Consequence Assessment in Earthquake Risk Management Using Damage Indicators

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ABSTRACT: The present paper reports on the methodical developments in regard to the modeling and assessment of consequences due to earthquakes within a multidisciplinary research project presently performed at the Swiss Federal Institute of Technology. The research project aims to develop a generic decision theoretical framework for the consistent quantitative and rational management of earthquake risks in three situations, namely prior to, during and after an earthquake. First the general framework for the earthquake risk management project is outlined. Thereafter the specific issues relating to the modeling of consequences of earthquakes are addressed including a review of existing methodologies and results of research projects reported in the literature. Finally an example of a draft Bayesian Probabilistic Net model considered in the project for consequence analysis is presented and it is explained how the net may be utilized for assessing the consequences of relevance prior, during and after an earthquake.

1 INTRODUCTION

The developments in earthquake engineering research during the last 2-3 decades provide, within acceptable limits, reliable design of new structures against earthquake loads. In the more developed part of the world, such methods are presently implemented in the best practice design of new structures. However, the existing older building stock still represents a significant risk in regard to the safety of people as well as to the economical assets of the society. In less developed countries, both the new building stock and the existing building stock exhibit a significant vulnerability, mainly due to inadequate design, missing supervision during construction, insufficient quality of construction materials and inadequate ground investigation/interpretation.

The recent series of earthquakes, Turkey (1999), Taiwan (1999), India (2001) and Iran(2003) not only lead to an improved awareness with regard to seismic hazards, but also highlights the difficulties involved in an efficient decision making process in such situations, especially in less developed countries. Consistent and quantitative risk assessment tools for buildings and infrastructure in seismic active areas are urgently needed to ensure an efficient decision making process that facilitates the optimal allocation of available economical resources for the management of risks before, during and after an earthquake.

The present paper reports on the methodical developments in regard to the modeling and assessment of consequences due to earthquakes within a multidisciplinary research project presently performed at the Swiss Federal Institute of Technology (ETH Zürich), see Bayraktarli et al. (2004). The research project aims to develop a generic decision theoretical framework for the consistent quantitative and rational management of earthquake risks. It is anticipated that the decision support framework shall be designed for decision makers responsible for the safety of personnel, environment and assets of a larger area such as e.g. a region or a city. The system will be generic in the sense that it is formulated in terms of characteristic descriptors (indicators) which can be observed. It can thus easily be adapted to the characteristics of a specific region or city. The main emphasis will be on the risks due to
potential failures and collapse of building structures as well as infrastructure systems such as bridges, tunnels, sewer systems and etc.

In the following first the general framework for the earthquake risk management project is outlined. Thereafter the specific issues relating to the modeling of consequences of earthquakes are addressed including a review of existing methodologies and results of research projects reported in the literature. Finally an example on a preliminary Bayesian Probabilistic Net model considered in the project for consequence analysis is presented and it is explained how the net may be utilized for assessing the consequences of relevance prior, during and after an earthquake.

2 GENERAL FRAMEWORK FOR THE EARTHQUAKE RISK MANAGEMENT

An important feature of the earthquake risk management framework is that it provides cost efficient decision support on how to optimize investments into risk reducing measures in three situations, namely, prior, during and after an earthquake, see Figure 1. It should be noted that the “during” period corresponds to the period between the occurrence of the first ground motions till the end of the last after shocks, i.e. in the order of 4-6 weeks.

![Figure 1 Illustration of the different decision problems in earthquake risk management (adapted from Aslantürk (2003)).](image)

A key element in the pursued approach is the quantification of the effect of various types of determinable (e.g. by observation or calculation) information (indicators) on the risks. These risk indicators may have very different characteristics and necessitate that different expertise’s are integrated into the project, see Figure 2.

![Figure 2 Illustration of the interrelationships between the research groups and the tasks of the project.](image)
An example of such a risk indicator is the information about the structural design codes applied for
the design of a group of structures. Another indicator could be the characteristics of the soil implicitly
describing how the energy from a given earthquake will be transferred from the bedrock to the
structures. In addition, more traditional indicators of accumulated damage in structures, such as
deflections and cracks, will be utilized in the formulation of the framework. Many indicators are based
on the availability of spatial data, describing the terrain, building structures and traffic networks.
Specially designed GIS technology can serve as a platform for collecting, storing and analyzing the
original and the derived data.

In fact all the above mentioned indicators have bearing on the consequences resulting from an
earthquake as well as the assessed consequences and the information of the indicators in this regard
plays a cornerstone in any earthquake risk assessment. The subsequent section outlines the decision
theoretical framework for the earthquake risk management and summarizes the results of a literature
survey where the possible different types of consequences are identified and classified together with
the indicators by which their main characteristics may be described in a generic risk assessment.

3 CONSEQUENCES MODELING IN EARTHQUAKE RISK MANAGEMENT

An earthquake can cause significant property damage and loss of life. The threat of earthquakes is
magnified by the fact that they usually occur with little or no warning. With mitigation and emergency
preparedness planning, these risks can be reduced, see PDC (2004), and for this purpose, the
consequence modelling becomes a powerful tool in hand.

Estimation of losses requires the development of relationships between damage and losses, see
William M.S (1995). In addition to costs of repairs, income losses such as lost rental income can be
significant. Losses can be highly dependent on the use or occupancy of a building. For example, if two
buildings of the same structural type sustain the same amount of structural damage, but one is a
warehouse and the other is an office building, the associated losses will be different. This is because of
different interior and exterior finishes, different types of plumbing and electrical systems and a variety
of other considerations that depend on occupancy. Therefore another requirement for a complete
inventory is occupancy. Occupancy is one of the easier types of information to obtain. The challenge
is to obtain reliable structural information for each occupancy class. In calculating losses, regional
factors such as the cost of labour and supplies must be accounted for. For more detail see WSSPC
(1999).

3.1 Risk assessment framework

Risk assessments may be facilitated by consideration of the framework illustrated in Figure 3.
In this framework three levels are distinguished, namely the exposure, the vulnerability and the robustness. The exposure can be considered an indicator of the hazard potential for a given object or system of consideration. Considering earthquakes the exposure $EX$ is an inherently uncertain phenomenon with probabilistic characteristics usually provided in terms of earthquake intensities and corresponding return periods. The vulnerability $P(D|EX)$ can be considered an indicator of the immediate consequences (or damages to the system) associated with a given exposure event. Considering an earthquake event the vulnerability is associated with significant uncertainty and is appropriately described by a probability distribution of different damage states of structures and lifelines conditional on the exposure event, e.g. the earthquake intensity. The robustness $P(C|D,EX)$ is an indicator of the indirect consequences due to the damages of the considered system. Considering again the event of an earthquake the robustness is associated with the conditional probability of losses of various degrees conditional on the exposure and a given damage state. For a system corresponding to a city or region societal losses including loss of lives as well as economical losses may depend strongly on e.g. the specific time of the year, week and day where an earthquake occurs. In this way the robustness of the system exposed to an earthquake will be dependent on the specific time when an earthquake takes place. Whereas the uncertainty modeling associated with the assessment of exposure and vulnerability may be based on well established frameworks such as the Joint Committee on Structural Safety Probabilistic Model Code the uncertainties involved in the assessment of the robustness are generally subject to significant subjective (epistemic) uncertainty.

One of the reasons for the significant subjective element of uncertainty in consequence modeling is the uncertainty on the decision maker in regard to appropriateness and completeness of the applied consequence assessment models. However, in correspondence with the risk assessment framework outlined in the above and consistent with Faber and Maes (2003, IFIP) it is proposed to perform the risk assessment on the basis of the following expression for expected consequences

$$E[C_D + C_{ID}] = \int \int \int \int C_D P(D|EX) P(EX) dD dEX + \int \int \int C_{ID} P(C|D,EX) P(D|EX) P(EX) dC_{ID} dD dEX$$

(1)

where $C_D$ and $C_{ID}$ are the direct and indirect consequences respectively. An earthquake can cause significant property damage and loss of life.

### 3.2 Categorization of consequence and corresponding indicators

Losses due to earthquakes include not only the cost of repairing or replacing damaged buildings and infrastructure, but also costs associated with damaged contents, damaged inventory, removing debris, renting alternative space, moving to new locations and lost revenues resulting from business interruption. In addition, there are social losses that cannot be directly measured in terms of monetary amounts, but instead can be quantified in terms of injuries, deaths, and the need for emergency shelter. The estimation of losses involves two steps: first the estimation of the level of damage for each type of structure, and second the estimation of losses associated with the damage, see WSSPC (1999).

Estimates of damage are computed by using relationships between structural performance and ground motion. These relationships, called fragility curves or damage probability matrices, provide the probability of a structure sustaining a specified amount of damage given that it is subjected to a certain level of ground motion. Each type of structure has its own set of fragility curves or damage probability matrices. Examples of characteristics that can affect the level of damage are the type of structural system, the code used for design, the height of the structure, and the types of non-structural elements that are attached to or housed in the structure. Development of damage/motion relationships is a challenging and imperfect process. Ideally the relationships should be based upon a statistical analysis of earthquake damage data, see WSSPC (1999). In this project, the fragility and vulnerability curves, and as a result, the damage state of the structures will be provided by other working packages.
As a first step, the consequences are categorized; see Figure 4, and the characteristics of each are identified. Also the related indicators in each case are discussed.

**Figure 4 Categorization of Consequences in Earthquake risk management**

### 3.2.1 Structural and lifeline consequences

Loss-estimation methods currently exist to project direct damage to buildings from ground motion; see Committee on Earthquake Engineering (1992). In determining and quantifying the consequences regarding the lifelines and structures two important issues should be considered: description and damage. The important factors defining these two are shown in Figure 5.

**Figure 5 Important Factors in Structural and Lifeline Consequences**

In this category only the direct physical losses resulting from the damage or failure of the structures and lifelines are considered and no indirect consequences are taken into account for this purpose the vulnerability curves play an important role, which themselves are an outcome of Earthquake intensity, distance from the center, structural type, age and height of the structure, soil profile and etc. also, for assessing the loss of inventory the occupancy classes are needed. At the end the costs of debris removal should be added to the whole calculations of structural and lifeline’s monetary consequences.

The primary type of information needed is inventory of existing buildings and structures. Such an inventory might include: ages of the structures, construction types (e.g., configuration, height, and materials), usage patterns, and number of inhabitants. From this structural inventory, response to ground motion estimates, and hazard characterizations, projected damage estimates could be made, including economic costs for replacement and repair of the structures, following earthquakes of
various magnitudes for specific communities. Without good inventory data, however, these damage estimates are, at best, educated guesses, see WSSPC (1999).

3.2.2 Medical consequences

The medical consequences are considered to be the costs related to injuries, evacuation and reallocation of the people. The main factor determining the size of sanitary losses (SL) and the share of injuries with different degree of severity is intensity of earthquake, which is resulted in severity of damage. At the same time number of people at risk and number of injured allow substantiating the common medical-and-evacuation indices of the casualties for the given intensity of earthquake; see Goncharov SF (2001). The important factors identifying the costs can be summarized as: Cause of injury (EQ-relatedness, Structural relatedness, Secondary hazards, Injury mechanism), Severity, Treatment (Level, Immediacy), Costs (Direct medical care costs, Indirect costs), Diagnosis and Location of individual when injury occurred, see Jones Barclay (1997).

3.2.3 Psychological consequences

Relationships between self-reported psychological distress (Symptom Checklist) and experience with two earthquakes are presented for a group of male factor workers (N = 772) from Naples, Italy, participating in the 1987 follow-up of the Olivetti Heart Study. Although all were exposed to the 1980 earthquake that racked southern Italy, only men residing in the Naples suburb of Pozzuoli experienced the continuing swarm of earthquakes ("bradyseism") of 1983-1984, allowing for the observation of a "natural experiment" of sorts. Levels of psychological distress were found to be higher 7 years after the first earthquake for those men who reported damage from that earthquake. Overall, findings were similar for those who were evacuated, or suffered financial loss from the 1983-1984 bradyseism earthquakes. Stratification by 1980 earthquake damage revealed that 1983-1984 evacuation or financial loss was associated with increased distress reporting only for those men who had not reported damage from the 1980 earthquake. Overall, however, distress scores tended to be higher for men evacuated in 1983-1984 if they had also reported damage from the prior earthquake (only the F ratio for anxiety reached criterion for statistical significance), see SH Bland (1996). Given the large study population and individual information available to identify victim status other studies were able to detect a statistically significant earthquake effect on suicide rate. This effect on suicide might be diluted if only geographically based stratification were possible, as opposed to victim status stratifications. Mental health programs or other preventive strategies might be more effective by specifically targeting victims rather than by simply targeting individuals living in earthquake-affected areas, see Yiing-Jeng Chou (2003).

These findings summarized as: fear, helplessness, distress, depression and suicides, can suggest that the psychological consequences of earthquake exposure are long lasting and seem to be related to the consequences of the earthquakes in terms of damage/loss. All these aspects are indirect consequences which are rarely assessed in risk management area, but are of great importance and can cause less efficiency afterwards.

3.2.4 Social / Economical consequences

The concern with the economic and social consequences of earthquakes dates just over three decades since the Great Alaska Earthquake struck the Prince William Sound area at 5:36 -pm on Good Friday, March 27, 1964. The magnitude 8.3 earthquake, the most violent ever recorded in North America, devastated a large area containing about two thirds of the population and most of the economic activity. The highways and railroads were inoperable, the port facilities unusable, and water and sewerage systems out of operation, see Jones Barclay (1997).

The economic consequences of seismic events are becoming greater every year. The accumulation of investments in buildings, equipment, and infrastructure such as highways, bridges, gas, water and sewer pipelines, electricity, telephone and cable wires are mounting at enormous rates. The growth of the economy means that business disruption is more costly. Urbanization is occurring throughout the
world, and there are more extremely large metropolitan agglomerations than ever before. Potential losses are becoming greater than ever before at an enormous rate, see FEMA (1999).

The major economic consequences of earthquakes result from damage to elements of the built environment that are essential to the operation of the economic activities in the impacted region. Some economic sectors are by their nature more vulnerable than others. Some sectors will even find an increase in their activity because of demands placed on them by the disaster. Some activities will be winners while others will be losers. From the perspective of the market analyst, impact is gauged by product line, the specific good or service a business offers. Statistical and economic analysis deals with sectors of economic activity that group a number of products together. There may be both winners and losers in a particular sector. Factors that will cause businesses to lose include the direct damage they entail to their facilities because of their location in the area that was stricken. Other factors include their dependency on damaged or destroyed support systems of transport and communication for workers, customers, supplies, shipments, water, electricity, gas, telephone, and other services. Businesses that may benefit are ones for which there is an increased demand for their products or services for relief, clearing and removing debris, repair and restoration, and reconstruction. In total, to an extent depending on flows of external assistance from other regions and local accumulation of resources, the regional economy may experience an increase rather than a decrease in income. However, regardless of the level of specificity of analysis, whether product or sector or region, there is agreement that the funds that are spent will be diverted from other uses for which they were intended. Whether or not a business lose will be greatly influenced in addition to its sector, by the extent to which the managers have planned, taken precautionary preparations, and necessary measures to mitigate the impact of a seismic event.

The physical effects of earthquakes are considered as to their social and economic consequences:
- Numbers of casualties, see A. King (1997)
- Loss of employment
- Loss of employees/skills
- Loss of function, see A. King (1997)
- Business interruption
- Consumption of materials and energy (sustaining resources + human forces)
- Macro-economic impacts (negative and positive).

The number of casualties is considered to be the direct consequence and the rest, indirect consequences of an earthquake. For all these consequences, the indicator in charge is the number of people at risk, occupancy class and the damage state of the building, as discussed earlier.

As it will be mentioned in economic quantification of consequences, for estimating the loss of life, there is a need for the number of people at risk, which is a function of time. The effect of time on the expected number of people present at given location has to be seen on three levels; time of the day, day of the week and season, see Lentz A. (2003). Also the probability of successful escape plays a roll in estimating the loss of life.

3.2.5 Historical and archeological consequences

The history of humankind is partially represented in the historical monuments and sites around the globe and thus for sure need preservation. The vulnerability of the cultural heritage is growing every day, due to age, deterioration of materials by geophysical and environmental conditions as well as by human interaction. Cultural heritage is found in most of the countries and thus constitutes a growing concern among the governments and the population alike. This attracts enormous number of tourists and therefore is a great source of income for the area. The heritage is impacted in a number of ways, see ICOMOS (2001):

- Destruction of entire or particular elements of past cultures or phases of human activity, particularly the earliest or less monumental manifestations.
• Damage to the integrity of cultural landscapes by removing cultural features that are important archaeological evidence of the relationship between sites.
• Potential damage to sub-surface remains by changes to the surrounding environment as a result of development.

The loss of these heritages would be a great consequence of a natural disaster and because of that the decrease in the number of tourists in the area and the stagnancy in tourist industry, can have a great influence on the economical situation of the area. But it is possible that the loss of normal tourist income will be replaced, if not exceeded, by income from visitors involved in the reconstruction.

The historical consequences regarding the heritage itself are considered to be direct and the rest taking into account the tourist industry and loss of heritage is considered to be indirect consequences, both in relation with the age, material deterioration as discussed above.

3.2.6 Demographical consequences

The analysis of the previous information after earthquakes shows that during the years after disaster a sharp birth rate reduction and an increase of the death rate is seen, and that the median age of the population grows. This affects the process of achieving the pre-quake number of the people. The population of the area will reach its pre-quake level in ten to fifteen years at best. Restoration of the natural annual increase levels will take several years.

Delays in the arrangements of living conditions and employment of the refugees are also critical. So is procrastination in returning of data on the evacuated, mainly children and youth who have aspirations to remain where they were evacuated. So there is always an urgent need of a new demographic program for the survivors to normalise the demographic situation in affected areas and to stop the migration of people to other places.

The important demographical issues are categorized as:

• Age
• Gender
• Race/Ethnicity
• Level of education
• Occupation
• Income
• Disabilities and pre-existing conditions
• Dependency

The most important indicators for assessing the demographical consequences therefore are the number of people evacuated from the area (a function of number of people at risk), duration of reconstruction and the age of evacuated people.

3.2.7 Environmental consequences

Environmental consequences may have effects on plants, animals, and not least persons, see Faber M.H. (2004). These consequences can be classified as follow. The damage of water and sewer pipelines can cause the water and waste flow to the environment, see Shamsunlu (1999). Also considerable amounts of oil and chemical can be released into the underground waters and the ground surface. Moreover, the debris from the collapsed buildings and enterprises are sometimes of a problem to the environment. The probability of chemicals in the debris is another major environmental concern. The consequences of damage to structures housing intrinsically dangerous goods or processes is another category of consideration, and concerns the potential hazards of fire, explosion, toxicity or pollution represented by installation such as liquid petroleum gas storage facilities or nuclear power or
weapon plants. These types of consequences often become difficult to consider objectively, as strong emotions are provoked by the thought of them, see Hollings (1971).

3.3 Economic quantification of consequences

Different consequences of the earthquakes are determined by many factors and variables, as shown former, which are poorly known. Over time, the information basis has expanded, models (of earthquake occurrence, ground motion propagation, local effects, system response, etc.) have become more accurate and our ability to limit losses has improved, but uncertainties are bound to remain large for the foreseeable future, see Y.K. Wen (2003). One of the greatest problems in the consequence assessment area is to economically quantify different consequences and have a basis in hand for further studies and decision makings. In this direction, there is a need to model the loss of life on occasion of a failure.

Given the well-defined probability of failure, the obvious question to follow is “How safe is safe enough?” with respect to involuntary risks to an anonymous member of society. The life quality index (LQI) is derived to reflect the expected length of “good” life, in particular the enhancement of the quality of life by good health and wealth, see Nathwani J.S. (1997).

\[ L = \frac{g^q e}{q} \]  

(2)

In this formulation, \( g \) denotes the share of the GDP per capita which approximately is taken as an average individual’s personal consumption (roughly 0.6 GDP). \( e = e(0) \) is the life expectancy at birth, while \( q \) is equal to \( w / (1-w) \), \( w \) being the average fraction of life expectancy spent at work, see Lentz A. (2004).

For technical facilities exposed to adverse events, crude mortality is increased by

\[ dm = \frac{N_{LOL}}{N_{POP}} \cdot \frac{N_{LOL} d_p}{N_{POP}} \]  

(3)

with \( N_{LOL} \) quantifying the expected (yearly) number of fatalities due to a single structure or facility and \( N_{POP} \) being the total population referred to. \( N_{LOL} d_p \) is the expected number of lives lost on the occasion of a single event of failure \( F \), \( d_p \) denoting the (yearly) probability of failure and it is greatly dependant on the number of people at risk, probability of successful escape and the conditional probability of death. For further information refer to Lentz A. (2004).

4 EXAMPLE

As a small example, it has been tried to find out the relation between different indicators, outlined in the previous section. As a first step, different decision problems are identified and formulated such that they may be represented and assessed individually in prior decision analysis for the purpose of identifying how additional information may be efficiently used to reduce the risks. The risks will be quantified using influence diagrams or Bayesian probabilistic networks (see e.g. Jensen 1996) utilizing indicators. An overall theoretical Bayesian probabilistic network for a decision situation in risk management is exemplarily demonstrated in Figure 6.

This network outlines the simplest relationships between the earthquake, soil, structure, and consequences, using indicators, regarding the earthquake in a decision making situation before disaster. The damage indicator can be updated regarding the measurements in the real time and the whole network can be updated.
After defining a primary network for the purpose of risk management, the network can be completed as Figure 7 which includes more nodes concerning the ones defined in Figure 6, but as this is not the main issue of this study, only a rough overview of them will be given here. As it shows, the seismology node is replaced by *Magnitude* node, behind of which leaning the intensity and the return period of an *Exposure* namely Earthquake. Structural period, distance from the earthquake hypocenter, soil profile and also magnitude are identified by related research groups, as indicators defining the response spectra of a structure and therefore the related structural damage indicator.

At last, as Figure 8 shows, some of the consequences discussed earlier, are also taken into account. The effort has been made to develop a network that can be updated easily with the real-time
information for the rapid condition assessment, rescue work and optimal allocation of resources for rebuilding and strengthening.

![Developed Bayesian Network for consequence assessment](image)

**Figure 8: Developed Bayesian Network for consequence assessment**

5 CONCLUSIONS

In this paper, different consequences (direct and indirect) of an earthquake are briefly presented and the possible indicators for each consequence have been discussed. Then the Bayesian probabilistic network, for earthquake risk management, using these indicators, has been illustrated.

As discussed in the example, it is obvious that by considering all consequences, the network becomes really complicated and it is difficult to handle all inter-relations. Therefore, to be able to reach the target, it has been decided to focus on only two categories, namely; Structural and Lifeline consequences, and, Social / Economical consequences.

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