Decision Making Tools for Seismic Risk

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ABSTRACT: Earthquake risk, and the benefits and deficiencies of possible risk mitigation options, need to be communicated in such a way as to allow appropriate and responsible decision-making. This paper describes the difficulty in making a decision about whether or not to consider earthquake in design or retrofit. Then, a series of visual/graphical tools for presenting the benefits of design and retrofit options for new and existing structures are described. These tools, which are developed based on a life cycle methodology, allow a quantitative assessment of the best technical solution as an aid to decision-making. The need for standardization of loss estimation methods is emphasised.

1 INTRODUCTION

Whether or not it is carried out explicitly, owners and responsible officials are making decisions which affect the seismic vulnerability of their facilities. By not considering earthquake risk, officials cannot be certain of the gamble they are taking. Pressures, resulting from other natural disasters (such as recent earthquakes and Hurricane Katrina), and from scenario reports (such as the Seattle Fault Scenario, EERI 2005), are providing impetus for officials to develop explicit plans to manage earthquake risk. However, the plan which gives the most benefit to the stakeholders in the facility is not always clear. Some reasons for this are described in the twin perspective statements below.

- Severe earthquake shaking at a particular site is a high impact event possibly causing severe damage and loss of life. Therefore, they should be considered. Yet …
  - Severe earthquakes are low probability events. Therefore, it may not be worth considering them at all.
- Insurance, post-disaster search and rescue teams, and recovery plans may seem better economic alternatives than structural retrofit or design. Yet …
  - Structures kill people and damage affects the operations.
- Some responsible officials retrofitted their facilities a number of years ago. Yet …
  - New seismological information indicates that their facilities are inadequate again.
- A well designed structure (by itself) may behave well in a major earthquake. Yet …
  - A neighbouring building may collapse on it!
- We understand the shaking characteristics from many past earthquakes well. Yet …
  - The only thing that we know for sure about the next earthquake is that it will be different from any earthquake that ever happened before.
- If a structure is designed or retrofitted for earthquake, and no earthquake occurs during the life of the structure, the funds that were spent are largely wasted. Yet …
  - If an earthquake does affect a structure designed or retrofitted for earthquake, the investment may be worthwhile.
- Every structure already has some resistance against earthquakes. Yet …
  - Earthquake-proof structures do not exist.
- We currently have the state-of-the-art earthquake shaking predictions. Yet …
  - Earthquake shaking predictions will be different (probably bigger) in the future, in the same way that they were different (and smaller) in the past than they are now.
- Earthquake induced damage and loss of life can devastate a population and economy. Yet …
It can be argued that earthquake damage and loss of life may be better long term for a population. (For example, it provides an opportunity to renovate an older area in a city. The 1666 Great Fire of London enabled renovation and organization of the city providing an infrastructure from which Britain could rule the world for several hundred years).

Based on the points above, it may be seen that technical uncertainty, as well as value judgements, are part of the decision-making process. Even after it has been decided to design facilities to consider earthquake, it is not always clear what level of earthquake should be considered. A balance has to be found between earthquake protection and cost given that there is incomplete information about both. The level of protection to be provided is not only a technical decision, but it is a political decision affected by factors such as:

- Awareness raisers (e.g. media, lobbyists, friends, etc)
- Belief in earthquake information
- Changing state of earthquake information
- Level of earthquake already considered in codes and by other organizations
- Level of risk acceptance and method of decision making
- Resources and competing needs
- Understanding of earthquake damage

A framework for understanding how all the information is balanced together to develop a decision is carried out through a relatively simple three-step process (Petak 2001). Firstly, decision-makers must be made aware that there is a risk. This is usually the result of an experience which has involved some loss. Secondly, they must be made aware that there is a means of mitigating the risk. This may be the result of experience, or models (physical, analytical, sophisticated or simple) which are consistent with experience. Thirdly, the stakeholders/responsible officials must choose to allocate resources, which could be used for some other purpose, to provide some risk mitigation.

Loss-estimation tools have become useful in the decision-making process in the past. They are used in the determination of how many resources should be allocated to mitigate earthquake risk as a result of (or in the midst of) the twin perspective statements above.

This paper, describes how loss information can be communicated to a client to assist their decision-making. Tools to develop this information, using rigorous probabilistic theory, were developed as part of a fourth quarter postgraduate course on loss estimation (MacRae 2004) using range of methods (e.g. closed-form, numerical integration and Monte-Carlo numerical simulation).

2 THE PROBLEM

Methodologies for expressing seismic risk and the benefits of different mitigation alternatives are required for both individual facility evaluation (such as for ports, buildings, bridges), and for regional loss estimation (e.g. cities, provinces).

For simplicity, the problem will be illustrated for a steel building which has connections susceptible to fracture during an earthquake. The decision-making issue for such as structure/facility may be expressed as:

There is an important structure in an area of high seismic risk which is known to be is seismically deficient. If it will be pulled down in 1 year because it is old, then we probably would not retrofit it. If it is expected to be in use for the next 100 years, then it is likely that we would retrofit it. If the expected remaining life is 18 years say, how do we decide whether we should retrofit it or not? If it is decided to retrofit the structure, and there are several possible ways of retrofitting it, each with different costs and benefits, how do we decide which is best?

The building considered (MacRae 2004) was located near the site of the Civil Engineering department at the University of Washington, Seattle. The pre-Northridge connections are relatively brittle. In addition to an assessment, three retrofit options are evaluated. These include:

i) replacing the connections with improved connections
ii) placing unbonded braces in the frame to reduce the demands
iii) placing damping devices in the frame to reduce the demands
3 COMMUNICATION WITH THE CLIENT

In order to communicate effectively, the engineer must understand how the client thinks and use tools which the client/decision-maker will understand. The tools should be such that the client can take them and use them to describe the rationale for any decision to the stake-holders. They should not contain excessive technical engineering detail, although technical detail should be available if the client wants it. The communication should match the client’s absorptive capacity (Cohen and Levinthal, 1990) which is often related to profit and losses. A series of curves will be used to describe the losses. Descriptions of different types of curve are given in Appendix 1. The steps below present one way of communicating the losses. Since communication is an art form, and people communicate and learn in different ways, adaptations of this will be necessary.

The first curve shown is a loss vulnerability curve as shown in Figure 1a. It gives the client an immediate idea of the likely loss, given earthquake shaking of a particular intensity at the site. Because the estimates of loss come from probabilistic analyses which explicitly consider the uncertainty, median values, or values corresponding to a specific percentile, may be used. Losses should include the “3 Ds” which are important to the client. They are Deaths (involving human life or injury), Damage, and Downtime (e.g. business interruption). All of these, at least in the eyes of the insurance industry, can be expressed in units of currency such as Dollars. The loss vulnerability curve may have an upper bound associated with the total destruction of the facility.

Graphic photos showing related damage in past earthquakes can be used to give an indication of the upheaval caused. They are useful in appealing to the emotions, as well as to the minds, of the clients.

![Graph showing loss vulnerability curves](image)

(a) As-Built (with variation)      (b) Median for As-Built & Retrofit (Wacker)

Figure 1. Loss Vulnerability Curves

If the losses seen in Figure 1a are unacceptable to the client, then the reduction in loss with different mitigation measures may be seen in Figure 1b. Figures and drawings of the different retrofit (or mitigation) options, explanations of how they work and descriptions of why they cost different amounts may be useful. The higher intensities are less likely to occur, so a digression into seismology is useful here (see Figures 2-4). Figure 2 shows an Intensity Measure (IM) hazard curve. Such a curve can be expressed as a probability of exceeding a specific ground motion intensity, \( P(DV > dv|t_k) \), in a certain time, \( t_k \), which is usually one year. This is the annual probability of exceedance (APE). Additional curves can be placed on this graph to show the probability of exceedance for period of several years. A variation on the loss hazard curve uses the Annual Exceedance Rate (AER) rather than probability of exceedance. The AER is similar to the probability of exceedance for low values; however, it is different for high values.
Figure 2. IM Hazard Curve for One year (Wacker)

Figure 3. US IM Hazard Map (USGS)

Figure 4. Deaggregated Seismic Hazard (USGS)
To enhance confidence in the seismological data further, comparisons with the data at a couple of points (say, that corresponding to 2% probability in 50 years, and that at 10% in 50 years) with existing seismic maps, such as that in Figure 3, can be carried out. Maps showing locations of major faults, as well as a deaggregated hazard plot, showing the contributions of all the nearby faults to the hazard at a site, as shown in Figure 4, may also be useful. Deaggregated data is freely available directly from the World Wide Web (WWW) in the USA and it would be good if similar information were available in New Zealand.

It is necessary to combine the information from the hazard curve and the vulnerability curve to obtain a loss hazard curve as shown in Figure 5. This indicates the probability of exceeding a particular loss in a certain time frame.

![Loss Hazard Curve](image)

**Figure 5. Loss Hazard Curve for Structure with Improved Connections (Wacker)**

A probably loss curve, such as that in Figure 6, allows the loss associated with a particular state (e.g. as-built) to be described with time.

![Idealized Probable Loss Curve](image)

**Figure 6. Idealized Probable Loss Curve for particular facility state**

For a retrofitted structure, the total cost at any time (in present value terms) is equal to the cost of retrofit, plus the loss with time from Figure 6. This may be computed for a particular retrofit, or a series of retrofits and the as-built structure as shown in the total loss curve in Figure 7. The time where a particular retrofit line crosses the as-built line is the break-even time. For structures with shorter lives retrofit is not required, but for structures with longer lives, a retrofit is more economical on average. The best solution corresponds to the line with the lowest cost at a particular time. Other factors, such as ordinary deterioration of the structure over time (e.g. such as concrete cancer in concrete structures), can also be included in such a model.

While all of the plots above may be useful in assisting the client to make a decision, many other political considerations are also considered. One of these, as described by Peter May, is that since there...
is so much (epistemic) uncertainty in the information that is available to determine the loss curves and the probabilities associated with them, it may be best to under-retrofit to provide more options for future changes in knowledge. However, it may also be argued that seismic demands have tended to increase rather than decrease with the passage of time, so over-retrofitting may result in a structure not being seismically deficient in the future.

While the discussion above relates to a particular building being considered for retrofit, the methodology presented is also applicable for the design of individual new structures, for the design of groups of structures by the selection of an appropriate lateral force reduction factor, $R$, or to describe regional losses.

4 METHODS USED TO DEVELOP LOSS ESTIMATES

If several engineers were to develop the curves described above, there is a high likelihood that the curves would look quite different. This is because a number of assumptions are needed to develop the curves. These assumptions relate to the data used, the relationships between different types of data, and the methods of computation/modelling. An estimate of losses without a full description of these assumptions lacks credibility.

Some specific factors which should be considered and specified in the development of tools to communicate earthquake loss include the following. These were developed mainly for steel framed structures, and more general lists may be developed for other types of facility.

**Earthquake Hazard:** For example:
   a) Earthquake sources considered
   b) Faults causing the most contribution to the site hazard
   c) Basis for selection of earthquake ground motions (including attenuation information if relevant)

**Site Modelling:** For example:
   a) Site location
   b) Soil type
   c) Considerations of soil structure interaction
   d) Considerations/possibility of liquefaction/soil flow

**Structure:** For example:
   Type of structure and details.

**Structure Modelling:** For example:
   a) Modelling of joints (e.g. centreline, rigid offset, or explicit joint consideration)
   b) Considerations of P-Delta
   c) Considerations of torsion
   d) Diaphragm considerations
   e) Considerations of slab effects
   f) Considerations of beam elongation
   g) Computer program used
   h) Important program specific options

**Analysis:** For example:
   a) Method used (e.g. LSP, LDP, NSP, NDP)
   b) Design spectra for the LSP/LDP
   c) Target displacements and load patterns for NSP
   d) Records used for the NDP
   e) Vertical shaking considerations
   f) 1D/2D or 3D analysis
   g) Modification of analysis method to obtain more realistic results
   h) Different configurations considered (e.g. SAC PreN connections, PostN connections, unbonded braces, supplemental damping).
Demands: For example:
   a) Types of demand considered (e.g. drift, displacement, permanent displacement, member force demands)
   b) Consideration of epistemic uncertainty

Retrofit Configurations: For example:
   a) Method of choosing sizes for retrofit
   b) Whether or not retrofit optimization was carried out
   c) Figures showing retrofitted frames with sizes of members
   d) EDP Hazard curves for these configurations

Damage: For example:
   a) Types of damage considered
   b) Method of estimating damage
   c) Consideration of randomness and epistemic uncertainties in capacities

Losses: For example:
   a) Types of Loss Considered, e.g.
      i) Direct loss ($) (cost of damage and repair)
      ii) Downtime (days) (associated with loss of use of the structure)
      iii) Indirect loss ($) associated with loss of structural use
      iv) Life loss and injuries (# people)
   b) Method of estimating losses
   c) Consideration of randomness and epistemic uncertainties in losses

Limitations: For example:
   a) Any obvious limitations of the model

The inadequacies in any modelling method should be recognised. The only accurate model of a structure is a full scale one which has the same construction materials, details and defects as the prototype structure, which sits on an identical foundation, and which is subject to the same forces over its life. Any other model is simply a crude approximation, with the level of crudity being related to the calibration (which also affects the sophistication) of the model.

5 STANDARDISATION OF TECHNIQUES

As probabilistically based loss estimation (and performance based earthquake engineering tools) become more widely used, development of simple, step-by-step standardized methods will become necessary (e.g. Poland, 2004). They are necessary both for a facility evaluation (such as that described above), or for a regional loss estimation (such as HAZUS or RiskScape). Methods of differing complexity (such as those used in structural analysis – such as LSP, NDP, LDP, NDP etc.) are necessary for clients wanting studies of different detail (and expense) carried out. These standard methods should be as explicit as possible to allow the same loss estimates to be computed by different people. Such standardization should be developed out by a committee representing the academics, governmental/nongovernmental institutes, consultants and clients/decision makers. It is proposed that a group to develop and formalize standard methods and tools for loss estimation be developed within New Zealand to lead the world in this task.

6 CONCLUSIONS

In this paper, some of complexities relating to earthquake decision-making were described; a method for communicating losses using life-cycle loss considerations was discussed; and some recommendations were given regarding the type of technical information that should be presented as background to any loss estimation. It was proposed that a NZ committee be formed to develop standardized procedures for developing information to be used for earthquake decision-making.
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Engineering, University of Washington, Seattle.

Appendix 1. Loss Estimation Curves

<table>
<thead>
<tr>
<th>Relationship Measure</th>
<th>Hazard (PL)</th>
<th>Vulnerability (SL)</th>
<th>Fragility (SL)</th>
<th>Probable Loss (PL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IM</td>
<td>$P[IM &gt; im</td>
<td>t]$</td>
<td>$P[EDP &gt; edp</td>
<td>im]$</td>
</tr>
<tr>
<td>EDP</td>
<td>$P[EDP &gt; edp</td>
<td>t]$</td>
<td>$P[EDP &gt; edp</td>
<td>im]$</td>
</tr>
</tbody>
</table>

$IM$, $EDP$, $DM$ and $DV$ represent Intensity Measure, Engineering Demand Parameter, Damage 
Measure and Decision Variable respectively according to the PEER definitions. The letter in **bold** 
indicates what is plotted on the y-axis, and the parameter which is *not in italics* is plotted on the x-axis. 
The *capitalized parameter* is the one that is changing randomly (e.g. DM) and whose effect is being 
evaluated. The one in *small letters* (e.g. dm) indicates the parameter changes, thereby allowing a curve 
 to be plotted. The subscripts, $i, j, k$ indicate that the curve is based on one value of parameter (e.g. as in 
$dm$). The letters SL and PL describe whether the curve represents a Scenario Loss (which is event 
deependent), or a Probable Loss (which is time dependent).

A *distribution curve* may also be found. For example, the CDF for the distribution of loss 
corresponding to a particular damage level is $P[DV > dv|dm]$. This is different from the other curves 
above.