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Seismic Risk Management: A System-based Perspective

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Abstract

The deployment of seismic risk management is fraught with issues of complexity, ambiguity and uncertainty which pose critical challenges in assessing, modelling and management. The complexity of earthquake impacts and the uncertain nature of information necessitate establishing a risk management system to address the risk of many the effects of seismic events in a reliable and realistic way. This study was launched to review and criticize appropriate risk assessment methods for different seismic applications focusing on general characteristics from a systems perspective. The outcome of this study demonstrates the importance of a system perspective, providing a deeper insight into the background characteristics and the potential challenges involved within seismic risk management. This allows users to compare various systems and to choose the most appropriate approach according to the scope, size, accuracy and complexity of the application.

Keywords: seismic risk management, risk assessment, system approach

1. Introduction

Earthquake events are inevitable, but the consequences of earthquake disasters are partially controllable using an effective risk management system, since the seismic risk is the interaction of multiple participant factors with likely consequences. Thus, it is important to address the seismic risk for any group of interest before taking any risk preventive measure. However, whilst it is impossible to estimate precisely the probability and severity of an earthquake due to stochastic (random) nature; while the adverse effects of an earthquake can be effectively reduced or avoided using appropriate risk assessment and management procedure (Bostrom et al 2006). Risk assessment provides a roadmap for estimating the adverse outcomes of earthquakes in order to reduce the fatalities, injuries and damages. Risk management helps communities to reduce significantly the severity of any losses by identifying and assessing the potential factors that contribute to the earthquake loss process and proposing the appropriate action (response). In a broad sense, risk management highlights strategies and measures to control and manage the adverse effects of earthquakes. Since the seismicity, severity and probability of earthquakes cannot be reduced and modified, the management of the risk would logically focus on reducing the vulnerability as an effective measure of loss/damage mitigation.

According to Vahdat et al (2014) seismic risk management is intrinsically complex in nature due to its multidisciplinary context that involves multiple sources, cause-effects and interaction within criteria, alternatives and stakeholders. Further, planning for disaster risk management deals with not only the physical and structural consequences of a natural hazard but also the different socioeconomic, environmental, historical considerations that might influence a population or even future generations. An effective risk management framework should capable of integrating various perspectives of seismic risk; conducting seismic risk assessment; evaluating the mitigation strategies; and performing a risk-based trade-off among mitigation strategies (retrofitting decision). Improvement in the seismic risk damage prevention and mitigation process directly depends on the perception of earthquake impact which in its most general sense relies on experience and the quality of the assessment. This could directly affect the investment in seismic risk mitigation and preventive measures as well as the development of legislation, standardization, and governmental regulations and control (Ahmad and Simonovic 2011).

Tesfamariam and Goda (2013) state that "the risk management must be capable of weighting alternatives (options) and selecting the most appropriate action". This can be achieved by integrating the results of risk assessment with engineering data as well as social/economic/political factors to reach an acceptable decision. However, identifying, sorting and prioritizing a large group of infrastructure requires a systematic and flexible approach to customize and balance the multiple risk variables which is beyond the scope of existing models. Viewed from this perspective, the study proposes a system based perspective that is capable of addressing multiple dimensions of seismic risk management effectively and efficiently.

2. Seismic Risk Management

Risk management is the systematic application of policies, procedures and practices to the tasks of identifying, analysing, assessing, controlling and monitoring risk (Standards Australia/Standards New Zealand, 1995). A generic version of this process in the disaster context was stipulated by the United Nation Strategy for Disaster Risk Reduction (UN-ISDR, 2004):

The systematic process of using administrative decisions, organization, operational skills and capacities to implement policies, strategies and coping capacities of the society and communities to lessen the impacts of natural hazards and related environmental and technological disasters. This comprises all forms of activities, including structural and non-structural measures to avoid (prevention) or to limit (mitigation and preparedness) adverse effects of hazards.

The universal framework for seismic risk management is defined in four distinct risk measures, including preparedness, mitigation, response and recovery which are performed in pre/during and post-disaster (Table 1). Neal (1997) states that disaster phases are "mutually inclusive and multidimensional" as they are strongly interconnected; while each measure maintains the individual aspects of disaster to enhance the tasks of risk management.

Table 1 – Generic seismic risk management process (Altay and Green 2006)

Measure	**Phase**	**Activities**
Preparedness	Pre-Disaster	Emergency response plan, shelter, public information and education Evacuation plan, Earthquake training, manoeuvring, Warning system
Mitigation	Pre-Disaster	Retrofitting, rehabilitation, augmentation, reinforcing Legislation, Code enforcement, zoning/land use management, Insurance, reserve fund, site improvement
Response	During Disaster	Response strategy, critical management centre, mobilizing and medical aid service, search and rescue team, locating(GPS) and recording intensity, communication
Recovery	Post - Disaster	Medical service, rehabilitation, reconstruction, financial assistance, Restore public infrastructure, essential service and business

According to UN-ISDR (2004), preparedness refers to promoting the inherent knowledge and capacities by governments, critical emergency organizations, disaster professionals, communities and individuals in preparing a response and recovery plans for any likely event. Mitigation refers to set of strategies to reduce and limit the exposure or potential damage due to an earthquake. Mitigation strategies pay attention to preventive measures as the key intervention for seismic risk management. Response measures include sets of emergency provisions to assist the public immediately after a disaster, in order to save lives, reduce health impacts and to ensure public safety. Recovery is an unavoidable reaction performed by governments. Obviously, additional investment in preventive measures and preparedness can be more effective and economically-justified compared to post-disaster actions and reduces the cost of response and recovery (Simonovic 2011). This is the reason why mitigation is highlighted as a critical measure within seismic risk management.

Essentially, identifying future mitigation is the main concerns of risk management, which closely links to vulnerability thereby requiring a reliable estimation of loss and potential capacity of damage within the built environment. Risk management aims to reduce the potential losses and damage within communities by identifying and assessing the potential factors that contribute to those effects and proposing appropriate response action. Since the seismicity and severity of earthquakes cannot be reduced or modified, the management of the risk logically focuses on reducing vulnerability as an effective measure for damage mitigation. It is impossible to predict the severity of an earthquake in a given area due to its stochastic (random) nature; however the adverse effects of an earthquake can be effectively reduced or avoided using appropriate risk assessment and management (Bostrom et al 2006). Thus, risk assessment and management are complementary processes, while the former uses a systematic method to determine the probability of adverse effects, the latter tries to systematically decide and choose the appropriate option to manage the risk (e.g. mitigate, transfer, response, recovery). The outcomes of system perspective collectively secure a proper integration of operational risk management into the policies, plans and mitigation programme.

3. Characteristics of Seismic Risk Management

Seismic risk management is characterized in multiple dimensions, typically as social, economic, political, environmental and others which can often be in conflict with each other. Several alternatives need to be considered and evaluated in terms of the many different criteria which results in a vast body of data that are often imprecise or uncertain. A large number of people are usually involved in the risk assessment process, including decision makers, planners, experts and other interest groups from organizations and the community all of whom may have conflicting preferences (Lahdelma et al 2000). The scope of seismic risk management involves balancing these variables as shown in Figure 1.

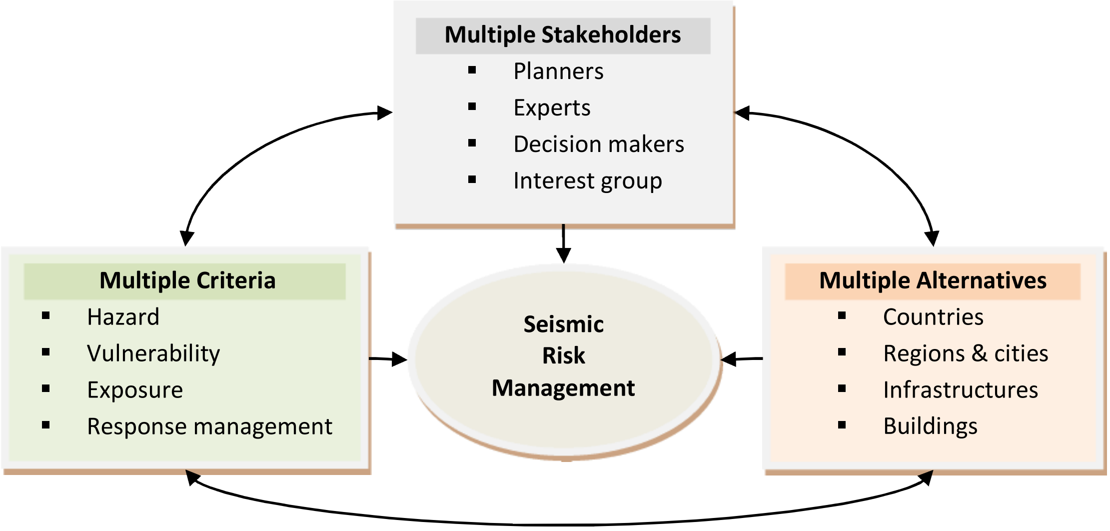


Figure 1 - Multifaceted aspects of seismic risk management (Vahdat et al 2014a)

Risk management is concerned with modelling and assessing risk which can refer to the inherent characteristics of the disaster risk system. This chracteristics of the systematic perspective would secure public engagement, imrpoved situational awareness and comprehensive picture of seismic risk, greater organizational agility for disaster management, more robust, interoperable communication and better resource allocation and tracking. The systematic perspective secures long-term strategic policies for disaster risk management, identifying the potentially weak point that require special attention during disaster management, ensures an preparedness and an effective response prior to an earthquake. The multiple views and interactions within risk factors, alternatives, individuals and organizations cause an inherent complexity that requires a systematic, structured reconciliation of these disparate, often conflicting factors with the contradictory information (Avouris 1995). System perspective can effectively address the potential challenges caused due to complex multidimensional aspects of seismic risk and handle uncertainties present in decision process due to spectrum of objective and subjective information.

4. System View of Seismic Risk Management

Risk analysis is naturally involved with a complex, multidimensional process that requires the integration of myriad information from multiple sources to characterize the seismic risk. According to Haimes (2012a) “the entire process of risk assessment, management, and communication is essentially a synthesis and an amalgamation of the empirical and the normative, the quantitative and the qualitative, and of objective and subjective evidence”. Different thinking is required to address the challenges associated with defining, modelling and quantifying the risk which is often influenced by the modeller’ skills and experience. Several quantitative and qualitative tools and techniques contribute to risk analysis to improve understanding of risk in specific disciplines. However the intricacy and complexity involved in risk assessment cannot be modelled, understood and addressed through ad-hoc approaches. Given the diversity in size, scope, functionality and configuration of current infrastructure and given the immense uncertainty associated with risk management process, modelling should be grounded on a systemic and repeatable basis presenting the multidimensionality characteristics of seismic risk through integration of multiple metrics.

A systems approach is appropriate to manage complex problems by decomposing them into simpler sub-systems or components (Deng et al 2011). This approach usually focuses on interactions among the myriad elements involved in risk assessment and on the effects of their interaction in future decisions. System-based risk modelling can effectively address the multifaceted composition of seismic risk by incorporating levels of uncertainty and complexity due to nonlinear natures of the states of all human and built environments (Haimes 2009). Aven (2011) argues that risk and vulnerability are the manifestation of the inherent state of the system and its environment and hence should be dealt with and quantified through a system-based hypothetical and methodological approach. Haimes (2012b) advocates that the process of risk modelling, assessment, and management must be holistic, comprehensive and repeatable and must be handled systemically to perceive the state of the system and model the system blocks. Accordingly, the system approach is required for complex situations to improve the understanding of the system's characteristics including function, behaviour and interactions.

Hence, a system-based approach to risk assessment and management is of utmost importance for the credibility and effectiveness of decision making and the ultimate quantification of the complex multidimensional aspects of the seismic risk.

5. Classification of Seismic Risk Models

Seismic risk management occurs from a nationwide to a regional scale. This universality disables its applicability for a given specific practice, consequently customization is required according to local conditions. Klugel (2008) asserts that seismic risk assessment must be conducted in a way to minimize the effort needed to obtain the results based on the client's need. Risk assessment should consistently address the importance of application. The form and richness of the results should also correspond with application needs and objectives. Because of the difficulties involved with evaluation of hazard and vulnerability, risk assessment models could vary considerably from well-structured analytical models to empirical heuristic approaches. In this light, several seismic risk models can be distinguished in literature which has been designed for a particular application. Reviewing the literature, the most common variants of seismic risk assessment can be identified in four categories as indicated in Table 2.

Table 2 – Different classes of seismic risk assessment

Class	Model	Scope of application	Parameter used	Risk analysis		Reference
				Hazard analysis	Vulnerability analysis	
I	Deterministic	Critical infrastructure	Detailed geological	Deterministic	Analytical	Klugel (2006)
		High importance facility	Seismo-tectonic data			Konakli &Kiureghia(2011)
		Specific studies	Detailed Structural	Stochastic		Berrah & Kausel (1992)
II	Probablistic	Noncritical infrastructure		Probablisitc	Empirical/ Statistical	Yakut et al (2006)
		Important building/facility	Magnitude Frequency Relation			Yucemen et al (2004)
		Infrastr. Network analysis				Kiremidjian et al (2007)
		Local and regional studies	Damage Index		Analytical	Park and Ang (1985)
			Detailed Structural			Gulkan and Sozen(1999)
			Hazard distribution functions			Bozorgnia & Bertero(2003)
						HAZAUS (2001)
III	Heuristic	Building in large area	General technical	Heuristic	Heurisitc	Carreno et al (2006)
		Mitigation programme	Inventory data			Tesfamariam & Wang(2011)
		Global/regional risk analyis	Economic Index			Karbassi & Nollet (2008)
		Urban /Mega cities studies	Social Index	Microzonation Maps		Sucuoglu & Yazgan (2003)
		Portfolio of buildings				Davison and Shah (1997)
		Resource allocation				Miyasato et al. (1986)
		Financing/insurance				Fruta et al (1991)
IV	Screening	Regional studies	General technical	Code-based	Judgmental / Expert opinion	ATC-13 (1985)
		Mitigation program	Inventory data	Screening		Rojhan (1986)
		Planning , management		Microzonation Maps	Checklist	ATC-21 (2002)
		Disaster risk management				ATC-40 (1996)
		Financing/Insurance				NRCC (1992)

5.1 Deterministic Model

For high importance applications and critical infrastructure (i.e. dams, nuclear plants) a deterministic model (DSRA) is the most appropriate option as there is no compromise between the simplification of structural models and the efficiency of analysis (Klugel 2008). DSRA is a deterministic approach since it is based on objective data, facts and physical models. DSRA in broader senses can be regarded as a stochastic process (Wen 2003). Using response spectrum and time-history analysis methods, Konakli and Kiureghian (2011) applied a stochastic dynamic analysis to investigate bridges considering the spatial variability of ground motions. A deterministic approach allows detailed investigation of structural response using advanced analytical models which allow a more precise interpretation of seismic risk with respective scenarios. However, developing such complex models requires sophisticated tools and expertise that can be used for single studies of high-importance infrastructure at detailed design stage.

