Economic Analysis of Structures Deficient in Earthquake Resilience

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ABSTRACT: The lack of earthquake resilience of many older structures poses a significant disaster risk to many communities in Australia and New Zealand. In considering the future of these structures several options are available including retrofitting to improve the resilience, demolition and replacement, or leaving them as they are. This paper describes the basic fundamentals of cost benefit analysis in respect of these different options, highlighting the importance of including the role of insurance in such analyses. A key input is the annual earthquake risk loss for the different options, the estimation of which is identified as one of the most difficult parts of such analyses. Furthermore there is a significant degree of uncertainty about most of the variables when analysing future costs and benefits. The insurance industry has developed two different tools to cope with these issues in respect of their own management of catastrophe risk. It is proposed that these tools be adapted for the detailed analysis of costs and benefits which is required for reliable decision making in dealing with structures perceived to be deficient in respect of their earthquake resilience. This will require multi-disciplinary research within the engineering, earth science and financial disciplines.

1 INTRODUCTION

In developed economies such as New Zealand and Australia building codes have been continuously improved as a result of increased knowledge of structural behaviour under the types of hazards to which they may be exposed during their lifetimes. This has resulted in a wide disparity in the vulnerability of buildings to these hazards in these countries. This is highlighted when major hazard events such as earthquakes occur with damage to older structures often being an order of magnitude greater than that to newer buildings constructed to recent building codes. While the current codes, amended where necessary to account for deficiencies highlighted by earthquakes, ensure that new construction should have a high degree of earthquake resistance, they do nothing to reduce the vulnerability of the stock of existing buildings.

Recent legislation in New Zealand requires identification of structures considered to pose a significant risk if a major earthquake occurs due to deficiencies in earthquake resistance relative to that implied by current building codes, and decisions made on what to do about them. The three basic options available are to upgrade the earthquake resistance by retrofitting, to demolish the structure and replace it, or to do nothing. In making this determination there are two main considerations, human safety and economic risk. Human safety is the first priority and effectively sets a lower limit to what is acceptable in terms of earthquake resistance. However this may not be sufficient in terms of economic sustainability which is becoming an increasingly important factor in respect of disaster mitigation. Reliable analysis of the costs and benefits of the different options available are important in the decision making process concerned with this.

A common form of cost benefit analysis is for two or more alternatives to be proposed, the costs of implementing them estimated along with the consequential benefits to the whole of society, and a
decision made considering both the total consequential benefits and the ratio of the consequential benefits to the implementation cost. This can be described as the global approach. Thomas and Irvine (2008) used this approach in analysing the costs and benefits of a proposal for upgrading the earthquake resistance of the foundations of old houses in the Wellington region. This approach is appropriate if there is only one group of stakeholders, the community, who share the costs and the benefits. However it is not very appropriate where there are several different stakeholders, which is the case in respect of many structures which are deficient in earthquake resistance. In this situation there is the owner, perhaps a tenant, the insurance industry, which comprises two groups of stakeholders with separate interests, insurance companies and reinsurance companies, government if it has to pick up any of the costs arising from earthquake damage, and third parties which may indirectly suffer loss as a result of damage to a structure. Additionally there is the national economy. All these groups have different interests in the outcome, and a benefit to one group, may be a cost to another as demonstrated by Walker and Musulin (2010).

2 SOME BASIC FUNDAMENTALS

2.1 Global Analysis of Retrofitting

Global analysis of the costs and benefits of retrofitting requires only a few pertinent variables expressed as a percentage of the replacement value of the building:

RFC  = the estimated cost of retrofitting the current building
CLR  = the estimated annual loss risk of the current building
RLR  = the estimated annual loss risk of the retrofitted building

If it is assumed that building costs will increase in line with inflation then the calculations can be undertaken in present day values without any need for adjustment.

