, observed value was found within the range where the membership function of predicted damage is non zero. It is also somehow difficult to compare the measurements of Table 3, for which only one SI value is given for a large area, with the results of the presented method which are supposed to be valid only for a small area corresponding to a given SI. Also, when other parameters such as epicentral distance and magnitude will be taken into account (cf Figure 1), estimation can be expected to fit observation better.

Another way to present the results is to compute predicted damage for each and every value of SI and A_{max} on one hand and each and every value of SI and H_s on the other hand. Figure 5 and 6 show the centroid of the obtained fuzzy set on z axis as a function of A_{max} on x axis and SI on y axis for Figure 5 and a function of H_s on x axis and SI on y axis for Figure 6. As expected, the trend is that predicted damage is an increasing function of SI and A_{max} and of SI and H_s, with steps due to the approximation of the fuzzy method.

Table 3 : Obtained damage estimation results for some past earthquakes

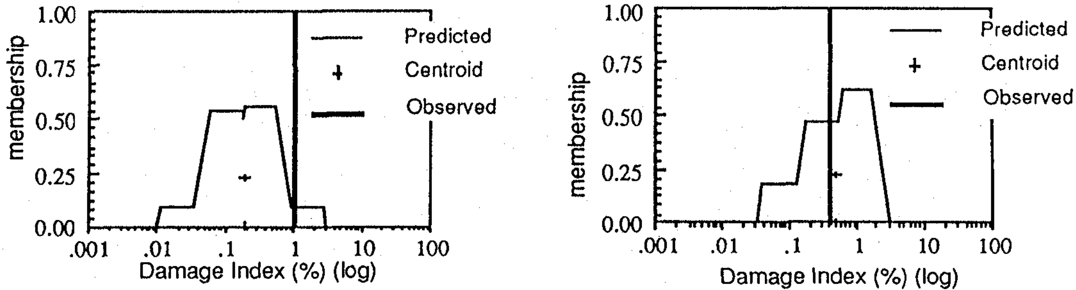
Data Set Number	Earthquake Event, Place of Observation	SI (cm/s)	Amax (cm/s^2)	Observed Damage (%)	Predicted Building Damage (%)	Note
1	1964.6.16 Niigata Earthquake, Niigata	32.0	159.0	-	0.04	Liquefaction occurred
2	1966.4.5 Mastuhiro Earthquake, Hoshina	26.7	601.9	0.19	0.21	
3	1966.4.17 Mastuhiro Earthquake, Hoshina	10.1	331.2	0.0	0.03	
4	1968.5.16 Tokachi-oki Earthquake, Aomori	39.7	252.0	0.96	0.18	
5	1968.5.16 Tokachi-oki Earthquake, Hachinohe	37.6	224.4	5.16	0.10	
6	1978.6.12 Miyagi-ken-oki Earthquake, Shiogama	59.1	316.7	0.43	2.70	
7	1978.6.12 Miyagi-ken-oki Earthquake, Sendai	48.8	258.1	0.4	0.51	
8	1983.5.26 Nihonkai-chubu Earthquake, Akita	34.0	205.2	0.2	0.06	
9	1987.12.17 Chiba-ken-toho-oki Earthquake, Chiba	15.2	322.3	-	0.03	No damage
10	1987.12.17 Chiba-ken-toho-oki Earthquake, Kisarazu	35.0	384.5	-	0.18	Almost no damage Displaced seawalls
11	1989.7.9 Izu-hanto-toho-oki-gunhatsu Earthquake, Ito	41.8	233.4	-	0.21	No damage to buildings. Damage to gas pipes in 10 places
12	1989.10.17 Loma Prieta Earthquake, Corralitos	59.0	617.7	-	20.4	Heavy damage
13	1989.10.17 Loma Prieta Earthquake, Watsonville	55.1	352.3	-	1.78	Heavy damage
14	1989.10.17 Loma Prieta Earthquake, Menlo Park VA	26.9	288.0	-	0.05	No damage



a) Data Set No2

b) Data Set No6

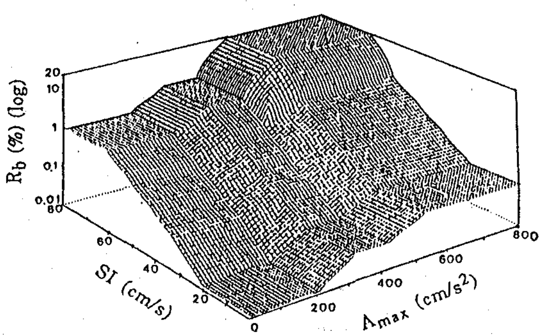
Figure 4 : Results of fuzzy inference for a few data sets from Table 3



c) Data Set No4

d) Data Set No7

Figure 4 (continued) : Results of fuzzy inference for a few data sets from Table 3



