The 14th World Conference on Earthquake Engineering
October 12-17, 2008, Beijing, China

SEISMIC RISK ASSESSMENT OF REINFORCED CONCRETE BUILDINGS USING FUZZY RULE BASED MODELING

S. Tesfamariam[1] and M. Saatcioglu[2]

[1] *Assistant Professor, School of Engineering, University of British Columbia | Okanagan, Kelowna, British Columbia, Canada*
[2] *Professor and University Research Chair, University of Ottawa, Ottawa, Ontario Canada*
Emails: solomon.tesfamariam@ubc.ca, murat@uottawa.ca

ABSTRACT :

Seismic resiliency of new buildings has improved over the years due to improved seismic codes and design practices. However, vulnerability of seismically deficient older buildings, designed and built on the basis of older codes of practice, poses a significant threat to life safety and survivability of buildings. It is economically not feasible to retrofit the entire seismically deficient infrastructure. Therefore, there is need for a comprehensive plan to identify critical structures and prioritize their retrofit requirements. Risk-based seismic assessment approach is proposed for prioritizing buildings for retrofit. Risk-base prioritization incorporates engineering decision making aspects, such as damage estimation, and societal value, tolerance to the consequence of failure. This is done by integrating site seismic hazard, building vulnerability, and importance/exposure factors. The complexity of building vulnerability assessment is handled through a systems theory where the complex problem is managed through hierarchical structure. The vagueness uncertainty encountered as a result of subjective walk down survey is handled through a fuzzy set theory. Fuzzy rule based modeling is used to incorporate decision maker's attitude and intuitive knowledge in the aggregation process. The proposed method is illustrated through the use of May 1, 2003 Bingöl Earthquake damage observations. Results of the proposed risk-base prioritization method show good correlation with observed damage, albeit extracted from limited data sets.

KEYWORDS: retrofit prioritization, risk assessment, building vulnerability, fuzzy rule base

1. INTRODUCTION

Reported damages from recent global earthquakes, 2008 Sichuan earthquake in China, 2004 Sumatra earthquake in Indonesia, 2003 Bingöl earthquake in Turkey, and 1994 Northridge earthquake in USA, for example, highlight vulnerability of existing buildings and importance of seismic retrofit implementation. The building vulnerability is due to older building design codes, poor design practices and poor code enforcement. Most of these buildings are currently operational and are required to be further assessed and upgraded to minimize seismic damage and improve life safety. From a city manager's decision making perspective, comprehensive evaluation all buildings are not economically feasible, and it is desirable to screen out deficient buildings.

Different regional seismic vulnerability screening tools are reported. In California, a point scoring method was first proposed in the mid seventies (Boissonnade and Shah, 1985), subsequently, in the mid eighties, expert derived damage probabilities are proposed (ATC, 1985). A rapid visual screening (RVS) is developed by FEMA 154 (ATC 2002). A three-tier process is developed by FEMA 310 (ASCE 1998). Other reported regional damage estimations are Canada (NRC 1992, 1993), New Zealand (NZSEE, 2006). Due to large volume of existing vulnerable buildings, retrofit prioritization using a risk-based seismic assessment is desirable (Ellingwood, 2001). Seismic risk may be defined as the probability that a specified loss will exceed some quantifiable value during a given exposure time (EERI Committee on Seismic Risk, 1989). A generalized notion of earthquake risk assessment is illustrated in Figure 1 with a Venn diagram. Figure 1 illustrates the seismic risk assessment can be undertaken by integrating site seismic hazard, building vulnerability (likelihood of failure), and importance/exposure factor (consequence of failure). Quantifying seismic hazard, building vulnerability and consequence of failure is a daunting task that is often subject to model and input data uncertainty. The reported regional screening techniques don't explicitly quantify prevalent risk of each building.