5.2 Probabilistic Models

Probabilistic seismic risk assessment (PSRA) in a broader sense focuses on the most probable earthquake by defining the frequency of events or the frequency of exceedance of ground motion (or exceedance probability). A PSRA can be implemented for less important applications such as regular infrastructure, facilities and buildings in both regional and local studies. Unlike DSRA, in PSRA all possible earthquakes that may affect the system may be considered and imported into the model. Quantification of the most probable mode of damage is a challenging task because different states of damage have to be distinguished objectively in terms of material, age, quality and functionality. Generally, potential losses for different classes of structures are based on prior historical damage. The potential damage is often presented in two forms of fragility curves (or vulnerability functions) and damage probability matrix (DPM). Intersecting the most probable earthquake with fragility curves, the most likely damageability level of a building can be estimated for a given earthquake magnitude. Essentially, the vulnerability function is a subjective metric for assessing and predicting the potential damage of buildings which is developed by clustering the statistical damage records for different classes of buildings. Historical records of damages are evaluated following an earthquake by groups of experts. Hence the accuracy of the functions relies on the quality of records and expert's experience. Coburn and Spence (2003) developed typical vulnerability functions for masonry buildings for different states of damages as a metric of intensity measure. More complete databases for vulnerability functions were documented in ATC-13 (1985) and HAZAUS (2001) which covers the most typical classes of structures in the US.

In probabilistic approaches, macro seismic intensity scales and fragility curves establish the underlying concepts of probabilistic risk models. However, analysing the seismic risk on the basis of vulnerability functions and intensity scales raises some issues. According to Coburn and Spence (2003) significant uncertainty due to variations in observed data can potentially be imported to the fragility curves while distinguishing the threshold among the different states of damages relies on the perception of the experts and can significantly vary among different groups of survey in different places. Another issue is the estimating of intensity which is inherently a descriptive, not a continuous scale, which makes it difficult to use for predictive purposes since intensity scales assume a relationship between the performance of typical building types with certain configurations which may not precisely match in practice.

There have been several attempts to improve the quality of vulnerability analysis using analytical and empirical methods. Yucemen et al (2004) proposed a simplified damage index to estimate the seismic vulnerability of low-rise to mid-rise reinforced concrete buildings. Yakut et al (2006) developed a scoring system for estimating the damage within low rise buildings using different structural and seismic modifiers. Park and Ang (1985) developed an analytical damage index for estimating the vulnerability of RC buildings. The potential levels of damage were characterized as a function of seismic intensity based on two probable earthquakes, 1971 San Fernando earthquake and 1978 Miyagiken-Oki earthquake, for calibration and verification. Basoz and Kiremidjian (1996) used the PSRA to prioritize the risk within bridge networks that intended for retrofitting. In this process the basic hazard and vulnerability factors (ground motion, expected structural damage) was combined to estimate the expected utility of the bridge. Temporal variation in seismic hazard was implicitly included in the analysis by taking the maximum credible earthquake (500-year-return period intensity measure). Using a damage index as the sole criterion for estimating the risk is a reliable measure, although the threshold of structural damage can also be correlated with other indirect consequences and socioeconomic losses (e.g. human losses and casualties, costs of rehabilitation) to get better performance (Coburn and Spence 2003). Nevertheless, importing such indirect effects into the existing frameworks is problematic.

5.3 Heuristic Models

Probabilistic models have been used extensively in regional risk assessment due to the inherent simplicity. These methods require extensive damage records from previous events which may not always available. Heuristic models are an alternative mid-range option that can be used flexibly in conjunction with analytical and empirical models to overcome existing limitations. The common feature of heuristic models is the use of a systems approach as an underlying concept.

Basically, seismic risk management requires not only the estimation of seismic risk, but it also needs the detailed values of risk factors to effectively support mitigation decisions. This need requires a comprehensive systemic view that can be achieved through heuristic frameworks. The holistic view allows customizing of the structure of risk, thereby decision makers can better focus on different pieces of knowledge and clearly identify the critical attributes within the risk system. A heuristic model in a broader sense can be regarded as "a transparent simulation box" while is applicable as an information system and useful tool for higher classes of mitigation programme. However the scope of these models is limited to approximate risk assessment for disaster planning and management and they are not precise enough to be used in the detailed design stage, comparing to deterministic and probabilistic models.

The application of systems approach in modelling the seismic risk has been reported in literature. Miyasto et al (1986) have developed a hierarchical risk system for preliminary evaluation of seismic risk for different types of buildings. Fruta et al (1986) proposed a knowledge-based expert system for assessing the damage status of bridge structures based on the fuzzy reasoning method. Gulkan and Yakut (1996) developed a rule-based expert system for integrating various seismic and structural attributes for estimating the damage levels of the buildings. Davison and Shah (1997) introduced a linear additive model for evaluating and comparing earthquake risk between major metropolitan cities worldwide. Cardona et al (2004) developed a holistic risk system, taking into the account socioeconomic aspects of seismic risk, including physical exposure, social fragility and resilience. Using the structural damageability index as the major factor, Tesfamariam and Wang (2012) established a fuzzy-based risk assessment system for prioritizing civic infrastructure in the US. Using a weighted arithmetic mean (WAM), Sucuoglu and Yazgan (2003) have developed a two-level seismic risk assessment tool for Istanbul. The model integrates the most critical structural performance modifier using multivariable stepwise linear regression analysis procedure. Karbassi and Nollet (2008) developed a fuzzy inference system to evaluate the risk of failure in water main pipelines in Quebec. The common advantage of existing heuristic model is a systematic aggregation of likely impacts to evaluate the utility of the interest options for certain area that could effectively support disaster risk management. However, existing practices fail to provide a solid means to assess the accuracy and reliability of simulation. Another issue of heuristic is the scope of application of each model limited to the certain situations designed for and may not have a wide generality to be applied to other regions. Nevertheless, heuristic models are still an open context capable of addressing several policy challenges involved within mitigation programme at larger organizational scale.

5.4 Screening Models

Screening models provide a simple method for highlighting vulnerable buildings among large group. The process is conducted a rapid visual survey to identify inventory and thus classifies buildings that are potentially hazardous for safety (ATC-21 2002) by the mean of structural performance index (SPI). Hazardous buildings are identified by examining the building characteristics such as seismicity, soil condition, structure type and irregularities, usage and occupancy to determine the overall SPI. Different versions of screening procedures have been suggested by ATC for evaluating the potential hazardous buildings (ATC-10 1982; ATC-13 1985; ATC-14 1987; FEMA-154 2002). ATC-13 and ATC-14 provide data and methodology that serve as the basis for "Rapid Visual Screening "(RVS) updated in FEMA-154 particularly developed for the hazardous regions of US such as California. A similar process was developed in Canada (NRCC 1992) and NewZealand (NZSEE 2009).

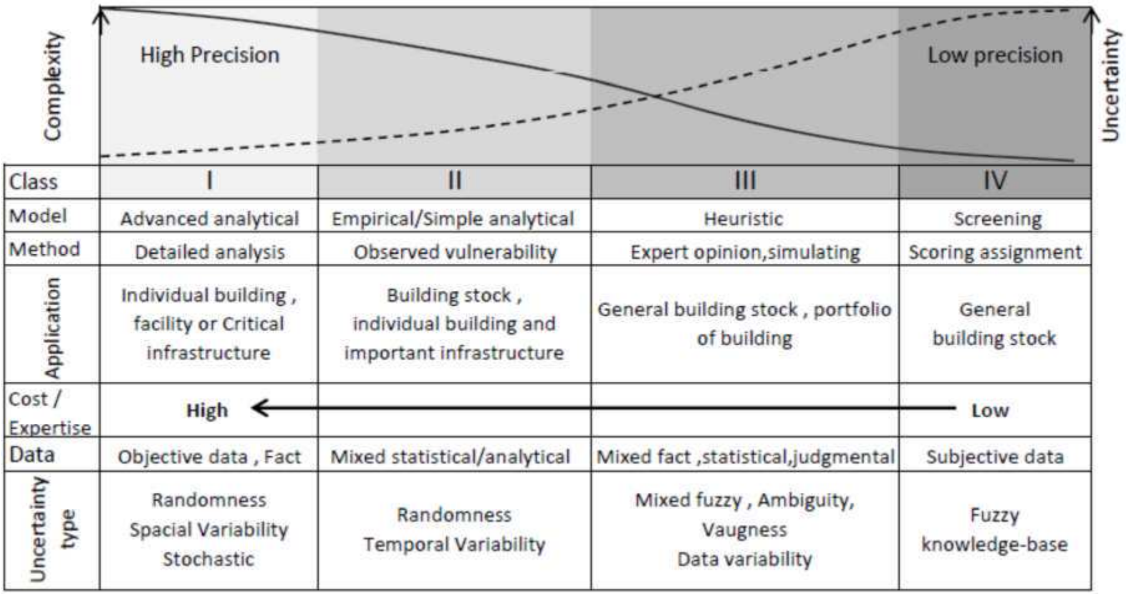
Screening models follow a simple procedure to rapidly evaluate those buildings that require urgent mitigation action. The process supports the mitigation process by addressing the public safety concerns within the community. However the scope focuses on structural damage as direct mean of vulnerability assessment; other indirect damage induced by earthquake hazards such as ground failure (e.g. Liquefaction, landslide) is not addressed in these models. In addition, the form, quality and accuracy of scoring tactics is a major concern in screening models. The information collected from a field survey is always prone to high subjective error. As a result, great amount of uncertainty can be imported into the model due to variability between the observed and actual data. Other shortcomings of screening models are addressed in the literature (Rojhan 1986; Karbassi and Nollet 2008). The scoring model and its weight are pre-set and provided for facilities in California. The procedure uses general buildings with average conditions as representative of the whole structural group. There is the largest margin of uncertainty within the visual survey, which is still not addressed by this procedure. Further, large amounts of information are required for verification and validation of the model. In a broader sense, screening models can be regarded as a specific case of heuristic models as they use the simple additive model to score the alternative buildings according to their structural type, age, material and configurations. The scope of screening models and rigidity in using built-in criteria limits their applicability to preliminary risk assessment.

6. Problems in Seismic Risk Management

Risk assessment entails the process of quantifying the risk and essence of any disaster management process. It offers a reliable tool for making rational decisions that is often used prior to rehabilitation and developing emergency response and recovery plans. Decisions about mitigating seismic risk rely on the quality of the risk assessment and the spectrum of uncertainties in risk parameters and process. Some of these uncertainties can be addressed and reduced stochastically through standard procedures (i.e. ATC-14 1987). Eguchi and Seligson (2008) note about evaluation pitfalls that commonly occur in standard procedures and lead to under-prediction within large scale and over-prediction of losses in small earthquake events. They justify that the damage functions developed for such earthquakes are mostly based on specific scenarios derived from severe earthquakes in California (1971 San Fernando and 1994 Northridge) thereby covering a narrow range of magnitude (strong to severe), and essentially ignoring the potential losses within areas experiencing lower or greater (outrange earthquakes) (Eguchi et al 2008). The mitigation decisions made based on these models could be valid only for a specific geographical area and may not reliable for other regions. For example, ATC-14 method of “Evaluating the seismic resistance of Existing Buildings” deals with regions experiencing few, but low intensity earthquakes which is applicable to certain regions of the US. Thus, the selection of appropriate analysis should be based on understanding the underlying concept, scope of analysis and considering its strength and limitation to different applications.

From a system viewpoint, various classes of applications can be distinguished according to their accuracy and complexity of modelling as indicated in Table 3. The complexity and uncertainty of each procedure might significantly vary dependant on the scope and type of problems for which they designed. For example, some deterministic models are suitable for detailed individual studies; whereas screening procedures can be useful for large group evaluation and prioritizing. Thus, to handle the problem of seismic risk management, the prospective models should have adequate functionality and structure to address the multifaceted nature of risk. The risk analysis must be appropriate to the scope of application, not be too complex that make the process expensive, and also not too simple to trade-off the simplicity for effectiveness. The model should also have adequate preciseness to handle both objective and subjective uncertainties commonly involved with different types of qualitative and quantitative information.

Table 3 – Complexity and uncertainty within different classes



Class	I	II	III	IV
Model	Advanced analytical	Empirical/Simple analytical	Heuristic	Screening
Method	Detailed analysis	Observed vulnerability	Expert opinion,simulating	Scoring assignment
Application	Individual building , facility or Critical infrastructure	Building stock , individual building and important infrastructure	General building stock , portfolio of building	General building stock
Cost / Expertise	High ←			Low
Data	Objective data , Fact	Mixed statistical/analytical	Mixed fact ,statistical,judgmental	Subjective data
Uncertainty type	Randomness Spacial Variability Stochastic	Randomness Temporal Variability	Mixed fuzzy , Ambiguity, Vaugness Data variability	Fuzzy knowledge-base

Currently, the majority of existing models has primarily focused on the structural system performance, building capacity, layout and certain response parameters. Detailed risk analysis relying on a comprehensive data collection that are generally employed for the assessment of individual buildings, as they require sophisticated modelling, thereby aim to determine whether the building needs rehabilitation (Yakut et al 2006). Although detailed analysis provides high-precision results, it is restricted to individual case studies and thus cannot be used for regional studies in which a large number of buildings is involved. Furthermore, these methods are based on underlying theory that could only handle the inherent variability of the hazard data (randomness) and are unable to address the uncertainties commonly involved in decision process due to modelling, parameters and modellers perception of risk. Klugel (2008) reviewed different versions of seismic risk assessment approaches and identified that the traditional probabilistic concept has insufficient understanding of modern risk analysis. This could result to inability to present a correct definition of the true relationship and hence proposes inappropriate treatment of uncertainty. For such situations, heuristic models utilizing limited data and simple simulation are preferred because they require less cost and expertise to deal with and take into consideration more practical factors tailored for regional studies. These models have the flexibility to deal with a broad range of data and precision in practice. Hence, the research study seeks to establish a heuristic model, able to handle a portfolio of building in regional level effectively and efficiently.

Viewed from this perspective, the heuristic method was identified as the best category that fits the scope of study and thus adopted for the problem of seismic risk management for several reasons. First, the risk management process is an interdisciplinary concept that several risk parameters (expressed in various forms, accuracy and quality) from multiple sources have to be combined as an input data; while processing such a complex information system is beyond the ability of conventional methods. Second, the subjectivity involved within seismic risk management requires a flexible, well-structured methodology that could simply handle the predominant form of knowledge consistent with uncertainty theories. For example, risk analysis is concerned with estimating the potential impacts and disastrous consequences. The diagnosis of damage is a subjective process that is largely based on the intuition and experience. A knowledge based system provides a consistent means of system approach that is capable of handling vague, imprecise knowledge and addressing the subjectivities involved within the process. Third, decision making in mitigation is a multidisciplinary process and requires detailed information within each category (e.g. Hazard and Vulnerability) along total risk. Heuristic (system) view of risk suggests a comprehensive picture of seismic risk by the means of detailed knowledge, thereby supports seismic risk management. Overall, heuristic model can explain and clearly address the systemic interaction involved with the process of seismic risk assessment and management.

7. Challenges in Seismic Risk Management

Risk management strategies are concerned with an objective risk assessment that is based on hazard analysis (e.g. intensity) and vulnerability analysis (e.g. potential damage). Ultimate efficacy of risk management is to provide an effective and efficient risk assessment to support decisions and policy options (Smith et al 2006). Underestimation of risk may result in ineffective mitigation and inadequate preparedness and response measures; while over-estimation of risk could lead to costly mitigation efforts. Decisions about risk management are made upon risk assessment results which are rarely free of the multidimensional aspects of the earthquake, including social, political, economical and strategic considerations. Thus, seismic risk management can be particularly challenging because multiple participants with different sorts of influence and behaviour are involved in the risk process (Bristow et al 2012). Further, the difficulties in processing risk can be referred to two major concerns and limitations; The complexity of the disaster system due to the interactions among multiple quantitative/qualitative, linear/non-linear risk variables. Establishing the proper relationships among risk input parameters and output consequences is difficult. The uncertainty involved within seismic risk assessment are related to describing the level of hazard (identification of initiating events, measurements of severity of ground shaking and frequency of occurrence which is random in nature) and to the vulnerability of facilities (estimate of loss to facilities for various levels of intensity is subject to ambiguity in knowledge and lack of experience)

This implies that the characterization of uncertainties is critical in both hazard and vulnerability assessment. According to McGuire (2008) unbiased quantification of uncertainties is crucial to making rational decisions for risk mitigation and seismic risk cannot be accurately estimated without quantifying the epistemic uncertainties in ground shaking or in building response and damage. The need to quantify uncertainty has been extensively addressed in risk applications such as NERHP, PEER and FEMA. However the reliability of these models in describing and incorporating the uncertainties within the process has not properly examined. For example HAZUS provides a standard loss estimation model through probability estimation of credible earthquakes for high seismic regions in the US; although the inability to explicitly address the uncertainty reduces the cost-effectiveness of retrofitting options proposed by the model (Davison 2008; Durham et al 2008). The standard procedure enhanced within FEMA-154 (2002) or similar versions in

Canada (NRCC 1992) serve as a rapid diagnostic tool for prescribing ‘retrofit’ or ‘not to retrofit’ decision. Essentially, these approaches target a broad range of buildings through simple walk-down survey; while they fail to clearly address the detail reasoning for the decision. Analytical approaches provide an in-depth investigation of earthquake hazard, although it is limited to merely provide a random picture of seismic risk. Further, existing risk assessment approaches provide a prescriptive procedure that covers general types of problems. Predefined (built-in) risk parameters in such approaches can be adapted to cover broad spectrum of facilities in terms of size, functions, occupancy load, etc. In addition, current approaches integrate some information with pre-set-weights based on the common statistical cases. The main issues in these prescriptive approaches are inability, inflexibility to add/remove new variables/options due to prescriptive concept; the inability to change the importance (or weight) of the variables for certain problems; the inability to track the operation and parameters in the model; the inability to apply for particular seismic application (i.e. critical portfolio of buildings); the inability for tuning due to the low sensitivity of model to small changes in risk input parameters (i.e. screening models).

Rational risk management should be capable of comparing and prioritizing multiple alternatives effectively. The ability to compare risk across regions becomes more critical to both private and public stakeholders who have competing priorities for urgent retrofitting action. Inadequate risk-informed decisions could compromise the mitigation measures by retarding the retrofitting, renovation and even reconstruction process. Moreover, there is a need for a simple but a well-grounded risk management system to interplay within different levels of risk knowledge and decision makers. Therefore, a rational risk management system to address multidimensional impacts of earthquakes and support mitigation decisions is paramount.

8. Uncertainty in Disaster Context

The nature of uncertainty in a problem is crucial and should be carefully considered prior to the selection of an appropriate method (Ross 2004). The challenge of selecting method is “to formulate suitable numerical models in a quantitative manner without ignoring significant information; inappropriate modelling of uncertainty can undermine the purpose of an analysis, computational results may deviate significantly from reality and associated decision may lead to serious consequence" (Beer et al 2013). Basically, a mathematical model can be formulated by analysing the nature of the available information. In reality, available information may appear in various forms, objective or subjective, imprecise, incomplete vague, ambiguous, conflicting and linguistic. The appropriate model should support the type and quality of information to consistently address the problem in a particular case.

Table 4 gives a summary of information commonly used in various seismic risk applications. Refer to various classes of risk analysis already discussed in Chapter 2 (section 2.6), the role of vulnerability or hazard analysis might vary considerably. For example, the stochastic nature of the earthquake (or randomness) in terms of time (temporal) and location (spatial) is a core concept within DSRA and PSRA; while in heuristics and screening approaches the vulnerability assessment is highlighted. Decisions regarding risk mitigation have been highly focused on estimating the capacity of damage within existing buildings rather than spatial or temporal considerations of an event. The inherent ambiguity and vagueness associated with vulnerability assessment make a compelling reason that seismic risk assessment is prevailed by subjectivities as results of vague or imprecise terms frequently used in risk assessment, damage assessment and expert judgments. Vague, imprecise and incomplete nature of inputs of the risk parameters can be suitably handled using fuzzy set theory.

Table 4 - Generic information/policies involved within seismic applications

Application	User	Policy	Information	Category

Urban planning	Planners	Identify high risk locations for urban design and infrastructure development	Risk mapping	Risk
Building Retrofit	Owners	The best retrofitting option	Structural capacity Cost-benefit	Vulnerability Economy
Mitigation Programme	Disaster manager	Identify high-risk portfolio screening	Potential buildings capacity	Vulnerability
Insurers and reinsurers	Insurer company	Set insurance premium	Annualized loss exceedance probability	Hazard
Emergency planning	Civil protection agencies	Plan size and location of emergency facilities	Estimate potential fatalities, injuries, damages	Hazard Vulnerability Exposure
Building code development	Building regulators	Determine optimum resistance levels	Structural algorithm Experiments cost-benefit data	Vulnerability, Hazard Economy

Sources: Ozcan et al (2011), Birkmann (2006), UN-ISDR (2004), NRC (2011)

Furthermore, “the level of uncertainty within a system is proportional to its complexity, which arises as a result of vaguely known relationship among various entities, and randomness in the mechanism governing the domain” (Deng et al 2011). Zadeh (1973) asserted “as the complexity of a system increases, our ability to make precise and yet significant statements about its behaviour diminishes until a threshold is reached beyond which precision and significance (or relevance) become almost mutually exclusive characteristics”. According to Blockley (2013) and Zadeh (1996) “complex systems cannot be dealt with effectively by the use of conventional approaches largely because the description languages based on classical mathematics are not sufficiently expressive to serve as a means of characterization on input-output relations in an environment of imprecision, uncertainty, and incompleteness of information”. In addition, it is difficult to precisely establish the temporal and spatial relation for earthquake events due to complexity and random nature of earthquake. Application of probability theory in the large complex disaster system is compromised.

9. Case Study 1: A National Risk Mitigation Programme for Schools

A mitigation programme is a good example of the application of systemic risk management. The vast majority of school buildings within high seismic developing countries requires urgent mitigation measures as they have been built upon outdated codes. Identifying the critical group and prioritizing them in order of urgency is crucial before any retrofitting commences. For instance, consider a mitigation programme in which large numbers of school buildings are competing for retrofitting funds. While the schools are subjected to varying degree of seismic hazard, the choice of alternatives is a multicriteria problem that not only involves with physical, structural aspects of buildings (i.e. structural performance) but it also contains socioeconomic dimensions (i.e. population exposed) and other background characteristics of community resilience (i.e. response management index, first aid facilities, shelters, hospitals, etc). The need to prioritize and decide on a large number of retrofitting projects with multiple interactions within tangible or intangible risk criteria require a systematic approach which is beyond the capability of conventional probabilistic methods. In addition, the efficacy of the right retrofitting choice of interest is important as it can affect the whole cycle of disaster management by improving the response, recovery service and ultimately strengthening the safety protection within the community.

Generally, several variables involved in such decisions including technical, social, economical, and environmental. In order to integrate several dimensions under a common framework, risk mitigation Programmes require a structured algorithm to initially recognize which class of buildings, under what conditions, and definition of safety level, and performance criteria should be imported into the Programme (Holmes 1996). Given the diversity in size, scope, functionality and configuration of existing school buildings and considering the immense uncertainty associated with risk management process, modelling should be grounded on a systemic basis presenting the multidimensionality characteristics of seismic risk through integration of multiple metrics. The questions and challenges in seismic risk management process cannot be addressed effectively and reliably without adhering to a systemic approach to risk modelling, assessment and management. Thus, prioritizing the retrofitting school buildings requires a holistic risk-informed system to effectively address not only physical impacts of the earthquake, but also the socioeconomic characteristics of disaster to support multiple stages of seismic risk management. The application of system-based risk management within multiple regions prone to varying seismicity has been extensively discussed by Vahdat et al (2014 a,b). Vahdat and Smith (2014) also demonstrated the application of system approach in prioritizing the seismic risk of school buildings. According to these studies, the application of system approach in school buildings is critical in three aspects. First, it identifies the potential impact of earthquakes on school buildings in terms of multiple dimensions. Second, the new model offers a systematic method for aggregating risk factors and for studying the characteristics of seismic risk assessment of school safety. While, the conventional screening models can handle a limited number of retrofitting projects manually, which is costly, time consuming or require a great amount of information and experienced; the new models offers a systematic method, capable of handling large number of cases. Third, it demonstrates the importance of a multi-level hierarchy for structuring seismic risk. The advantage of this structured knowledge is providing a deeper insight to the seismic risk and its relevant impacts in different categories in a systematic manner. Unlike previous frameworks focusing only on physical aspects of seismic risk, the system-based approach improves the existing models, providing a comprehensive picture of seismic risk that allow incorporating multidimensional aspects such as socioeconomic criteria in the decision process. Consequently, any systematic methodology for aggregating, selecting and ranking risk must be within a system-based framework to systematically balance the multiple criteria, alternatives and stakeholders involved.

10. Case Study 2: Regional Risk Mitigation Programme

Another example that it might be considered is how to identify an appropriate system for assessing risk of failure within a portfolio of infrastructure exposed to varying degree of seismic hazard. Figure 2 illustrates the process of reasoning toward a seismic risk management system. The complexity of large scale disaster management programmes often involved with a balancing feedback between multiple stakeholders, different contexts (perspectives) and domains (scope of technical alternatives). Multiplicity of views and interests of individual and organization within risk management process causes an inherent complexity that requires a systematic, structured reconciliation of disparate, often conflicting goals and contradictory information (Avouris 1995). Such mitigation decisions require a 'continuous compromise' to address a wide range of conflicting demands in different levels of organizational, operational and local users. Unlike man-made systems that can be described through a finite number of states, predicting the consequence in such a natural system is difficult due to the dynamic nature of earthquakes. The estimation of the parameters involved in earthquake hazards usually involves imprecise or vague data, incomplete information or lack of historical data requiring an appropriate mechanism to capture, share, and process the information. Various uncertainties are present in identifying the hazard, modelling and assessing the risk, mainly stemming from knowledge deficiency. This can be even worse when the focus turns to regional risk management in which a large number of cases involved. For such a situation, a structured knowledge based approach is required to systematically manage the information in different layer of system effectively and efficiently.

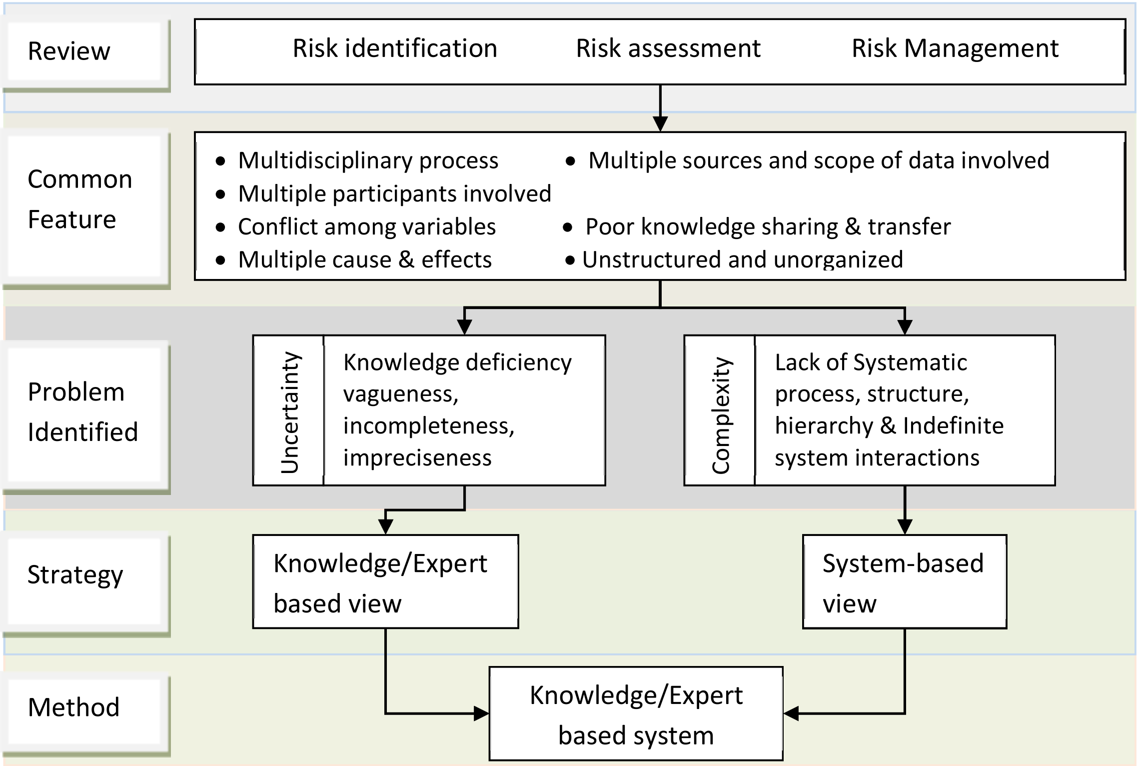


Figure 2 – Process of identifying a risk management system (Vahdat 2015)

Another dimension of the problem is type of knowledge involved in risk assessment process. Considering a large scale infrastructure network, ambiguity and vagueness is common form of uncertainty which can be found in many aspects of analysis including collection information, perception of data, knowledge base, statement of goals and objectives. For example, natural language is often used by experts to describe the potential vulnerability of existing facilities. The expert judgment could be a major source of knowledge deficiency in large complex systems. According to Bender (1996) providing the balancing feedback and facilitating the understanding of the various relationships among participants which frame the problem context, is essentially a knowledge-based problem and thus must be treated through a knowledge-based approach.

Therefore, artificial intelligence can be adopted as the overarching strategy to deal with such knowledge-centred challenge. The complex problem of risk assessment and management can be handled through a simple and manageable set of sub-systems. The underlying idea is to cope with the complexity of a problem by applying some kind of decomposition of large systems to lower complex systems. The problem can be framed in the form of computer software decision support which can take the shape of expert system or some other forms of AI technique. A risk assessment model based on the knowledge base expert system (KBES) is then defined as an objective for the regional risk mitigation programme.

11. Conclusion

Seismic risk management is multidisciplinary nature that concerned with both systematic and policy challenges to support different stages of preparedness, mitigation, response and recovery. The issues and challenges involved within risk management policies require a comprehensive, strategic and integrated approach in the disaster management cycle, including all aspects and levels and with due consideration to preparedness and mitigation and response management which cannot be achieved without a system-based view. A risk management system can effectively address this need, using a decision support system for greater public awareness, enhanced infrastructure resilience and organization agility to response and recover following an earthquake. In addition, it allows allocating and tracking the resource that ultimately secure the effectiveness and public engagement.

A key policy implication of the current study would be an adequate and consistent normative framework which is essential to implement risk management. Since, the existing frameworks are fragmented, a systematic integration of multiple policies within seismic risk management is paramount. A sample system policy challenges are shown in Table 5.

Table 5 – Key challenges and support policy

Phase	Key Challenges	Support Policy
Pre Disaster	High uncertainty in loss prediction	• Risk assessment, vulnerability assessment and countermeasure • Decision structure development, Establishment of rules, regulations and clear decision role of parties involved
During Disaster	Disruption of infrastructure support	• Risk assessment of engineering and built civil infrastructures, communication connectivity and interdependencies • Efficient decision making speed for rapid intervention and prevention • Resource utilization,reallocation • Complete situation awareness, integrated and improved information
Post Disaster	Severe Resource Shortage Large-scale impact & damage	• Prioritizing, resource management, establishment of acquisition mechanisms for external resource • Efficient acquisition and distribution of resources, fast demobilization, quick maintenance

As a result, the study suggests a system perspective taking advantages of a robust, interoperable system to maintain a better situational awareness prior to an event. This helps decision makers to understand and evaluate the consequences of alternative courses of action and follow-up on decisions. This outcome reveals the fact that the holistic view of seismic risk can effectively address the existing constraints and policy challenges involved with seismic risk management.

12. References

Ahmad, S.S. and Simonovic, S.P. (2011) A three dimensional fuzzy methodology for flood risk analysis. Journal of Flood Risk Management (4): 53–74.

Altay, N. and Green, W.G. (2006) OR/MS research in disaster operations management. European Journal of Operational Research 175(1): 475–493.

ATC-13 (1985) Earthquake Damage Evaluation Data for California. Redwood City, CA: California Seismic Safety Commission.

ATC-14 (1987) Evaluating the Seismic Resistance of Existing Buildings. Redwood City, CA: California Seismic Safety Commission.

ATC 21 (2002) Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook. Redwood City, CA: California Seismic Safety Commission.

ATC-40 (1996) Seismic Evaluation and Retrofit of Concrete Buildings. Redwood City, CA: California Seismic Safety Commission.

Aven, T (2011) On some recent definitions and analysis frameworks for risk, vulnerability, and resilience. Risk Analysis. Vol. 31, No.(4).

Avouris, N.M. (1995) Cooperating knowledge-based systems for environmental decision support. Knowledge Based Systems 8(1): 39–54.

Basoz, N. and Kiremidjian, A. (1996) “Risk assessment of highway transportation systems” The John A. Blume Earthquake Engineering Center Report No. 118,

Department of Civil and Environmental Engineering, Stanford University, Stanford, CA.

Beer, M., Ferson, S. and Kreinovich, V. (2013) Imprecise probabilities in engineering analyses. Mechanical Systems and Signal Processing (37): 4–29.

Bender, M. and Simonovic, S.P. (1996) A systems approach for collaborative decision support in water resources planning. Int. journal of Technology Management, Inderscience publishers 3-5(19): 546–556.

Berrah, M. and Kausel, E. (1992) Response spectrum analysis of structures subjectedto spatially varying motions. Earthquake Engineering and Structural Dynamics 6(21): 461–470.

Birkmann, J. (2006) Measuring Vulnerability to Natural Hazards: Towards Disaster Resilient Societies. Tokyo, Japan: United Nations University Press, pp. 24–37.

Blockley, D. (2013) Analysing uncertainties: Towards comparing Bayesian and interval probabilities. Mechanical Systems and Signal Processing 37(1–2): 30–42.

Bostrom, A., Turaga, R. and Ponomariov, B. (2006) Earthquake mitigation decisions and consequences. Earthquake Spectra 22(2): 313–327.

Bozorgnia, Y. and Bertero, V.V. (2003) Damage spectra: Characteristics and applications to seismic risk reduction. Journal of Structural Engineering 129(10): 1330–1340.

Bristow, M., Fang, L. and Hipel, K.W. (2012) System of systems engineering and risk management of extreme events: Concepts and case study. Risk Analysis 32(11): 1935–1955.

Cardona, O., Ordazb, M.G., Yaminc, L.E., Marulandad, M.C. and Barbat, A.H. (2008) Earthquake loss assessment for integrated disaster risk management. Journal of Earthquake Engineering 12(S2): 48–59.

Carreno, M.L., Cardona, O.D. and Barbat, A. (2006) Evaluation of the Risk Management Performance. Proceedings of the 250th Anniversary of the 1755 Lisbon Earthquake. Lisbon, Portugal.

Coburn, A. and Spence, R. (2003) Earthquake Protection. Chichester, UK: John Wiley & Sons.

Davidson, R.A. and Shah, H.C. (1997) An Urban Earthquake Disaster Risk Index. Stanford, California: John A. Blume Earthquake Engineering Center. Report 121.

Davidson, R. (2008) Perspective on development and current applications for catastrophe planning. In: A. Bostrom, S.P. French and S.J. Gottlieb (eds.) Risk Assessment Modeling and Decision Support. Springer Verlag, pp. 17–133.

Deng, Y., Sadiq, R., Jiang, W. and Tesfamariam, S. (2011) Risk analysis in a linguistic environment: A fuzzy evidential reasoning-based approach. Expert Systems with Applications (38): 15438–15446.

Durham, S.D., Johari, P. and Bausch, D. (2008) Strategic directions in seismic modeling: HAZUS® development and current applications for catastrophe planning. In: A. Bostrom, S.P. French and S.J. Gottlieb (eds.) Risk Assessment Modeling and Decision Support. Springer Verlag, pp. 101–116.

Eguchi, T.E. and Seligson, H.A. (2008) Loss estimation models and metrics. In: A. Bostrom, S.P. French and S.J. Gottlieb (eds.) Risk Assessment Modeling and Decision Support. Springer Verlag, pp. 135–156.

FEMA 154 (2002) Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook. Washington DC: Federal Emergency Management Agency.

Fruta, H., Shiraihi, N., Umano, M. and Kawakami, K. (1991) Knowledge-based expert system for damage assessment based on fuzzy reasoning. Computers and Structures 40(1): 137–142.

Gulkan, P. and Sozen, M.A. (1999) Procedure for determining seismic vulnerability of building structures. ACI Structural Journal 96(3): 336–342.

Gulkan, P. and Yakut, A. (1996) An expert system for reinforced concrete structural damage quantification. In: J.K. Wight and M.E. Kreger (eds.) Mete A. Sozen Symposium-A

Tribute from His Students. ACI Special Publication No. SP-162. pp. 53–71. Haimes, Y. (2009) On the complex definition of risk: A system-based approach. Risk Analysis 29(12): 1647–1654.

Haimes, Y. (2012a) 'Systems-based guiding principles for risk modeling', planning, assessment, management, and communication. Risk Analysis 32(9): 1451–1467.

Haimes, Y. (2012b) Systems-based approach to preparedness for response to, and recovery from natural and human-made disasters. Leadership Management Engineering 12(4): 288–298.

HAZUS (2001) Earthquake loss estimation methodology, Technical and users manual, http://www.fema.gov/plan/prevent/hazus.

Holmes, W. (1996) Seismic Evaluation of Existing Buildings State of the Practice, 11th World Conference on Earthquake Engineering. Acapulco, Mexico: Pergamon.

Karbassi, A. and Nollet, M.J. (2008) Development of an index assignment procedure compatible with the regional seismicity in the province of Quebec for the rapid visual screening of existing buildings. Canadian Journal of Civil Engineering 35(9): 925–937.

Klügel, J., Mualchin, L. and Panza, G.F. (2006) A scenario-based procedure for seismic risk analysis. Engineering Geology 1-2(88): 1–22.

Klugel, J.U. (2008) Seismic hazard analysis. Earth Science Review 88(1–2): 1–32.

Kiremidjian, A, Moore, J., Fan, Y.Y, Yazlali, O., Basoz, N. and Williams, M. (2007) 'Seismic Risk Assessment of Transportation Network Systems'. Journal of Earthquake Engineering 3(11): 371–382.

Konakli, K. and Kiureghian, A. (2011) Stochastic Dynamic Analysis of Bridges Subjected to Spatially Varying Ground Motions. Berkeley, CA: Pacific Earthquake Engineering Research Center (PEER).

Lahdelma, R., Salminen, P. and Hokkanen, J. (2000) Using multicriteria methods in environmental planning and management. Environmental Management 26(6): 595–605.

McGuire, R.K. (2008) Seismic risk mitigation decisions under uncertainty. In: A. Bostrom, S.P. French and S.J. Gottlieb (eds.) Risk Assessment Modeling and Decision Support. Berlin Heidelberg: Springer Verlag, pp. 85–198.

Miyasato, G.H., Levitt, R. and Boissonnade, A. (1986) Implementation of a knowledge based seismic risk evaluation system on micro computers. Artificial Intelligence 1(1): 29–35.

Neal, D.M. (1997) Reconsidering the phases of disaster. International Journal of Mass Emergencies and Disasters 15(2): 239–264.

NRCC (1992) Manual for Screening of Buildings for Seismic Investigation. prepared by Institute for Research in Construction Ottawa, Canada: National Research Council Canada.

NRC (2011) National Earthquake Resilience, Research, Implementation and Outreach. Washington DC: National Academy Press.

Park, Y.J. and Ang, A.H.-S. (1985) Mechanistic seismic damage model for reinforced concrete. Journal of Structural Engineering 111(4): 722–739.

Rojhan, C. (1986) ATC methodology and data for rapid assessment of seismic vulnerability. In: C. Scawthorn (ed.) Techniques for Rapid Assessment of Seismic Vulnerability. Proceedings of a Session at Structures Congress' 86; 15–18 September, New Orleans, LA. New York: ASCE.

Ross, T. (2004) Fuzzy Logic with Engineering Application. The Atrium, Southern Gate, Chichester: John Wiley and Sons.

Simonovic, S.P. (2011) System Approach to Management of Disasters: Method and Application. Hoboken, NJ: John Wiley & Sons.

Smith, NJ., Merna, T. and Jobling, P. (2006) Managing Risk in Construction Projects. Blackwell Science Ltd.

Standards Australia/Standards New Zealand (1995) Australian/New Zealand Standard – Risk Management. Sydney, Australia: Standards Australia.

Sucuoglu, H. and Yazgan, U. (2003) Simple survey procedures for seismic risk assessment in urban building stocks. In: S.T. Wasti and G. Ozcebe (eds.) Seismic Assessment and Rehabilitation of Existing Buildings. Dordrecht, The Netherland: Kluwer Academic Publishers.

Tesfamariam, S. and Goda, K. (2013) Handbook of Seismic Risk Analysis and Management of Civil Infrastructure Systems. Cambridge, UK: Woodhead Publishing Limited.

Tesfamariam, S. and Wang, Y. (2012) Risk-based seismic retrofit prioritization of reinforced concrete civic infrastructure: Case study for state of Oregon schools and emergency facilities. Natural Hazards Review 13(3): 188–195.

UN/ISDR (2004) Living with Risk: A Global Review of Disaster Reduction Initiatives. International Strategy for Disaster Reduction, 2004 version Geneva, Switzerland: UN Publication.

UN-ISDR (2006) Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters, United Nations International Strategy for Disaster Reduction, Extract from the final report of the World Conference on Disaster Reduction (A/CONF.206/6), March 16, 2005, Hyogo, Japan.

Vahdat, K. and Smith, N.J. (2014) A risk-based system for managing the retrofitting of school buildings in seismic prone areas: A case study from Iran. International Journal of Risk Assessment and Management 17(4): 311–331.

Vahdat, K., Smith, N.J. and Amiri, G.G. (2014a) Fuzzy multicriteria for developing a risk management system in seismically prone areas. Socio-Economic Planning Sciences (48): 235–248.

Vahdat, K., Smith, N.J. and Amiri, G.G. (2014b) Developing a Knowledge Based Expert System (KBES) for Seismic Risk Management. Proceedings of the Second International Conference on Vulnerability and Risk Analysis and Management (ICVRAM), Liverpool, UK: ASCE (American Society of Civil Engineer), pp. 1746–1755.

Vahdat, (2015) Seismic Risk Management, PhD Thesis, University of Leeds, Leeds, UK.

Wen, Y.K., Ellingwood, B.R., Veneziano, D. and Bracci, J. (2003) Uncertainty Modeling in Earthquake Engineering, MAE Center Project FD-2 Report http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.115.1598&rep=rep1&type=pdf.

Yakut, A., Ozcebe, G. and Yucemen, M. (2006) Seismic vulnerability assessment

using regional empirical data. Earthquake Engineering Structural Dynamic 35(10): 1187–1202.

Yucemen, M.S., Ozcebe, G. and Pay, A.C. (2004) Prediction of potential damage due to severe earthquakes. Structural Safety 26(3): 349–366.

Zadeh, L. (1973) Outline of a new approach to the analysis of complex systems and decision processes. IEEE Transactions on Systems Man and Cybernetics MC-3(1): 28–44.

Zadeh, L. (1996) The role of fuzzy logic in modeling, identification and control. In: L.A.

Zadeh, G.J. Klir and B. Yuan (eds.) Fuzzy Sets, Fuzzy Logic and Fuzzy Systems: Selected Papers. Singapore: World Scientific, pp. 783–795.