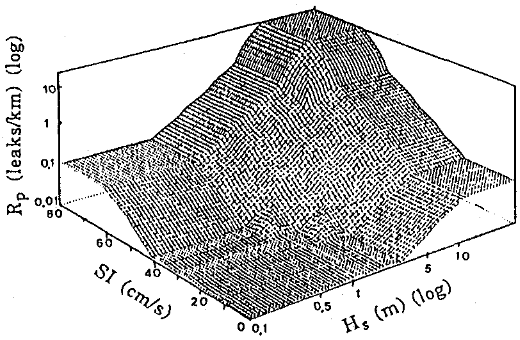


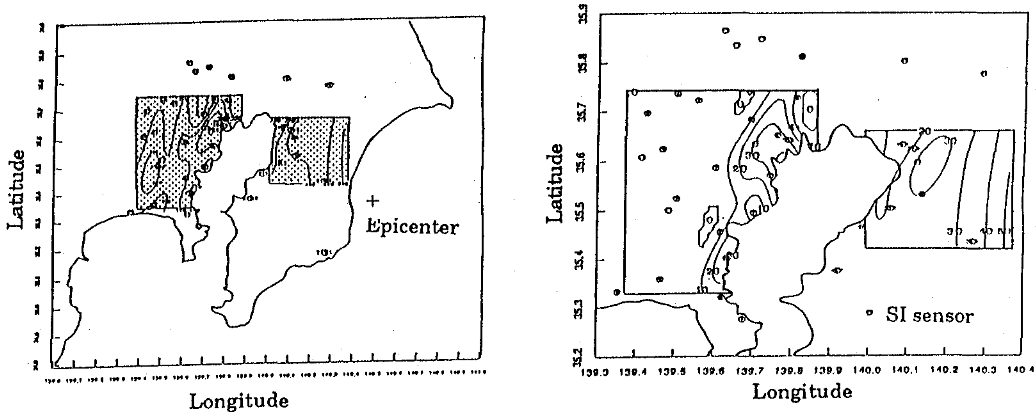
Figure 5 : Predicted building damage as a function of SI and A_{max}

Figure 6 : Predicted pipe damage as a function of SI and H_s

3.4 Graphic Presentation of the Results

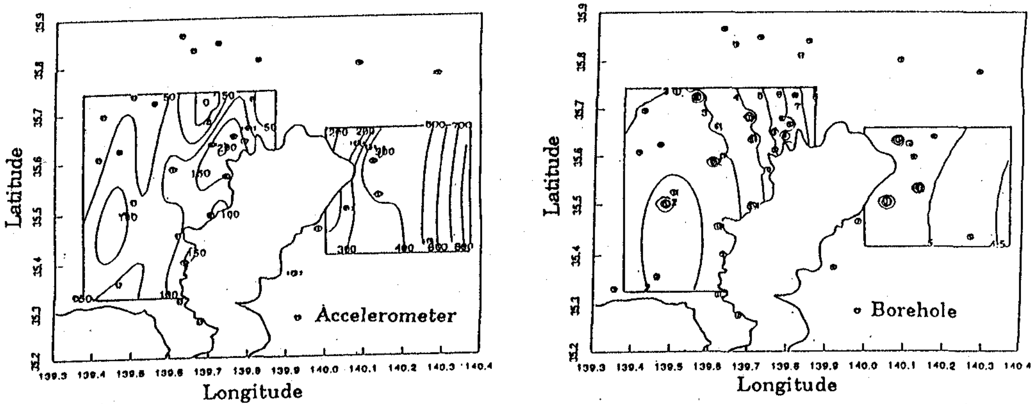
Section 3.3 explained how to estimate damage at one point. Consider a supply block for which the question of whether to cut or to maintain the supply is asked. We can estimate damage for each sub-zone of this block and then display the results as a map. This enables the decision maker to visualize the results of fuzzy inference presented in a synthetic and useful way,

Figure 7 shows results obtained for two (ficticious) blocks with Chibaken-Toho- Oki earthquake (December 17th 1987; M = 6.7; focal depth 58 km) in Kanto area. SI, A_{max} and H_s are measured at discrete points and the values of the variables are interpolated in the whole area using a two-dimensional probabilistic interpolation method (actually Figures 7 b) c) d) show contours for the mean value). Damage estimation is then made at each point as explained earlier and the maps of Figures 7 e) and f) show the centroid of the obtained fuzzy result. It should be born in mind that the vertical axis on Figures 5 and 6 has a logarithmic scale and that the considered damage indices are mostly smaller than 1. On Figures 7 e) and f) the scale for contours is no longer logarithmic and this explains why a very sharp increase of predicted damage can be seen. As A_{max} has been taken as a secondary parameter and variations of H_s are small, influence of SI is seen to be preponderant for both damage indices.



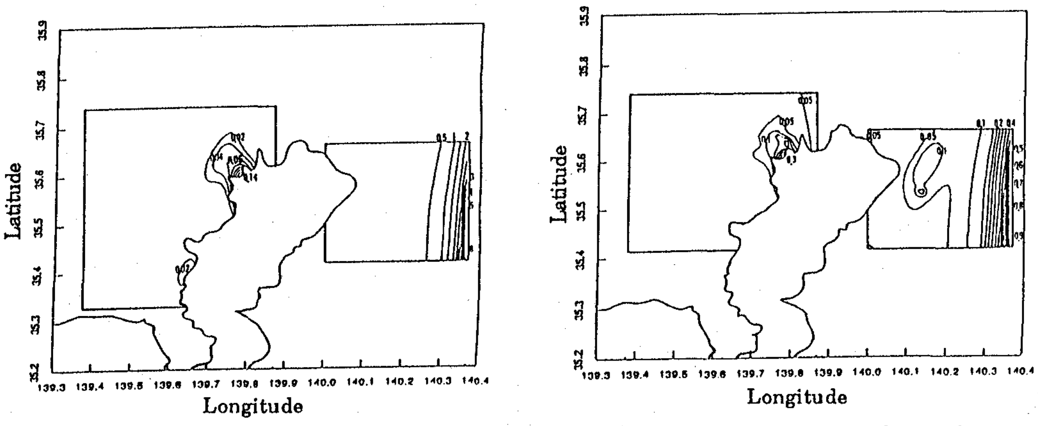
a)Position of considered supply blocks

b) Contour map of observed SI values



c) Contour map of observed Amax values

d) Contour map of observed Hs values



e) Contour map of predicted building damage

f) Contour map of predicted pipe damage

Figure 7 : Sample calculation for damage prediction in Kanto area using Chiba ken Toho Oki earthquake (M = 6.7, focal depth 58 km)

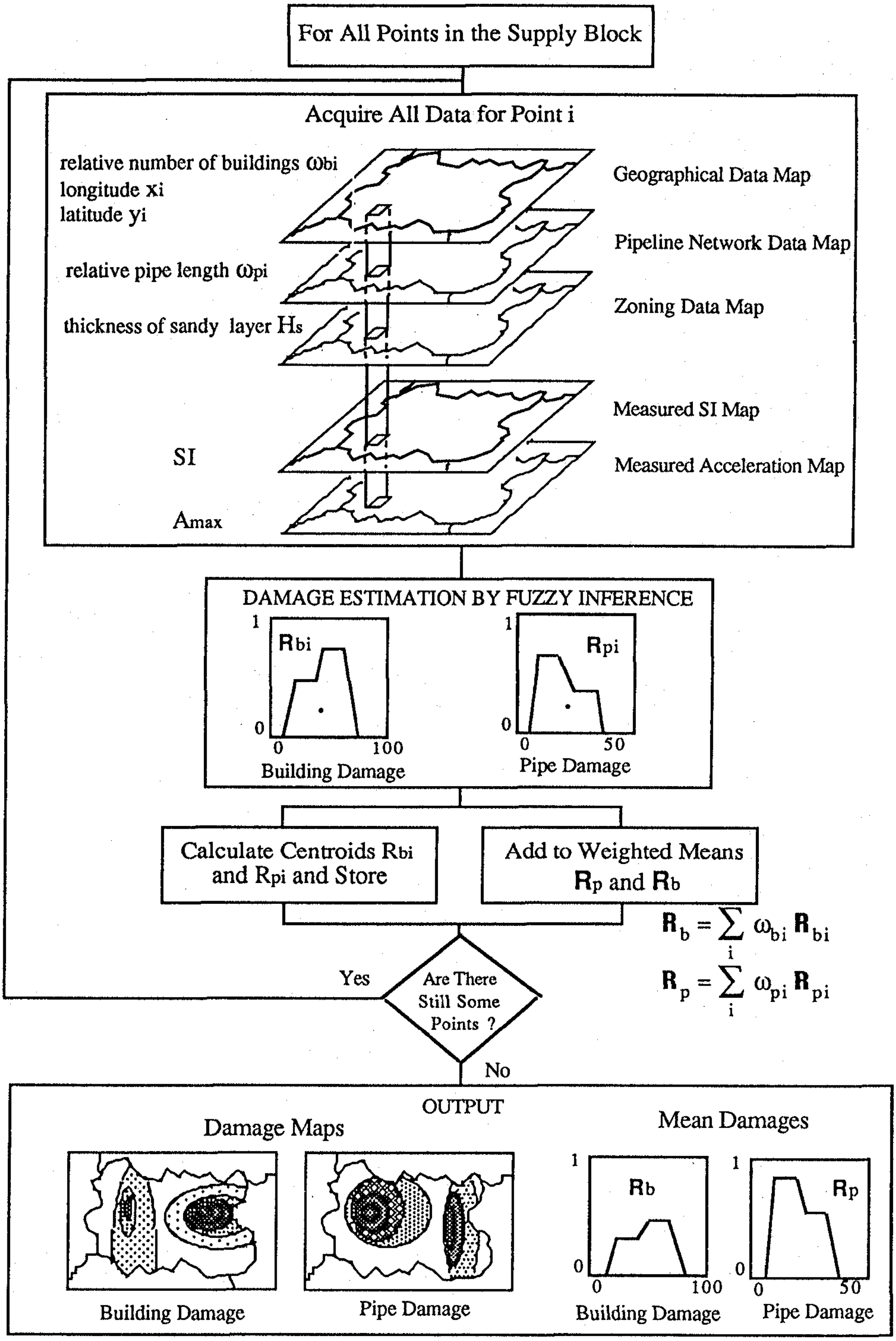


Figure 8 : Outline of damage estimation for a whole supply block

4. FURTHER DEVELOPPMENT OF THE DECISION ASSISTING SYSTEM

To enable the decision maker to act as quickly as possible after the earthquake occurs, it seems interesting to construct a system on computer that would enable to synthesize all useful information about the network.

The final result yielded by this system is an advice about whether to cut or to maintain the supply. Nevertheless it is also necessary to know why such an action is desirable. For synthetic and easy to understand presentation, a graphic screen is used to display maps of the variations of the different variables in the considered area.

The procedure for global evaluation in a supply block is shown on Figure 8. To produce the damage maps, similar to the ones of Figures 7 e) and f), the data contained in several other maps are superposed. This "superposition" is made by fuzzy inference as explained earlier.

As shown on Figure 8, damage to buildings and damage to pipes are calculated for each point by fuzzy inference : the results are two fuzzy sets $\mathbf{R}_{bi}$ and $\mathbf{R}_{pi}$. The centroid of each of these fuzzy sets is taken and stored in order to be displayed when evaluation at all point is finished. At the same time, $\mathbf{R}_{bi}$ and $\mathbf{R}_{pi}$ are added to the partial sums $\mathbf{R}_b$ and $\mathbf{R}_p$ that will lead to evaluation of mean damages for the whole block when calculation is complete.

The final result of this procedure is :

* on one hand two maps displaying damage to buildings and damage to pipes in the considered area. This enables to visualize the results of fuzzy inference.
* on the other hand two fuzzy sets representing weighted average in the block for damage to buildings and damage to pipes respectively. After incorporating information coming from hypocenter and magnitude estimation, these two fuzzy sets will be used later for decision analysis (cf Figure 1).

5. CONCLUSIONS

This study proposes a damage assessment method for lifeline system in a large city. SI Sensors and accelerometers being laid in the whole service area, damage is evaluated at each point of the considered zone from their measurements using fuzzy reasoning.

This method gives relevant results although available data are limited. Results are displayed in a comprehensive way in maps to make them easier to understand and to use. The procedure presented here is only a part of a whole system for monitoring a buried pipe network. This system is aimed at determining whether it is preferable to cut or maintain the supply in the considered area, assisting the decision maker in his judgement.

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