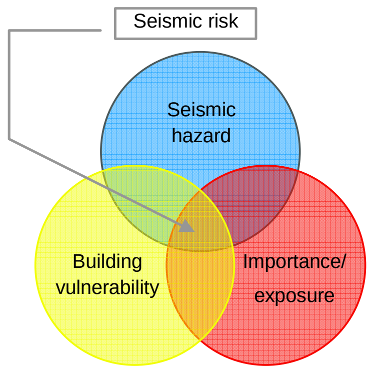


Figure 1 Earthquake risk assessment

Various techniques are used to assess building vulnerability assessment and loss estimation; empirical method; heuristic method; and analytical method (FEMA 249, 1994; Boissonnade and Shah, 1985). The complexity of building vulnerability assessment can be handled through a system based approach. A system is defined as an "assemblage of components acting as a whole" (Meirovitch, 1967). Building structures are essentially an assemblage of different components, e.g. beams, columns, slabs; hence can be described as a system. Each system in turn encapsulates different subcomponents and be described as a subsystem. In structural safety and evaluation, system response to earthquake loading is of paramount importance. The system can be represented using continuous or discrete analytical models. Typically, system identification technique (Yao, 1985) is used to develop and validate the model. The different techniques can be described through mathematical models, which are an abstraction of the actual building. Joslyn and Booker (2005) have succinctly described the limitations of models: *all models are necessarily incomplete*; *all models are necessarily somewhat in error*; and *the system being modeled may have inherent variability or un-measurability in its behavior*. Nevertheless, despite these limitations, systems approach of building assessment has a utility in screening deficient buildings.

The problem of seismic risk assessment and decision making is further compounded due to ubiquitous uncertainty (Wen et al. 2003). The typology and definition of uncertainty within engineering community is vast and often conflicting (Parsons 2001). Klir and Yuan (1995) have broadly categorized uncertainty into vagueness and ambiguity (Figure 2). The vagueness (imprecision) refers to lack of definite or sharp distinction, whereas ambiguity is due to unclear distinction of various alternatives, which is further divided into discord (conflict) and non-specificity. Traditionally, uncertainties in earthquake engineering were handled using probabilistic methods, which necessitates acquiring large historical data (Wen et al., 2003; Dong et al., 1987). However, besides of the challenge of acquiring large historical data, as it was indicated earlier, seismic application must deal with ignorance, imprecision, vagueness, and subjective judgment. The taxonomy of uncertainty shown in Figure 2, albeit to a different degree, is reflected in the seismic risk assessment.

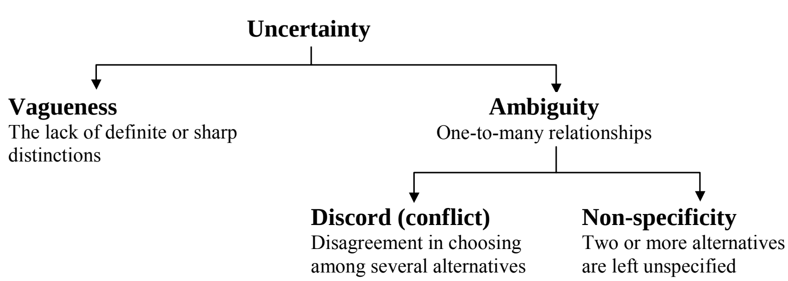


Figure 2 Typology of uncertainty (modified after Klir and Yuan, 1995)

This paper illustrates and present a case study for a heuristic based rapid visual screening of reinforced concrete (RC) building reported in Tesfamariam and Saatcioglu (2008).

2. HIERARCHICAL EARTHQUAKE RISK ASSESSMENT

The complex problem of risk-based inspection can be handled through a simple and manageable hierarchical structure. The hierarchical structure follows a logical order where the causal relationship for each supporting argument is further subdivided into specific contributors. Miyasato et al. (1986) proposed a hierarchical structure for seismic vulnerability assessment of buildings, which has been adopted in this paper after some modifications (Figure 3).

Figure 3 shows a six-level hierarchical structure. Level 1 of the hierarchy is the overall goal of the analysis, i.e., *seismic risk*. The seismic risk is computed by integrating the parameters at level 2 that reflects *building damageability* and *building importance/exposure*. At level 3, the building importance/exposure parameter is computed by integrating *building use*, *building occupancy* and *economic importance*. The building damageability in turn is computed by integrating the parameters at level 3, *site seismic hazard* and *building vulnerability*. The site seismic hazard is computed by integrating site seismicity, soil type and number of stories, details of which is outlined Tesfamariam and Saatcioglu (2008). The case studies are provided for building vulnerability, and the following discussion will be limited to these parameters that contribute to building vulnerability.