If the replacement value is RPV, then the accumulated expected risk adjusted costs in present day values over a time period of N years into the future related to earthquake can be expressed as:

If the building is not retrofitted  = CLR * RPV
If the building is retrofitted   = RFC + RLR * RPV

Figure 1 Relative future risk costs – global analysis

Figure 1 shows a typical plot of the results of this type of analysis. The payback period is the time period at which the two lines intersect. In this example it is assumed that RFC = 0.05, CLR = 0.002 and RLR = 0.0005 (ie a 75% reduction in risk), producing a payback period of approximately 33 years. But this analysis does not identify who pays the costs and who receives the benefits.
2.2 Allowing for Insurance

In Australia and New Zealand most buildings are insured for damage losses arising from earthquakes. If insurance is based on replacement value, which is the normal case in Australia and New Zealand, and premium rates are assumed to remain constant with time, then like global analysis a basic analysis of future costs and benefits related to upgrading for earthquake can be undertaken by using the present day values without any adjustment. Additional variables need to be introduced related to the price of the insurance. The earthquake component of the premium rate can be expressed in terms of a mark-up on the estimated loss risk from earthquakes. The earthquake mark up factor is a function of the size of the overall earthquake event risk which is related to the concentration of earthquake risk. If there is an increase in the mark-up after retrofit then it means the insurance company is not fully recognising the reduction in risk. However in many cases this does not happen and a larger mark-up is effectively applied. Consequently two additional variables need to be introduced:

\[
\text{CIM} = \text{the current earthquake insurance mark-up on the estimated earthquake loss risk}
\]

\[
\text{RIM} = \text{the insurance mark-up on the estimated earthquake loss risk of the upgraded building}
\]

While the payment of premiums is a cost to the owner, if damage occurs the owner can claim the costs of repair and replacement, which is an annual benefit to the owner equal to the expected annual loss.

For the simple case where all losses are insured the accumulated expected risk adjusted costs in present day values over a time period of N years into the future related to earthquake can then be expressed as:

- If the building is not retrofitted: \(\text{CLR} \times \text{RPV} \times (\text{CIM}-1)\)
- If the building is retrofitted: \(\text{RFC} + \text{RLR} \times \text{RPV} \times (\text{RIM}-1)\)

On average over a whole insurance portfolio for earthquakes the insurance mark-up will be considerably greater than one because of the inherent costs involved in reducing a risk with a very large coefficient of variation to a level that can be managed (Walker, 2008). For the earthquake component of property insurance in Australian and New Zealand it is typically of the order of 2.5.

![Figure 2](image-url)  

**Figure 2** Relative future risk costs to owner – including insurance

Figure 2 shows the plot of the accumulation of risk costs to the owner taking insurance into account assuming an insurance mark-up of 2.5 for both the retrofitted and non-retrofitted case – ie before retrofit the insurance premium approximates a risk rated premium and the owner receives the full benefit of the reduction of risk from the insurer after the building is retrofitted. In this case it will be seen that the payback period has been reduced to approximately 22 years, enhancing the incentive to upgrade. This is due to the cost of insurance increasing the annual loss to the owner as shown in Figure 2.
Figure 3 Relative future risk costs to owner with varying insurance mark-up

Figure 3(a) shows the effect on the cost-benefit analysis if the owner continues to pay the same premium after retrofit, which is the case for the New Zealand residential earthquake insurance scheme managed by the New Zealand Earthquake Commission (EQC). Because the risk has been reduced by a factor of 4 this means the insurance mark-up is increased to 10. In this case the owner will never get payback for the initial cost of undertaking the retrofit. Even if the insurance industry paid this cost the owner would still be worse off due to the divergence of the risk based costs in the future.

Figure 3(a) is based on the premium before retrofit corresponding to a risk rated premium. In practice for individual buildings the mark-up may vary widely depending on the degree to which the insurance company relates individual premiums to risk. For instance, the New Zealand government earthquake insurance scheme for dwellings is based on a fixed premium rate irrespective of the risk to individual buildings which means that the insurance mark-ups for old buildings in high earthquake risk areas like Wellington may well be significantly less than one, while the insurance mark-up for new buildings in low risk areas like Auckland may be greatly in excess of 2.5. Figure 3(b) shows the effect on the cost-benefit analysis if the initially premium is significantly lower than it would be if risk rated. It will be seen in this particular case not only would the owner be much worse off if no adjustment was made to the premium after retrofit, but even if full adjustment is made the owner would still be worse off as the initial cost of the retrofit would never be recouped. From a financial perspective there would therefore be a strong disincentive to mitigate as far as the owner is concerned.

