CRITERIA FOR STRENGTHENING BUILDINGS: COST-BENEFIT ANALYSIS IS MISLEADING

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ABSTRACT

Decisions on the merit of strengthening buildings to resist earthquakes should not be made on a cost benefit basis, and in particular should not use estimates of the benefit that are based on the average rate of occurrence of strong ground motion. The distribution of expected ground motion is so skewed that no central measure provides a good representation of the risk. A better procedure is to determine what is the unacceptable level of loss, and then to engineer to the strength that will prevent that loss.

1. INTRODUCTION

Hopkins & Stuart (2003) have given a method for estimating the cost benefit of strengthening buildings against earthquake damage, using annual probabilities. Their results are in terms of the expected value of the Benefit/Cost ratio. All losses are calculated as Nett Present Value.

The results show benefit/cost ratios for each building type in selected towns in New Zealand. The sensitivity of the results to the different chosen parameters was determined by varying the parameters. Ratios varied widely throughout the country, reflecting the wide variation in the level of earthquake hazard. But Hopkins & Stuart (2003) note that the benefit/cost ratio can be much higher than the average if a major earthquake occurs early within the analysis period.

There is however an important issue which needs to be addressed. This issue is whether the average reduction in loss due to strengthening is an appropriate and/or useful measure of the benefit. A simple analysis suggests that it is not, and that other criteria are more appropriate decision-making tools.

2. THE HOPKINS/STUART APPROACH

Hopkins & Stuart (2003) sought to extend earlier work on cost benefit analysis. They took four groups of commercial and large residential buildings (Pre-1935, 1935-65, 1965-76 and post-1976), in 32 cities and towns in New Zealand. They estimated the cost of enhancing the earthquake performance of these buildings under four different strengthening regimes: status quo, 33%, 67% and 100% of the new building standard. They then used estimates (obtained from the Institute of Geological & Nuclear Sciences) of the frequency of occurrence of each damaging level of MM intensity and their own estimates of the vulnerability of each class of building to calculate, on an annual basis, the damage that their set of buildings might sustain and the benefit of improving structural performance. Damage costs were aggregated over an exposure period of up to 100 years, and discounted back to Nett Present Value. Loss modelling included a variety of factors such as new construction cost, retrofit cost, depletion of building stock, business and social disruption, compliance costs and others. Surrogate costs to represent injuries and fatalities were also included.

Hopkins & Stuart (2003) found that there was considerable sensitivity to the choice of input parameters such as discount rate, difference in damage ratio between different types of building, etc. The resulting benefit/cost ratios varied widely throughout New Zealand, and depended rather strongly on the assumptions made. They drew a conclusion that there is a need to deal with existing buildings, and particularly high risk buildings, at least in those towns and cities that are subject to moderate to high seismicity.

3. ALTERNATIVE APPROACH: THE BENEFIT DISTRIBUTION

Hopkins & Stuart (2003) observed that the benefit/cost ratio can be quite high if a major earthquake occurs very soon. This suggests that representing the earthquake hazard by the average rate of occurrence has severe limitations. The mean value of the benefit/cost ratio is just that: a mean. Statistically it is the expected value of a distribution. What we really need is the full distribution.

The simple development below is not as detailed in its modelling as that of Hopkins & Stuart (2003), but it does illustrate the nature of the distribution of benefit/cost ratio and suggests that the mean benefit, on its own, is not particularly useful.

4. A SIMPLE MODEL

In order to examine the distribution of the benefit/cost ratio, it is sufficient to estimate only damage to buildings, i.e. ignoring ensuing losses such as injuries, casualties, business interruption, etc. These ensuing losses are often modelled by scaling them from the building losses anyway, so provided that we are not concerned with the total value of the loss but only with the nature of its distribution it is valid to ignore these scaling factors.

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Smith & Cousins (2002) have shown how to use Monte Carlo analysis to model earthquake risk to a given portfolio of buildings. The procedure involves synthesis of three models: (a) earthquakes that are likely to affect the buildings, their magnitudes, locations and frequency of occurrence; (b) the attenuation of strong ground motion, so that the severity of strong motion at any location can be estimated, due to an earthquake elsewhere, and (c) the vulnerability of buildings, i.e. the amount of damage that is likely to result, given the characteristics of the building and the severity of strong motion. By constructing a synthetic earthquake catalogue and exposing the building portfolio to the estimated effects of the earthquakes, loss statistics can be generated.

In order to estimate the benefit of strengthening, consider a building with replacement value $1 million, and assume that it is to be strengthened so that the likely damage will be halved at each intensity level. This is actually not a realistic outcome of strengthening, because the reduction to damage is likely to be a more complicated function of intensity, but the simple model serves the present purpose well.

Now expose the building to earthquakes over a simulated period of 100 years, both in its original state and after strengthening. The difference between the two estimates is the benefit of strengthening. For each damaging event in the 100 years period, convert the cost to the Nett Present Value (NPV) using an appropriate discount rate. This produces an estimate of damage cost that could be compared with the cost of strengthening. For the present purpose it is not necessary to include the cost of strengthening and calculate a benefit/cost ratio, because the saving in damage costs demonstrates the main point, as will be shown below.

The next step is to repeat the 100 years' simulation many times. This gives many estimates of the 100-year benefit, and their values can be plotted as a distribution. The calculation was actually done 1000 times, for a building located in Wellington. The annual discount rate for the NPV calculation was 3%.

Figure 1 shows part of the distribution of the 100-year benefit, for a $1 million building that has been strengthened to sustain only half the damage it would have sustained otherwise. The mean of the distribution is $13,000. As a check on this, the annual average method of Hopkins & Stuart (2003) was used as an alternative means of calculating the mean benefit, and a similar answer was obtained. But the distribution is highly skewed, with a long tail not unlike that of a lognormal distribution. The mode (most likely value) is $800. Over half of the 1000 estimates of the 100-year damage are less than $1000. The 16- and 84-percentiles are $0 and $16,000 respectively. The largest value of the 100-year benefit, from 1000 estimates, was $382,000.

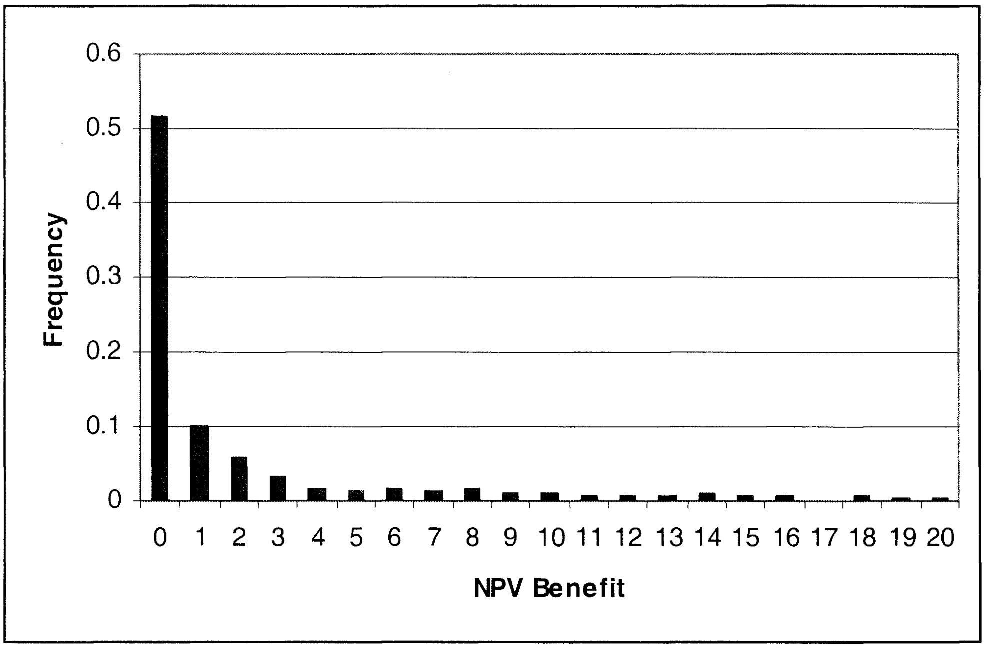

Figure 1. Frequency distribution of the benefit ($000) of strengthening a $1 million building in Wellington against earthquake, nett present value for 100 years. Strengthening involves reducing the damage by half at all intensities. The plot truncates the distribution at $20,000, although it extends to $382,000.

The spectrum as shown in Figure 1 does vary when the benefit of strengthening is determined for a portfolio of buildings, distributed geographically. In particular, the mode of the distribution moves away from zero a little more. But the character of the distribution remains, in particular its very strong skewness.

5. THE FALLACY OF THE EXPECTED VALUE

The mean benefit, as determined by Hopkins & Stuart (2003), is the expected value of the benefit distribution. But the extreme skewness of the distribution in Figure 1 implies that to characterise it only by the mean is inadequate and misleading. There is, after all, a probability of more than 50% that there will be essentially no losses over the 100-year period. The estimated mean value of the Benefit/Cost ratio seems irrelevant.

Haimes (1998) has made this point very strongly. He points out that the Expected Value is not the criterion used for the design of highways and bridges, telephone systems, emergency services or a number of other structures and infrastructure facilities. We do not design highways and bridges for the average size of vehicle and the average volume of traffic. We do not design telephone systems to cope with the average rate of calls. Electricity generating facilities should not be designed in terms of the average annual inflow to hydro lakes. These facilities demand that we look not at the mean of the relevant distribution but at its extremes. In earthquake engineering design the 95 percentile is commonly used, rather than the mean. Earthquake risk is another area where the expected value is not the best measure.

6. CRITERIA FOR STRENGTHENING

There is a need to strengthen weak buildings in New Zealand, especially those with high occupancy rates. If benefit/cost ratio is not an appropriate criterion for deciding the merit of strengthening buildings, on what criteria should decisions about strengthening be made? One possible criterion is the *unacceptable level of damage*. It would be possible to determine, on a somewhat subjective basis, what level of damage is unacceptable, and to engineer to prevent that. For a school, that level of damage is probably expressed in terms of casualties on a busy school day. For a city hospital it might be expressed in terms of loss of functionality. Heritage buildings may present issues in terms of preservation of architecture. For some other buildings the criteria may be in terms of damage to contents. For a commercial building the definition of the unacceptable level may well be in terms of both financial loss and of business interruption in the event of damage.

Note however that building codes do not entail the concept of zero damage, or of complete protection. Instead they seek to reduce the probability of loss to an acceptably low value. In setting criteria for strengthening buildings this concept must surely apply. It is unrealistic to expect complete protection against any damage. We should determine the unacceptable level of damage, and seek to reduce to some chosen figure the probability that that will occur.

This is essentially how we view insurance. The insurance company sets its premiums in terms of Average Annual Loss (for fire and general, and for life insurance, though not usually for earthquake insurance), because it is concerned with the aggregated cost of many policies. But the householder thinks in terms of the unacceptable level of loss, and insures accordingly. Probability plays a small part, as does the level of the premium, but the main issue is the unacceptable level of loss.

7. CONCLUSIONS

The mean rate of occurrence of strong ground motion is not an appropriate basis on which to derive useful criteria about the desirability of strengthening buildings against earthquake. The distribution of benefits is so skewed that the expected value, which is the mean of the distribution, has little meaning.

A better approach for decision-making is to determine, on any suitable criteria, what is the unacceptable level of loss, and to engineer for that. This takes into account the extremes of the loss distribution, rather than just the mean value.

ACKNOWLEDGEMENTS

I am grateful to Jim Cousins and David Rhoades for their very helpful comments.

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