DECISION PROCESS AND OPTIMIZATION RULES
FOR SEISMIC RETROFIT PROGRAMS

T. Zikas¹ and F. Gehbauer²

ABSTRACT

In earthquake-prone areas public authorities are dealing with the decision process of initiating retrofitting programs for a large building stock. By means of a cost-benefit-analysis decision makers can quantify all impacts of various investment alternatives to a society in monetary terms and make recommendations based on the net present value. In the case of seismic retrofit decisions the input variables, such as costs of alternative seismic upgrade levels, direct and indirect damage, and casualties, are influenced by many uncertain factors. This paper will analyse standard decision criteria under the aspect of uncertainty and introduce a probabilistic cost-benefit-analysis for seismic retrofit programs. The implication of influencing factors is analysed with Monte Carlo simulation and sensitive analysis. The presented methodologies are integrated in the loss estimation software EQSIM which has been developed by the Collaborative Research Center ‘Strong Earthquakes: A Challenge for Geosciences and Civil Engineering’ at the University of Karlsruhe in Germany.

INTRODUCTION

Residential, commercial and industrial buildings in many vulnerable cities worldwide are often built with poor construction quality and an insufficient design policy. Decision makers are dealing with the question of installing rehabilitation programs to reduce future loss and casualties caused by large earthquakes. An appropriate technique to evaluate different retrofitting options is the method of cost-benefit analysis. The analysis includes a systematic cataloguing of all impacts as benefits and costs, converting these impacts into monetary units, and then calculating and comparing the net benefit of different alternatives with the option of doing nothing (status quo) (Boardman et al., 2001).

The benefit of mitigation efforts is the reduced damage of buildings and infrastructure and the avoided casualties. Fig. 1 shows the exemplary loss before and the reduced loss after mitigation from future earthquakes and the initial cost of retrofitting.

![Figure 1. Loss from future earthquake events and the avoided loss in case of retrofitting.](image-url)

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Costs and especially benefits of retrofitting projects arise over the whole life cycle of a building, so future impacts must be discounted to their present value to be comparable. The net present value computes the difference between the present value of the benefits and the present value of the costs. Thus, the best alternative is the one with the highest net present. All Projects with a positive net present value are assumed to be worthwhile.

**STEPS OF A COST-BENEFIT ANALYSIS**

Basically, with a cost-benefit analysis decision makers evaluate projects which have an impact on society. The attractiveness of a rehabilitation project is calculated by comparing the loss with and without mitigation. Several procedures for the analysis exist and are described in more detail in (Boardman et al., 2001). For earthquake mitigation programs with alternative projects and restricted budget, the following procedure is suggested:

![Diagram of steps for a cost-benefit analysis]

Figure 2. Procedure for a cost-benefit analysis (adopted from Smyth et al., 2001).
Step 1 – Seismic Hazard Definition

The first step defines the seismic hazard. Important is the source and frequency of earthquake events, the maximum magnitude and the recurrence relationship. The site hazard is defined by using different attenuation functions for ground motion expected at certain distances from the source to the sites depending on the soil type. Generally, ground motions are expressed as maximum intensity, peak ground acceleration, peak ground velocity, or spectral accelerations, and depend on the earthquake source, the seismic wave propagation and the site response.

The frequency of Vrancea events in moment magnitudes $M_w$ with $N$ as the number of events per year is given by (Wenzel and Lungu, 2000):

$$\log_{10}(N \geq M_w) = 4.1 - 0.78M_w$$

Table 1. The number of earthquake events with various magnitudes and for different time periods.

<table>
<thead>
<tr>
<th>Mw</th>
<th>Years</th>
<th>10</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
<th>250</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.0</td>
<td></td>
<td>3</td>
<td>7</td>
<td>13</td>
<td>20</td>
<td>26</td>
<td>66</td>
<td>132</td>
</tr>
<tr>
<td>6.5</td>
<td></td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>8</td>
<td>11</td>
<td>27</td>
<td>54</td>
</tr>
<tr>
<td>6.8</td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>6</td>
<td>16</td>
<td>31</td>
</tr>
<tr>
<td>7.0</td>
<td></td>
<td>0.44</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>11</td>
<td>22</td>
</tr>
<tr>
<td>7.2</td>
<td>0.30</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>8</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>7.4</td>
<td>0.21</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>7.6</td>
<td>0.15</td>
<td>0.37</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>7.8</td>
<td>0.10</td>
<td>0.26</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

The annual probability of earthquake events is a key input in the cost-benefit formulation for the expected net present value in step 5.