If the owner does not get any benefit, who does? The insurance industry obviously, but because of reinsurance it may not be the local insurance company. Consequently the benefits may not even be restricted to the national economy. This is one of the weaknesses of the global approach to cost benefit analysis of retrofitting. The above analysis, relatively simplistic though it is, highlights the importance of taking insurance into account in considering the costs and benefits of upgrading buildings for earthquake – as well as highlighting the importance of premiums being risk rated, both before and after retrofitting, if there is to be any incentive for owners to do it.

2.3 The Demolition Option

Experience has shown that where upgrading of buildings has been mandated it is not uncommon for the buildings to be demolished and new ones constructed. This is another major option which needs to be subjected to cost-benefit studies. Depending on the nature of the building, its use, and its location, there are many different options that may be possible. The simplest is to demolish the inadequate building and replace it with a new one of similar size and function. This is more likely to be the solution adopted in the case of a single family dwelling than a commercial building, but is the one which is considered here as it highlights the general characteristics of considering this option.

This option requires an analysis of the relative net value to the owner in the future of keeping the present building, or demolishing and building a new one. Buildings depreciate in value with time in terms of present day values – it is the land on which they are located which appreciates in value. There
is also an erosion of the capital associated with them due to insurance costs less possible insurance
claims. Buildings also have amenity value. In the case of commercial and industrial buildings this is
reflected in rental values. In the case of owner occupied residences it is the rentable value. This is a
function of both the land and building value. The contribution due to the building decreases in real
terms with the depreciation in value of the building. If a building is demolished the existing capital in
the building is destroyed and external capital must be provided to build the replacement. This comes at
a cost represented by the interest on capital provided by a lender or foregone if provided by the owner
from other sources. With time the real value of both the amount borrowed and the interest repayments
decrease because of inflation. Because it will be a new building built to current building codes the
annual loss risk is also likely to be considerably less than that of the original building, whether or not it
is retrofitted, leading to lower insurance premiums if they are risk rated.

A basic cost benefit analysis requires the introduction of a number of additional variables:

\[
\begin{align*}
\text{AGE} & \quad = \text{the age of the current building} \\
\text{DPR} & \quad = \text{the annual depreciation rate of the buildings relative to its replacement value} \\
\text{INF} & \quad = \text{the assumed annual inflation rate} \\
\text{INT} & \quad = \text{the assumed interest rate borrowed money} \\
\text{AMV} & \quad = \text{the amenity value relative to the depreciated value of the building} \\
\text{NLR} & \quad = \text{the estimated annual loss risk of the new building} \\
\text{NIM} & \quad = \text{the insurance mark-up on the estimated loss risk used in insuring the new building}
\end{align*}
\]

After \(N\) years in the future the net capital value in respect of earthquake risk if nothing is done will be:

- The depreciated value of the building (DPV) = \(\text{RPV} \times (1-\text{AGE}+\text{N})\)
- Plus the accumulated amenity value = \(\sum (\text{AMV} \times \text{DPV})\) over \(N\) years
- Less the accumulated expected risk adjusted losses = \(\text{CLR} \times \text{RPV} \times (\text{CIM}-1)\)

If it is retrofitted the only change will be in the accumulated risk adjusted losses – see above.