Building vulnerability to ground shaking and associated damage can be grouped into two categories (Saatcioglu et al. 2001); factors contributing to an increase in seismic demand (e.g., soft story frame, weak column-strong beam, vertical irregularities); and factors contributing to reduction in ductility and energy absorption capacity (e.g., construction quality, year of construction, structural degradation). Obtaining and incorporating exhaustive detail of those factors is not feasible in a preliminary risk assessment of RC buildings. In this paper, the basic risk parameters considered in FEMA 154 (ATC 2002) for building vulnerability assessment have been adopted, i) *building type*, ii) *vertical irregularity* (VI), iii) *plan irregularity (PI)*, iv) *year of construction* (YC) and v) *construction quality* (CQ). Thus, given these five parameters, the building vulnerability can be computed by integrating inherent system deficiency, *structural system* (SS), e.g. shear wall or moment resisting frame buildings, and structural deficiency, e.g. vertical irregularity. The structural deficiency is subdivided into input parameters that contribute to an *increase in demand* and *decrease in resistance*. Parameters that contribute to an increase in demand are vertical irregularity and plan irregularity. On the other hand, parameters that contribute towards the decrease in resistance are construction quality and year of construction.

The site seismic hazard is quantified through fundamental period (T_1) of the structure and response spectra. The response spectra are obtained either through a site specific design response spectrum or existing representative earthquake record. Soil type is used to modify the corresponding design response spectrum. Finally, using the T_1 and corresponding response spectra, spectral acceleration $S_a(T_1)$ is obtained. The $S_a(T_1)$ is used in the fuzzification of site seismic hazard as will be discussed in the next section.

3. FUZZY BASED MODELING

Fuzzy logic provides a language with semantics to translate qualitative knowledge into numerical reasoning, which enables in modeling complex systems like buildings. The strength of fuzzy logic is that it can integrate descriptive (linguistic) knowledge and numerical data into a fuzzy model and use approximate reasoning algorithms to propagate the uncertainties throughout the decision process. The fuzzy inference system (FIS) contains three basic features (Zadeh 1973):

- linguistic variables instead of, or in addition to, numerical variables;
- relationships between the variables in terms of IF-THEN rules (rule-base); and

- an inference mechanism that uses approximate reasoning algorithms to formulate relationships.

The basic theory of fuzzy sets was first introduced by Zadeh (1965). It can deal with the nature of uncertainty in system and human error. A fuzzy set describes the relationship between an uncertain quantity x and a membership function μ_x, which ranges between 0 and 1. A fuzzy set is an extension of the traditional set theory (in which x is either a member of set A or not) in that an x can be a member of set A with a certain degree of membership μ_x. In this paper, a triangular fuzzy number is used for its simplicity.

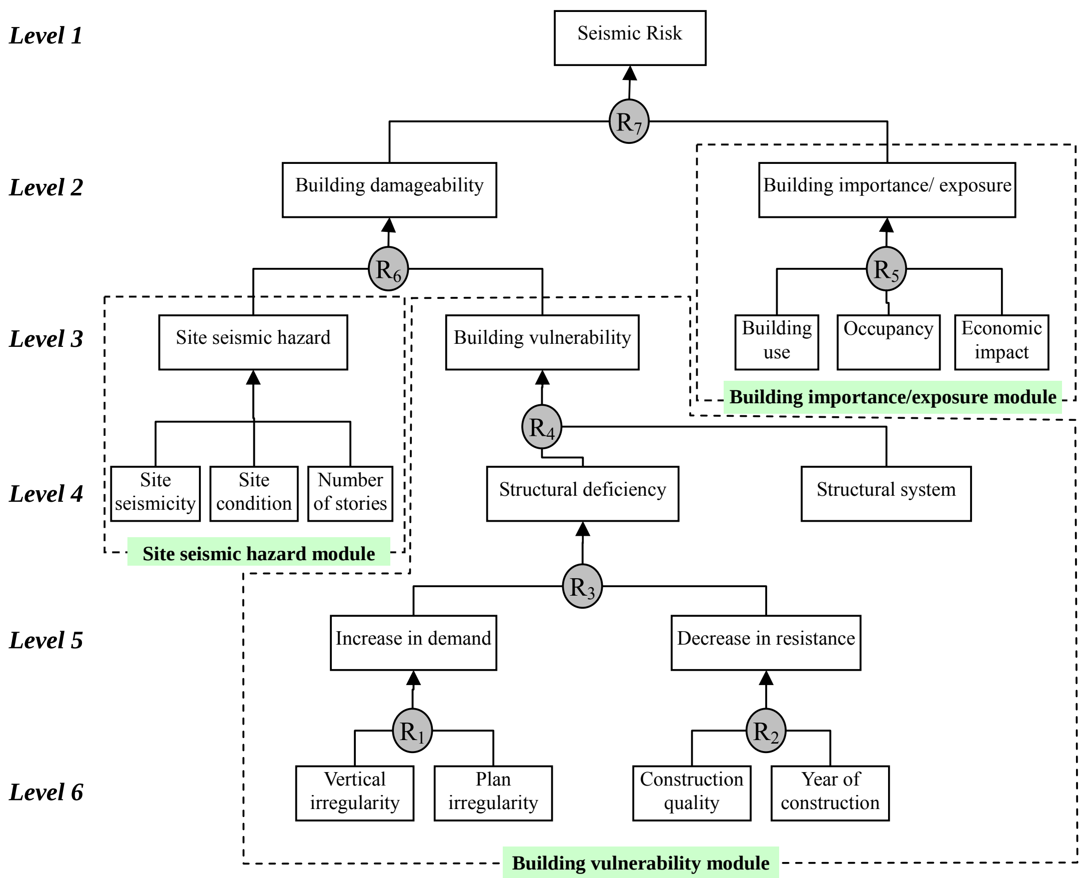
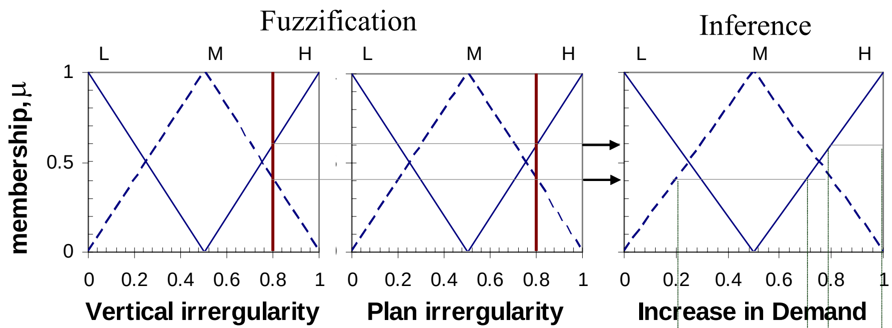


Figure 3 Hierarchical earthquake risk assessment of Reinforced Concrete Buildings (after Tesfamariam and Saatcioglu 2008)

A schematic of the FIS for quantifying increase in demand (ID) given the vertical (VI) and plan (PI) irregularities are depicted in Figure 4. Step 1 is the fuzzification process. Given the presence of VI and PI, the corresponding fuzzifications are $\left(\mu_L^{VI}, \mu_M^{VI}, \mu_H^{VI}\right)$ = (0, 0.40, 0.60) and $\left(\mu_L^{PI}, \mu_M^{PI}, \mu_H^{PI}\right)$ = (0, 0. 40, 0.60), respectively. In Step 2, using the inferencing for the fuzzy rule base R_1 is illustrated (Figure 3). For linguistic consequent parameters, Mamdani type inferencing can be used (Mamdani, 1977). Mamdani's inference mechanism consists of three connectives: the aggregation of antecedents in each rule (AND connectives), implication (i.e., IF-THEN connectives), and aggregation of the rules (ALSO connectives). The IF-THEN rules can be established as:

$$R_i : \text{IF} \quad x_1 \text{ is } A_{i1} \quad \text{AND} \quad x_2 \quad \text{is} \quad A_{i2} \quad \text{THEN} \quad y \text{ is } B_i \quad , \quad i = 1, \ldots, n \qquad (1)$$

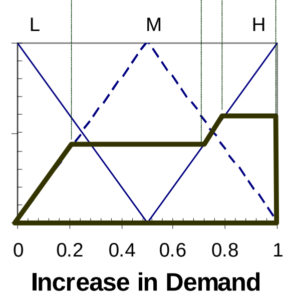
Thus, using the Mamdani type inferencing, the ID is computed to be $\left(\mu_L^{ID}, \mu_M^{ID}, \mu_H^{ID}\right)$ = (0, 0.40, 0.60). Finally, Step 3 entails the defuzzification process using a simple weighted average method, where the ID is computed to be 0.80. This will be used as in input of ID into R_3 (Figure 3).



Fuzzy rule base $\mathbf{R_1}$ for ID

Rule *i*	VI	PI	ID
1	L	L	L
2	L	M	L
3	L	H	M
4	M	L	L
5	M	M	M
6	M	H	H
7	H	L	M
8	H	M	H
9	H	H	H

VI = vertical irregularity; PI = plan irregularity;
ID = Increase in demand



Defuzzification

ID = 0.25*0 + 0.5*0.4+1*0.6 = 0.80

Figure 4 Fuzzy rule base inferencing

4. CASE STUDY

On May 1, 2003, the city of Bingöl, Turkey, was struck by an earthquake of moment magnitude M_w=6.4, resulting in 168 casualties, 520 injury and several building damages. The total economic loss to the Turkish national economy was estimated to be over 400 million US dollars (Doğangün, 2004). Summary of the Bingöl Database[1] is shown in Table 1. The damage is classified into five discrete stages: none (N), light (L), moderate (M), severe (S) and collapse (C). The reinforced concrete buildings are classified as frame building, RCF and shear wall building, RCSW.

For the N10E component, the reported peak ground acceleration PGA (cm/s^2), peak ground velocity PGV (cm/s) and peak ground displacement PGD (cm) were 535.3, 36.1 and 26.6, respectively (Gülkan and Akkar, 2004). The geotechnical investigation (Bobet et al., 2004) indicates that the buildings are located in an alluvial deposit, which is classified as stiff soil. The response spectrum provided in Gülkan and Akkar (2004) is used for quantification of hazard. The five-percent damped response spectra reported in Gülkan and Akkar (2004) don't take the hazard spatial variability. Thus, the single response spectrum may not be representative for all buildings. Thus, only the building vulnerability I^{BV} results are reported.

[1] SERU, Middle East Technical University, Ankara, Turkey; Archival Material from Bingöl Database located at website http://www.seru.metu.edu.tr.

Table 1 Summary of 2003 Bingöl Earthquake database.

	BUILDING ID	SS	N	VI	PI	YC	CQ	Observed Damage	I^{BV}
1	BNG-10-3-10	RCF	3	Yes	Yes	-	Poor	Moderate	0.80
2	BNG-10-3-3	RCF	3	No	No	1975	Poor	Moderate	0.58
3	BNG-10-4-4	RCF	4	Yes	Yes	1998	Average	Moderate	0.82
4	BNG-10-4-6	RCF	4	Yes	Yes	1976	Average	Light	0.80
5	BNG-10-4-7	RCF	4	Yes	Yes	1988	Average	Light	0.80
6	BNG-10-4-9	RCSW	4	Yes	Yes	2002	Good	None	0.80
7	BNG-10-5-1	RCSW	5	Yes	Yes	1990	Average	Moderate	0.80
8	BNG-10-5-11	RCF	5	Yes	No	1988	Average	Light	0.72
9	BNG-10-5-2	RCSW	5	No	Yes	1990	Good	Light	0.72
10	BNG-11-2-3	RCF	2	No	No	-	Poor	Moderate	0.58
11	BNG-11-4-1	RCSW	4	Yes	Yes	1998-1999	Poor	Severe	0.58
12	BNG-11-4-2	RCF	4	Yes	Yes	1989	Poor	Severe	0.80
13	BNG-11-4-4	RCF	4	Yes	Yes	2000	Poor	Moderate	0.80
14	BNG-11-4-5	RCF	4	No	Yes	1997	Average	Light	0.74
15	BNG-3-4-1	RCF	4	No	No	1998	Poor	Light	0.59
16	BNG-3-4-2	RCF	4	No	No	1996	Average	None	0.58
17	BNG-3-4-4	RCF	4	No	No	-	Average	None	0.11
18	BNG-5-5-1	RCF	5	Yes	Yes	1990	Average	Light	0.80
19	BNG-6-2-8	RCF	2	Yes	Yes	1992	Poor	Severe	0.80
20	BNG-6-3-1	RCF	3	Yes	No	1991	Average	Moderate	0.72
21	BNG-6-3-10	RCF	3	Yes	Yes	1995	Good	None	0.50
22	BNG-6-3-11	RCF	3	Yes	Yes	-	Average	None	0.50
23	BNG-6-3-12	RCF	3	Yes	Yes	-	Average	Light	0.50
24	BNG-6-3-4	RCF	3	No	No	2003	Average	Light	0.58
25	BNG-6-4-2	RCF	4	Yes	Yes	2001	Poor	Severe	0.80
26	BNG-6-4-3	RCF	4	Yes	Yes	2003	Poor	Collapse	0.70
27	BNG-6-4-5	RCF	4	No	Yes	1996	Good	None	0.70
28	BNG-6-4-7	RCSW	4	No	No	1996	Poor	Severe	0.40

The FIS is performed on the datasets summarized in Table 1 and corresponding I^{BV} values are computed. A through and detailed discussion on the FIS is provided in Tesfamariam and Saatcioglu (2008). The linguistic transformation of the basic risk parameters are modified for the Turkish earthquake, and summarized in Table 2.

Table 2 Transformation of linguistic inputs

Basic parameter	Linguistic parameter	Transformation
Vertical irregularity	Yes, No	0.75, 0.20
Plan irregularity	Yes, No	0.95, 0.20
Construction quality	Poor, Average, Good	0.90, 0.75, 010
Year of construction	1940-1953, 1954-1967, 1968-1971, 1972-1996, 1997-2005	0.95, 0.80, 0.75, 0.55, 0.15
Building type	RCF, RCSW	0.55, 0.10

For plotting purpose, the five discrete damage states, N, L, M, S and C, are assigned numeric values, 1, 2, 3, 4, and 5, respectively. For the RCF and RCSW buildings shown in Table 1, I^{BV} values are plotted in Figure 5 with respect to the observed damage states. From Figure 5, it can be discerned that the I^{BV} shows an increasing trend with respect to the observed damage. The model uncertainty is reflected with variability of the I^{BV} values at each damage states, reflected through a scatter at each damage state. This scatter highlights the need to gather more information on the potential causes of building vulnerability and site seismic hazard.

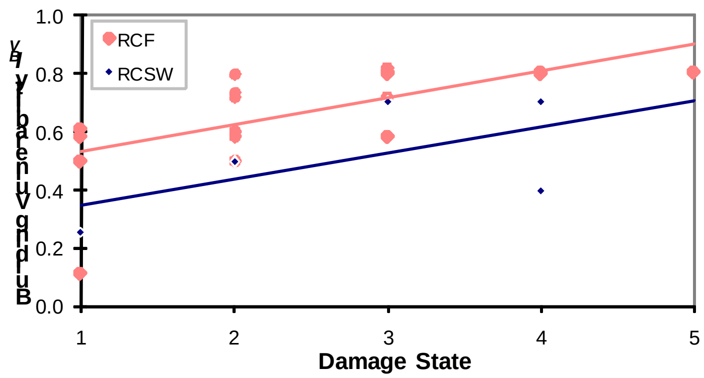


Figure 5 Building vulnerability index for 2003 Bingöl Earthquake

5. CONCLUSION

Risk assessment of existing structures is paramount importance in the management and mitigation of risk. Different building vulnerability techniques have been reported, each with different levels of complexity, ranging from a simple scoring method to more complex methods of nonlinear structural analyses. The complexity of building assemblage model and its response to seismic loading are handled through a simple hierarchical structure. In this paper, a risk-based RC building assessment is presented. The proposed method risk-based prioritization is undertaken by integrating site seismic hazard, building vulnerability, and importance/exposure factor. The basic risk items are obtained form a walk down survey. The subjective evaluation of the walk down survey is prone to vagueness uncertainty. Thus, a fuzzy based system modeling using fuzzy synthetic evaluation technique is proposed and illustrated through the 2003 Bingöl earthquake.

The FRB modeling of 2003 Bingöl earthquake show a good correlation with observed damage. The hierarchical structure and basic risk items identified are intended to capture the structural deficiencies identified in FEMA 154 (ATC 2002). The hazard considered for the 2003 Bingöl earthquake is only using a single response spectrum. However, since, site seismic hazard has spatial and temporal variability; two building with the same building vulnerability will have different building damageability. Hence, in further implementation of the proposed risk assessment, the proposed method has to be implemented in a GIS based platform to capture spatial variability. Furthermore, sensitivity of different hazard quantification need to be considered. Albeit limited data, the proposed heuristic method of estimating seismic risk is promising.

REFERENCES

ASCE. (1998). Handbook for Seismic Evaluation of Buildings – A Prestandard. Prepared by the American Society of Civil Engineers, published by the Federal Emergency Management Agency, (FEMA 310 report), Washington, D.C.

ATC. (1985). Earthquake Damage Evaluation Data for California, Applied Technology Council, ATC-13 Report, Redwood City, California.

ATC. (2002). Rapid Visual Screening of Buildings for Potential Seismic Hazard: A Handbook. (Second edition), prepared by the Applied Technology Council, published by the Federal Emergency Management Agency, (FEMA 154 report), Washington, D.C.

Bobet et al. (2004). Geotechnical aspect of Bingöl Earthquake, 1 May 2003 Bingöl Earthquake Engineering Report, Chapter 4 (ed. G. Özcebe, J. Rairez, S.T. Wasti and A. Yakut),

http://www.seru.metu.edu.tr/archives.html.
Boissonnade, A.C. and Shah, H.C. (1985). Use of Patter Recognition and Fuzzy Sets in Seismic Risk Analysis, Report 67, Stanford, California: John A. Blume Earthquake Engineering Center.
Doğangün, A. (2004). Performance of reinforced concrete buildings during the May 1, 2003 Bingöl earthquake in Turkey, *Engineering Structures* **26**, 841-856.
Dong, W., Chiang, W.L., and Shah, H.C. (1987) Fuzzy information processing in seismic hazard analysis and decision making. *Soil Dynamics and Earthquake Engineering* **6:4**, 220-226.
EERI Committee on Seismic Risk. (1989). The basics of seismic risk analysis, *Earthquake Spectra* **5:4**, 675–702.
Ellingwood, B. (2001). Earthquake risk assessment in building structures, *Reliability Engineering and System Safety* **74**, 251-262.
FEMA 249. (1994). Assessment of the State-of-the-Art Earthquake Loss Estimation Methodologies.
Gülkan and Akkar (2004). Evaluation of the strong ground motion, 1 May 2003 Bingöl Earthquake Engineering Report, Chapter 2 (ed. G. Özcebe, J. Rairez, S.T. Wasti and A. Yakut), http://www.seru.metu.edu.tr/archives.html.
Joslyn, C. and Booker, J. (2005). Generalized Information Theory for Engineering Modeling and Simulation, Engineering Design Reliability Handbook, ed. E Nikolaidis et al., pp. 9:1–40, CRC Press.
Klir, G.J. and Yuan, B. (1995). Fuzzy Sets and Fuzzy Logic: Theory and Applications, Prentice Hall International, Upper Saddle River.
Meirovitch, L. (1967). Analytical Methods in Vibrations, Macmillan, New York.
Miyasato, G.H., Dong, W., Levitt, R.E. and Boissonnade, A.C. (1986). Implementation of a knowledge based seismic risk evaluation system on microcomputers. *Artificial Intelligence* **1:1**, 29-35.
NRC. (1992). Manual for Screening of Buildings for Seismic Investigation, Institute for Research in Construction, National Research Council of Canada, Ottawa, Ontario.
NRC. (1993). Guidelines for Seismic Evaluation of Existing Buildings, Institute for Research in Construction, National Research Council of Canada, Ottawa, Ontario.
NZSEE. (2006). Assessment and Improvement of the Structural Performance of Buildings in Earthquake, New Zealand Society for Earthquake Engineering, Aukland, New Zealand.
Parsons, S. (2001). Qualitative methods for reasoning under uncertainty, MIT, Cambridge.
Tesfamariam, S. and Saatcioglu, M. (2008). Risk-based seismic evaluation of reinforced concrete buildings, *Earthquake Spectra* **24**:**3**, 795–821.
Wen, Y.K., Ellingwood, B.R., Veneziano, D. and Bracci, J. (2003). Uncertainty Modeling in Earthquake Engineering, MAE Center Project FD-2 Report.
Yao, J.T.P. (1985). Safety and Reliability of Existing Structures, Pitman, Boston, 130 pp.
Zadeh, L.A. (1965). Fuzzy sets, *Information Control* **8**, 338-353.
Zadeh, L.A. (1973). Outline of a new approach to the analysis of complex systems and decision processes. *IEEE Transactions on Systems, Man, and Cybernetics* **3**, 28–44.