Step 2 - Define building inventory and mitigation alternatives

The inventory information is required in order to conduct any earthquake damage assessment. Similar buildings should be grouped into a set of building classes based on, e.g. structural parameters, occupancy, height, and design codes.

The building inventory of Bucharest in the EQSIM application contains 1305 buildings with all kinds of building classes and occupancies. The area is located in the inner city between Piata Roamana and Bodul Unirii. For each building the database contains detailed information about the structural type, occupancy, building year, area, and more.
For each building, one of the following alternative objectives can be distinguished:

- A0: do nothing
- A1: risk reduction
- A2: life safety
- A3: damage control
- A4: immediate occupancy

The option risk reduction includes only rehabilitating parts of a structure without considering any life-safety performance. The life safety objective allows for unreparable damage of the building as long as life is not at risk. The damage control objective has a greater performance than life safety objective and protects features or functions of the building. Immediate occupancy allows for only minimal earthquake damage and disruption, and is reserved for critical or hazardous facilities and is not a part of the calculation.

**Figure 3. Test area in Bucharest.**

**Step 3 – Mitigation costs and benefit estimates**

For all alternatives the costs to implement the mitigation measure must be specified. The highest costs are most likely to occur for the structural retrofit and they depend on the performance objective, such as life safety, risk reduction, damage control or immediate occupancy.

The seismic rehabilitation cost estimation is based on (FEMA 156, FEMA 157), in which more than 2000 seismic rehabilitation projects were analysed. Basically, the building construction year, the performance objective of the rehabilitation, the seismic zone, the building class and the building area are used for the estimation. The mitigation method is not part of this analysis framework.

**Table 2. Estimation of average seismic rehabilitation costs for pre code buildings in high seismic zone and alternative performance objectives.**

<table>
<thead>
<tr>
<th>Building area</th>
<th>Risk reduction</th>
<th>Life safety</th>
<th>Damage control</th>
<th>Immediate occupancy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 100 m²</td>
<td>&gt; 100 m²</td>
<td>&lt; 100 m²</td>
<td>&gt; 100 m²</td>
</tr>
<tr>
<td>Q1</td>
<td>$9.79</td>
<td>$182.01</td>
<td>$114.20</td>
<td>$182.12</td>
</tr>
<tr>
<td>Mean</td>
<td>$24.22</td>
<td>$278.24</td>
<td>$202.57</td>
<td>$278.24</td>
</tr>
<tr>
<td>Q3</td>
<td>$58.02</td>
<td>$439.16</td>
<td>$362.63</td>
<td>$439.16</td>
</tr>
</tbody>
</table>

Estimation $/m² in 2002 dollars

One general benefit of seismic rehabilitation results from reducing the risk of death. Thus, it is necessary in the analysis to evaluate and monetize the benefit of saving human lives. One measure which economists use to estimate the value of life is how much people are willing to pay to reduce their risk of death. Boardman suggest a plausible range between $2.5 million and $4.0 million in 1999 dollars. The sensitivity of the value should be analysed with Monte Carlo in step 6. Alternatively, appropriate values for Romania could be surveyed.
Step 4 – Probabilistic damage estimation before and after mitigation

The basic source parameters of a seismic event in Step 1 include event date, time, magnitude, epicenter location and focal depth. The damage estimation with EQSIM is based on seismic response spectra. These spectra can either be obtained from recorded time histories or they may be calculated with earthquake specific parameters. For the second case, the peak ground acceleration can be calculated with local attenuation functions. Local soil conditions and building codes, such as EC 8, are then used to transform PGA to standardized response spectra. The building behavior for different building classes is described by capacity curves. These curves compare the spectral displacement of a building class with the spectral acceleration. To find the relevant spectral displacement for a specific earthquake scenario, the capacity spectrum method is used. In the capacity spectrum method the elastic response spectrum of the earthquake is transformed to different inelastic response spectra. For these inelastic spectra the intersections with the capacity curves are calculated. If the ductility of the building class equals the ductility of the inelastic demand spectrum, the respective spectral displacement is determined. For details of the capacity spectrum method see e.g. (ATC, 1995) or (Freeman, 1998). From spectral displacement values the damage probabilities can be calculated by means of fragility curves. These curves depend on the building type, too, and contain for possible displacement values the probabilities for a building to be in a certain damage class. If the determined maximum displacement is used, the damage probabilities can easily be drawn from the fragility curve. Because this method computes only possible damage distributions, different calculation methods, such as Monte Carlo, worst case scenario or expected value, can be applied to calculate a deterministic damage state for each single building from the inventory.

For the damage estimation after mitigation, capacity curves and fragility curves from other regions with various assumptions are taken and analyzed (Smyth, 2004). For example, one assumption could be that a retrofitted building has the same seismic behavior as a new constructed building. Also capacity curves are transformed and modified using probability distributions. But more accurate curves for retrofit techniques in Bucharest based on the local buildings, have to be developed.

The methodology for casualty estimation is based on the HAZUS methodology (NIBS, 2001). The casualties can be calculated for three different scenarios (day, night and rush hour) and are separated into four injury severity classes. As the input, the casualty estimation methodology requires the damage state probabilities of the different building classes, information on the distribution of building classes in the study region and population distribution data. To estimate the human losses casualty rates are used. The casualty rates describe the probability for occupants of buildings to be in any of the four injury severity levels at the time of an earthquake. These probabilities are given per building class for the five possible damage states of buildings. The calculation estimates the casualty probabilities for each building class and the deterministic casualties and injuries for all buildings.

The direct economic losses caused by the damage of the buildings contain the costs of repair and the replacement costs. The probabilities for being in the damage state are calculated for all buildings and are expressed in monetary terms using local economic data. Each of the four damage levels has associated costs consisting of the percentage loss of the value of structure and the number and value of lives lost. It is assumed that the only damage level in which lives are lost is the total collapse case. In this case, the number of lives in this building will be assumed to be lost. The replacement value of the structure is calculated with a percentage given for the four damage cases. For the major and total collapse state the percentage are 100%, while for slight damage we set 1% and for moderate damage 20%. The total replacement costs are reported for each building and can also be summarized into the different building classes or occupancy classes.
To compare damages caused before and after mitigation, the following factors can be used:

The Damage Factor, denoted $DF$, before and after an alternative $a$:

$$DF_a = \frac{Dollar/Euro\ Loss}{Replacement\ Value}$$

The Mean Damage Factor (MDF) is defined as the mean losses of a building stock with similar structure to the same intensity $i$:

$$MDF_a = \frac{1}{n} \sum_{i=1}^{n} \frac{Monetary\ Loss}{Replacement\ Value}$$

The Damage Ratio (DR) is the ratio of the damaged buildings to the total number of the buildings:

$$DR_{DMG} = \frac{Number\ of\ Buildings\ Damaged}{Total\ Number\ of\ Buildings}$$

$$DR_{DS} = \frac{Number\ of\ Buildings\ Destroyed}{Total\ Number\ of\ Buildings}$$

Other indicators to quantify the seismic damage, are the Probable Loss indicator, the Scenario Loss and the Probable Maximum Loss.

Fig. 4 shows the Damage Ratio for all buildings with different magnitudes in the test area and the damage ratio for 257 pre code buildings. In Fig. 5 the Damage ratio for the complete damage is shown.

![Figure 4. Damage Ratio for all buildings and concrete C1/C2/C3 buildings.](image-url)
Step 5 – Benefit-cost analysis

The net benefit of a project, $NB$, is calculated by subtracting the sum of the costs $C$ from the sum of the benefits $B$:

$$NB = \sum B - \sum C$$

Benefits of retrofitting measures derive from future earthquakes over the life cycle period of a building, and most of the costs typically occur when the project starts. The decision maker has to compare benefits and costs that appear in different time periods. For this reason, all benefits and costs should be discounted to their present value to compare projects with different time frames. The discount rate is often set by a public authority.

By adding the present value in period $t = 0,1,2,...,T$ denotes the life cycle of the building and $i$ the discount rate, the present value of the costs, $PV(C)$, is given by:

$$PV(C) = C_0 + \frac{C_1}{(1+i)} + \frac{C_2}{(1+i)^2} + \cdots + \frac{C_T}{(1+i)^T}$$

$$= \sum_{t=0}^{T} \frac{C_t}{(1+i)^t} \text{ for } t = 0,1,...,T$$

Similarly, the present value of the benefits is:

$$PV(B) = B_0 + \frac{B_1}{(1+i)} + \frac{B_2}{(1+i)^2} + \cdots + \frac{B_T}{(1+i)^T}$$

$$= \sum_{t=0}^{T} \frac{B_t}{(1+i)^t} \text{ for } t = 0,1,...,T$$

Respectively, the difference between the present value of the benefits and the present value of the costs equals the net present value, denoted with $NPV$, and formulated by the following basic equation for a cost-benefit analysis:
\[ NPV = PV(B) - PV(C) = \sum_{t=0}^{T} \frac{B_t}{(1 + i)^t} - \sum_{t=0}^{T} \frac{C_t}{(1 + i)^t} \]

\[ NPV = \sum_{t=0}^{T} \frac{B_t - C_t}{(1 + i)^t} \]

Assuming that costs occur only in the present and benefits arise constantly over time with a constant discount rate, the equation simplifies to:

\[ NPV = -C + \sum_{t=0}^{T} \frac{B}{(1 + i)^t} \]

\[ = -C + B \left[ \frac{1 - (1 + i)^{-T}}{i} \right] \]

Several types of uncertainty for the earthquake consequences exist, and it is reasonable to divide the future in terms of a number of distinct contingencies. The probabilities of occurrence in each of the contingencies should be integrated in the analysis. Modeling the uncertainty starts with the specification of a set of contingencies, such as the costs and benefits with different strong magnitudes or the event time. With the specification and their probabilities it is possible to calculate the expected net benefit (Boardman, 2001). The expected net benefit, \( E[\text{NB}] \), is given by:

\[ E[\text{NB}] = p_1(B_1 - C_1) + p_2(B_2 - C_2) + \cdots + p_n(B_n - C_n) \]

Where for \( n \) contingencies, \( B_i \) be the benefits and \( C_i \) be the costs under contingency \( i \), \( p_i \) are the assigned probabilities. The sum of the probabilities \( p_1, p_2, \ldots, p_n \) must be one. The expected value of the net present value is given by the formula:

\[ E[\text{NPV}] = p_1(\text{NPV}_1) + p_2(\text{NPV}_2) + \cdots + p_n(\text{NPV}_n) \]

With this equation the expected net present value for different magnitudes and other contingencies can be calculated. Also, the specific time of the earthquake occurrence should be varied, because the case with an event with a magnitude of 7.2 in year 5 and the same earthquake 20 years later has a strong influence on the net present value.

**Step 6 – Sensitivity analysis**

The inputs of a quantitative analysis are often incomplete because of a lack of data or knowledge, and alternative interpretations of these inputs can be made. Significant uncertainty exists in the modeling of earthquake consequences and the decision process of mitigation projects. Magnitudes of future earthquakes and the produced severity of ground motion can’t be predicted precisely. Also, the performance of the building structure and the resulted damage cannot be calculated very accurately, the economic consequences and the development after a strong earthquake are unknown, too. Thus, the variability in the input
parameters of the loss estimation has to be taken into account with Monte Carlo simulation (MCS). Fig. 6 shows the uncertain elements in the decision process.

Exemplarily, some distributions are shown:

**Discount rate:**

\( i = (t_{\text{min}}, t_{\text{exp}}, t_{\text{max}}) \)

The direct costs of a retrofitting alternative can be expressed as triangular distribution for alternative \( x \) at time \( t \):

\[
(C_{x,t}^{\text{direct}}) = \text{triangular}(C_{x,t,\text{min}}^{\text{direct}}, C_{x,t,\text{exp}}^{\text{direct}}, C_{x,t,\text{max}}^{\text{direct}})
\]

The associated probability density function is:

\[
F(C_{x,t}^{\text{direct}}) = \int_{C_{x,t,\text{min}}^{\text{direct}}}^{C_{x,t,\text{max}}^{\text{direct}}} f(C_{x,t}^{\text{direct}}) \, dC_{x,t}^{\text{direct}}
\]

With Monte Carlo simulation several scenarios are generated. The variety of parameters and their consequences on the complete damage state is shown in Fig. 7:
Step 7 – Decision for best alternative

Finally, once the input parameters and their influence on the net present value are analysed, the alternative with the highest expected net present value should be chosen. Often alternative projects are compared in terms of benefit-cost ratios, but a project with the largest net present value does not necessarily have the best B/C ratio. For example, consider that project A with costs of 1 million Euro and benefits of 10 million Euro has a benefit-cost ratio of 10, project B with costs of 5 million Euro and benefits of 15 million Euro has a larger net benefit, but the ratio is only 5. Although the costs of project B are higher, the project with the largest net benefit should be selected. Under budgetary constraints and more than two projects, a combination of those alternatives should be chosen which maximize the net present value. Relying on ranking the alternatives based on their benefit-costs ratios would not maximize the investment benefit. Furthermore, if the same cost or benefit elements in all examined alternatives would be removed by the analyst, such as costs for the building site equipment or costs for service disruption, to simplify the calculation, the highest benefit-cost ratio could swap between the alternatives.

EQSIM FRAMEWORK

EQSIM is a client/server application and divided into three main parts. The information component is integrated in Google Earth and so accessible over the Internet via Web browser. The inner city of Bucharest with over 1300 buildings is modeled in 3D and exact information about housing population, occupancy, structure, and storey can be retrieved. By clicking on the information point of a specific building, up to five building pictures about the original building state can be viewed. Potential losses from future earthquake are calculated with the simulation part of EQSIM. The simulation component is responsible for estimating potential losses from historical and hypothetical earthquakes. The calculation is based on the capacity-spectrum method. A more detailed description about the used methodology for the structural damage and casualties can be found in (Fiedrich, 2002). Based on the structural damage and casualties direct and indirect losses are summarized. The decision support component assesses retrofit projects for an urban area and evaluates these projects through Monte Carlo simulation as described in the previous section.
Figure 8. EQSIM architecture and components.

All results of the simulation are stored in the database and adequate thematic maps for Google Earth are created to visualize the results of the scenario. Additionally, reports for spreadsheet applications can be used to analyse the damage scenarios.

Figure 9. EQSIM Screenshot (Google Earth view).
Figure 9 shows a screenshot from EQSIM in Google Earth. On the left side the damage states 1-5 are clustered with graduated colors. On the main window the test area in the inner city of Bucharest with three-dimensional buildings is shown. On the bottom of the picture, the EQSIM frontend is shown, where the input parameters are defined and the simulation can be started.

**CONCLUSION**

This paper outlined some research topics around EQSIM and the decision support for rehabilitation programs. The decision process as shown is complex and many uncertainties in the input parameters exist. Huge efforts have to be made to gather all input data. With sensitivity analysis the most influential parameters can be found, in order to specify these values more accurately in a next step. With EQSIM a very powerful application exists which is also open for other regions. The information, simulation and decision support components are accessible over the internet and via Google Earth. It is possible to see 1304 buildings in the centre of Bucharest in 3D and to get detailed information about construction type, construction year, height, occupancy, occupants and more. The earthquake simulation component can be configured and started with Web2.0 technology and simulation results like structural damage, casualties and economic losses can be viewed and analysed directly in Google Earth. Once having the economic and financial losses after an earthquake the user can calculate the costs of retrofitting alternatives for specified buildings and compare the different alternatives. Moreover, the software is connected with more applications developed by the CRC, for instance the resource allocation system for the emergency operating center during earthquake events.

Further developments will refine the cost calculation to more region specific data and the dynamic optimization to maximize the net present value. Additionally, a user management system and a front end should be integrated to allow for affected people to enter own data, such as inventory data, lease prices, and incomes.

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