If the building is demolished and replaced then the net value after \(N\) years in the future, with
intermediate years being designated by \(n\), will be

- The depreciated value of the building (DPV) = \(\text{RPV} \times (1-\text{N})\)
- Plus the accumulated amenity value = \(\sum (\text{AMV} \times \text{DPV}(n))\) over \(N\) years
- Less the principal of the loan depreciated for inflation = \(\text{RPV} \times (1-\text{INF})^\text{N}\)
- Less accumulated interest payments depreciated for inflation = \(\sum (\text{INT} \times \text{RPV})^*(1-\text{INT})^n\) over \(N\) years
- Less the accumulated expected risk adjusted losses = \(\text{NLR} \times \text{RPV} \times (\text{NIM}-1)\)

Figure 4(a) shows the results of such an analysis assuming \(\text{AGE} = 50\), \(\text{INF} = 4\%\), \(\text{INT} = 6\%\), \(\text{DPR} = 1\%\) per annum, \(\text{AMV} = 5\%\), \(\text{CLR} = 0.002\), \(\text{RLL} = 0.0005\), \(\text{NLR} = 0.0002\), and \(\text{CIM} = \text{RIM} = \text{NIM} - 2.5\) – ie the insurance premiums in each case are approximately risk rated. Figure 4(b) shows the
results if the age of the original building is reduced to 30 years. For this particular combination of
assumptions it will be seen that while there could be long term benefits for the owner from replacing
the building if it is 50 years old, there would not be a benefit if it was 30 years old. Although the
analysis is relatively simplistic it nevertheless indicates that demolition and replacement may be the
best option for an owner, but it will depend on the relative values of a number of critical variables
including the age of the building.
2.4 Comments

The above analyses are simplistic because

- They only look at the analysis from the viewpoint of the owner, whereas in practice there are other stakeholders such as the insurance companies, the government and the national economy, and maybe other third parties, which should also be considered in a full analysis of the costs and benefits of mitigation;
- Not all losses will be insured;
- Insurance is more complex as usually the owner retains some risk through a deductible, and in the case of the New Zealand residential earthquake insurance, the EQC insures the loss up to a fixed limit for a uniform premium, with the additional risk being carried by private insurance companies who charge premiums which are more risk related;
- Fixed values have been assumed for many of the variables whereas in practice they may have more complex characteristics, including variation with time and being subject to considerable uncertainty. This is particularly true of inflation and currency exchange rates, but may also be true of the insurance mark-up factors which can change with time as a result of changing global demographic factors including insurance penetration and the growth in number and size of major urban concentrations of population.

While the simplistic analysis is indicative of the overall characteristics of cost benefit analysis of the different options, in practice a detailed cost benefit analysis needs to take into account these limitations leading to the need for a much more sophisticated approach than described. Kleindorfer, Grossi & Kunreuther (2004) have demonstrated how tools used in the insurance industry for managing catastrophe insurance risk can be adapted to do this.

3 DETAILED ANALYSIS

3.1 Loss Risk Analysis

Estimating the annual risk of loss for the different options is critical for reliable cost benefit analysis of the different options, and is also the most difficult part of the analysis. Historically there has been great reliance on expert opinion in conjunction with relatively simple analysis. However earthquake loss risk models as initially developed in the 1980’s, and now widely used in earthquake insurance risk assessment, have the potential to provide much more reliable loss risk estimation. These models were largely developed in a commercial environment as a customised tool for the insurance industry, being designed for assessing the risk from large groups of roughly similar buildings, not individual buildings differing only in the detail of their structural design. Being commercial developments, the details of
these models were not available in the public domain. However in recent years there has been an increasing level of development of open source models in the public domain which are much more accessible to researchers and analysts outside the commercial insurance world (Daniell, 2009). These models have great potential for use in cost benefit analysis.

Researchers can adapt open source models to their specific needs. These models require a combination of expertise from the engineering, earth science and financial disciplines. In general the modelling of earthquake hazard risk is much more reliable than the modelling of the vulnerability of structures to loss from earthquake damage. The vulnerability modelling in insurance models is usually largely empirical in nature based on recorded insurance loss across relatively large classes of structures. What is needed for cost benefit analysis is vulnerability modelling based on an engineering analysis of the behaviour of specific structural systems and sub-systems under earthquake loading to determine damage risk in conjunction with analysis of the financial losses arising from different levels of damage. The damage risk component of this is known as fragility analysis. This is an emerging area of structural research that currently appears to be driven by the move towards performance based structural design (Li & Ellingwood, 2009). However it also has great potential for application to cost benefit analysis of different options for dealing with earthquake deficient buildings.

Assessing the loss arising from different levels of damage is a separate area of research. Insured losses are generally those arising from the cost of repairing the damage, the cost of replacing damaged contents and the costs arising from loss of profits due to business interruption. The insured losses will not necessarily be the total of these as they are subject to policy conditions which may include deductibles retained by the owner, and limits to the amount of cover, especially in regard to business interruption. The uninsured losses which are carried by the building owner or tenant also need to be accounted for. If the damage is such that emergency services get involved in the emergency response stage then this is another cost, as is the cost associated with injuries arising from the damage. A more difficult issue is loss of life. It is common to include this in cost benefit analyses by ascribing a cost to life, but the amount is always a contentious issue. There is a strong argument for treating it separately by specifying a maximum daily life risk to which a building occupant should be exposed which would set the lower limit of earthquake resistance below which a building would have to be strengthened or demolished.

The catastrophe loss models described are probabilistic in form, generating estimated losses from a large sample of all the earthquake events which it has been ascertained could affect the building together with the estimated frequency of occurrence of each event. From this information the average annual loss can then be determined. By considering the uncertainties associated with the input data information about the reliability of these estimates can also be obtained. In general the estimated annual loss will need to be determined separately for the various stakeholders since in general these will all be different.

Catastrophe loss models are complex by nature, but their widespread use in the insurance industry has demonstrated this is not a handicap to their utilisation. However, considerable research is required if they are to be adapted for general use in the cost benefit analysis of the different options for dealing with earthquake deficient buildings.

3.2 Financial Analysis

Undertaking cost benefit analysis in a probabilistic manner requires modelling that incorporates Monte Carlo simulation of the annual financial flows and financial loss risks that impact on the cost benefit analysis of different options for dealing with earthquake deficient buildings, in conjunction with simulating these on an annual basis for a relatively large number of years into the future. Again this is similar to the requirements for managing catastrophe insurance risk in a sustainable manner by reinsurance and insurance companies, for which an actuarial tool known as dynamic financial analysis (DFA) has been developed. For forecasting into the future these are used in conjunction with a tool developed by financial analysts called economic scenario generators. An example of a financial risk management system incorporating both DFA modelling and economic scenario generation was the Minerva software system which was developed for the EQC to assist them in the management of the New Zealand residential earthquake insurance scheme (Middleton, 2001, Shephard et al, 2002), which
also incorporated an earthquake insurance loss risk model. The Minerva system was developed to enable financial forecasting of the future performance of the New Zealand Disaster Fund managed by the EQC for up to 10 years into the future, allowing for future portfolio growth varying with location and time, as well as variations in economic parameters such future inflation, investment returns and currency exchange rates. Development of such systems is inherently multi-disciplinary. The adaptation of these tools for use in cost benefit analysis of options for dealing with earthquake deficient buildings will therefore require multi-disciplinary research.

4 CONCLUSIONS

The principal conclusions regarding cost benefit analysis in regard to dealing with structures which are considered deficient in their resilience to earthquakes are

- In general, restricting the analysis to global costs and benefits will be inadequate, since the impact on the different stakeholders is important;
- In respect of property owners at least it is necessary to consider the effect of insurance;
- For retrofitting to be beneficial to the owner insurance premiums need to be risk rated;
- In addition to increasing resilience by retrofitting existing buildings it is also important to consider the option of demolition and replacement;
- Tools developed within the insurance industry such as earthquake loss risk modelling and dynamic financial analysis (DFA) have significant potential to be adapted for this use;
- Considerable research is required within both the engineering discipline is respect of structural fragility under earthquake loads, and the financial disciplines in respect of analysis of losses in terms of damage, and the adaptation of economic scenario generators and DFA techniques to the cost benefit analysis.

REFERENCES:


