Evaluation the ratio of benefit to cost for retrofitting tall buildings

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Abstract: In this study, a benefit cost analysis methodology is introduced for the comparative evaluation of several seismic retrofitting measures applied to a representative building. To improve safety and serviceability of tall buildings, aerodynamic optimization of building shapes is considered to be the most efficient approach. The urgent need has arisen to evaluate the benefits of loss mitigation measures that could be undertaken to strengthen the existing housing stock. The analysis is performed probabilistically through the development of fragility curves of the structure in its different retrofitted configurations. By incorporating the probabilistic seismic hazard for the region, expected direct losses can be estimated for arbitrary time horizons. By establishing realistic cost estimates of the retrofitting schemes and costs of direct losses, one can then estimate the net present value of the various retrofitting measures. Aerodynamic optimization is aimed at solving the problem from the source in contrast to structural optimization which is aimed at increasing the structural resistance. The analysis in this work implies that, even when considering only direct losses, all of the retrofitting measures considered are desirable for all but the very shortest time horizons. This conclusion is valid for a wide range of estimates regarding costs of mitigation, discount rates, number of fatalities, and cost of human life. The general methodology developed here for a single building can be extended to an entire region by incorporating additional structural types, soil types, retrofitting measures, more precise space- and time-dependent seismic hazard estimates, etc. 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.

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1. Introduction

The purpose of this paper is to provide a systematic assessment of the expected direct benefits and costs of alternative retrofitting measures to a typical apartment building. In undertaking this analysis we recognize that there are indirect benefits (which are not accounted for in this study) of avoiding the collapse or damage of residential buildings that should also be taken into account. There is also a need to expand this analysis by considering the differential impact of these measures on tenants in the buildings, their neighbors, owners, city, provincial, and central administrators, each of whom have different stakes in the resistance of a building to earthquake damage.

The analysis also does not consider all the costs associated with retrofitting the building. For example, we have not taken into account the possible effect of a widespread demand for retrofitting on the cost of undertaking the proposed measures nor the impact of the disruption of normal activities of the residents in the building while the structure is being retrofitted.

Then combine the computed fragility curves of the building with information about the expected shaking. This shaking information is derived from the expected distribution of future earthquakes in space and time and is expressed in a hazard curve as the probability of exceeding various PGA levels. Simulated ground-motion time histories with PGA levels appropriate to the generic site conditions in the hazard curve are then modified to reflect site conditions at the building. The benefits in terms of avoided damage or collapse are then compared with the costs of each of these retrofitting measures. How representative some of the input parameters are of the actual situation for this experiment is somewhat dependent on results from ongoing studies.

Significant changes may be expected in the hazard curve (hazard mapping, Atakan et al. 2000), site conditions and amplification (microzonation, e.g., Kudo et al. 2002), and construction practices (e.g., USGS 2000) that may supersede local variations in the ground motion. Such changes will most probably update the benefit/cost ratio, but are not expected to alter fundamentally the conclusions of this study. The results of this study suggest that retrofitting may be cost effective for many of the buildings.

We hope that this work can support some of the most urgent decisions and serve as a benchmark for more realistic and targeted cost-benefit analyses.

Benefit-cost analysis (BCA) is a systematic procedure for evaluating decisions that have an impact on society. In this section we specify the steps that are part of a standard BCA for the comparative evaluation of alternative mitigation measures. Later in the ‘‘Application’’ section, it is shown how this technique can be utilized for evaluating alternative retrofitting measures for a prototype apartment building in Istanbul by incorporating the relevant scientific and engineering data that are quantified in the ‘‘Probabilistic Seismic Loss Estimation Methodology’’ section.

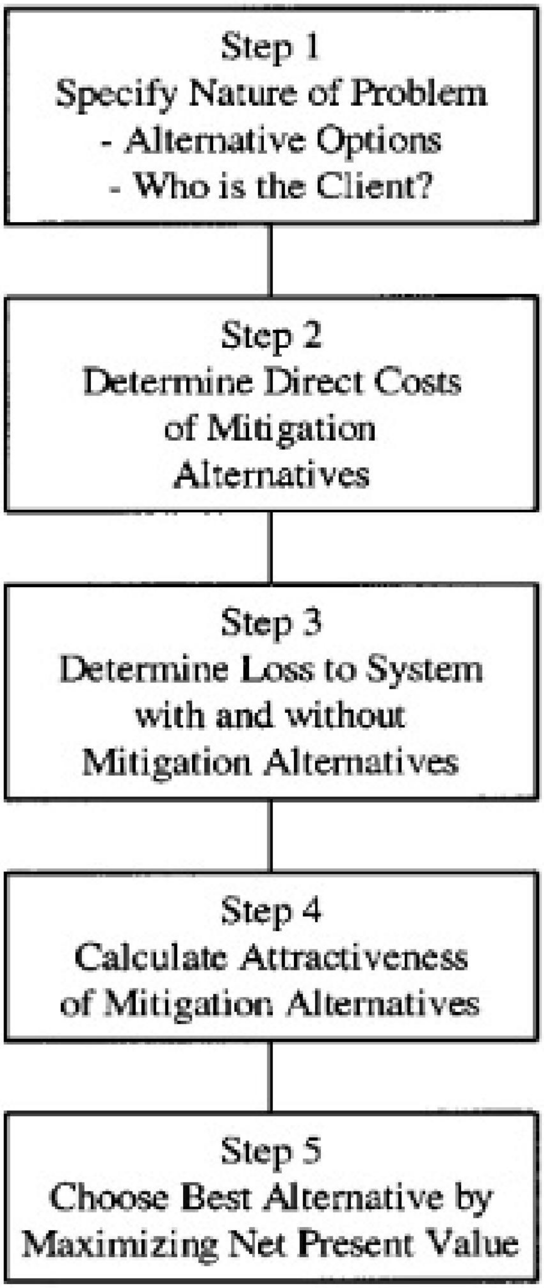

Figure 1. Simplified benefit-cost analysis

Figure 1 depicts a five-step procedure for undertaking a BCA. A more comprehensive approach, which incorporates several additional steps, is discussed in Boardman et al. (2001). Previous studies have evaluated the cost-effectiveness of mitigation to buildings in Los Angeles, California, (Schulze et al. 1987) and to residential structures in Oakland, California (Kleindorfer and Kunreuther 1999). In both of these studies there was no detailed discussion as to how the estimates of the probabilities of different levels of shaking were determined nor how the reduction in damage to the structure was accomplished through a shift in the fragility (i.e., vulnerability) curves.

In evaluating the benefits and costs of alternative mitigation measures, it is important to determine who the client is. In the context of this problem, the client is the government which wants to determine whether or not apartment buildings in Istanbul should be retrofitted so as to reduce damage from a future earthquake, and if so, what standards should be imposed. In evaluating alternative options, government needs to determine who has standing, that is, whose benefits and costs should be counted. In the case of an apartment building, the parties that will have standing include tenants in the building, the owners, public sector agencies that must respond and fund the recovery process after a disaster, as well as the taxpayer who is likely to bear some of the repair costs of the damaged property.

The likely interference of owners unwilling or unable to contribute financially to retrofitting measures for their apartment building looms as a large factor in forestalling the implementation of cost-effective mitigation measures. In one of the previously mentioned survey studies, only 18% of the respondents (89 out of 502) reported that there was a consensus among the apartment owners having their buildings inspected and if necessary, retrofitted (Onculer et al. 2003). In the surveys undertaken by Fisek et al. (2003), the inability of residents to agree on an appropriate mitigation measure was cited as one reason nothing was done to make the apartment building more earthquake resistant.

There are other indirect benefits that also need to be considered in evaluating the cost-effectiveness of mitigation measures. For example, if families are forced to leave their apartment units due to damage that would have been obviated by mitigation mea-sure then this cost needs to be taken into account when tallying up the benefits of mitigation. There are also intangible factors such as psychological trauma and stress from having to relocate to a new location (Heinz Center 2000) or moral sentiments that involve the concern for the welfare of others (Zerbe 2002) that may also have a place in evaluating alternative risk reduction strategies. These additional components deserve serious consideration in a full-blown BCA but will not be included in our analysis.

There is normally uncertainty and disagreement among experts regarding the cost and benefit estimates associated with different alternatives. In order to determine which of these estimates really matter, one should undertake sensitivity analyses by varying their values over a realistic range to see how it affects the choice between alternatives. To the extent that one alternative dominates the picture over a wide range of values for a particular cost or benefit, one knows that there is little need to incur large expenditures for improving these estimates. On the other hand, if the choice between alternatives is highly dependent on a particular cost or benefit, then one may want to incur some time and effort into refining this estimate.

The first step in establishing analytically the building's fragility curves is to generate sample ground-motion time histories at different levels of ground motion intensity. This is accomplished by simulating response-spectrum compatible acceleration time histories. These time histories can then be used as input for the nonlinear dynamic structural analyses. The simulation of spectrum-compatible earthquake acceleration time histories is performed using a methodology developed by Deodatis (1996).

While there are many different measures to describe earthquake intensity, the measure most commonly used in building codes and in practice when one is interested instructural response is the peak ground acceleration (PGA). It should be mentioned here that PGA is certainly not a perfect measure to describe the intensity of strong ground motion. It does not provide any information about the frequency content or the duration of ground motion. It is adopted here, however, because of its simplicity and because there is no other single measure that has proven to be universally superior for nonlinear dynamic problems without strength degradation.

For the current study, the direction of the earthquake is always assumed to be per- ventricular to the weak axis of the structure, i.e., only horizontal ground motion was considered parallel to the y-direction, as indicated in Figure 7 (i.e., the weak axis of the structure is parallel to the long side of the structure). This is a worst-case scenario and the results should therefore be interpreted as an upper bound on the risk in that sense. More sophisticated simulation is needed to incorporate directivity variability of ground motion and this will be done in a future extension of this work.

In a time-dependent characteristic rupture renewal model, the hazard will continue to rise in time until one or more of these segments rupture. In this study, however, we adopt this curve as time-stationary, i.e., this annual ascendance curve, denoted as R (a), will be considered to be the same for all future years considered in the time horizon (T*), until a damaging earthquake does happen. This simplifying assumption gives a lower bound for the hazard and hence it is a lower estimate of the expected benefit of the mitigation measures. A time-dependent model for the hazard curve would yield a greater earth- quake hazard and thus greater benefit from retrofitting. Unfortunately, such a time- dependent model is not currently available.

There are four factors in addition to the scientific and engineering data that are relevant to evaluating the benefits of different mitigation alternatives:

- Time Horizon (T*): Although the apartment building may be expected to last for 50 years if the area does not experience a severe earthquake, there may be an interest in evaluating the attractiveness of the mitigation alternatives using shorter time horizons. There are several reasons for this. A much more important consideration from a political vantage point is that the government may want to invest in measures that offer the best return over a relatively short time horizon. If one can show that the proposed mitigation alternatives will be attractive even when T* is relatively short, then it will be easier to justify this decision to the different interested parties.
- Social Discount Rate(d): A recent proposal by the U.S. Panel on Cost-Effectiveness in Health and Medicine recommends the use of a real 3-percent social discount rate (SDR) for cost-effectiveness studies with additional sensitivity analysis at rates between 0 percent and 7 percent. (Weinstein et al. 1996).

We will utilize 53% for the analysis that follows and then show how to deter- mine the maximum discount rate for which mitigation will still be cost effective.

- Number of Fatalities (NL): Following a severe earthquake there are likely to be some individuals who are killed because they are trapped in a collapsed building. When it comes to estimating the expected number of fatalities (NL) from earthquakes of different magnitudes, we are on much less solid ground than in estimating physical damage. Even if an earthquake destroys a residential building, there may be relatively few individuals actually in the structure at the time of the earthquake, if it occurs during the day. Should the earthquake occur in the middle of the night when most of the residents will be inside the structure, a number of them may still be able to escape before the building collapses.
- Value of Life (V):

Economists have used several estimation techniques for estimating the value of life. These range from hypothetical surveys where people are asked how much they must be paid to accept certain risks, to examining the wage premium people working in hazardous jobs are given to compensate them for the additional risks they are incurring. A review of surveys by Miller (1989), Fisher et al. (1989) and

Viscusi (1993) suggest that a plausible range for the value of a statistical life saved in the United States is between $2.5 million and $4.0 million in 1999 dollars. (Boardman et al. 2001).

Given the nature of the predictions by seismologists regarding the likelihood of future severe earthquakes in the Istanbul region over the next 30 years, this case study suggests that retrofitting a five-story apartment building in Istanbul may be a desirable thing to do if one takes into account the costs of fatalities and that there is a sufficiently long time horizon to reap the expected benefits of mitigation.

The sensitivity analyses conducted in the previous section indicate how to determine the bounds of such a conclusion for a wide range of estimates regarding costs of mitigation, discount rates, and time horizons, number of fatalities and value of human life. In fact, the estimates of benefits are quite conservative since they do not take into account indirect benefits such as the costs associated with evacuating residents should an earthquake damage the apartment building and assume that the probability of an earthquake area does not increase over time.

The one striking conclusion that can be made, assuming that the structural and ret refitting cost data provided are reasonably accurate, is that the direct losses of the structure itself are relatively small compared to the cost of loss of life. This work therefore provides constructive support for the concept of a ‘‘limited’’ retrofit level that is designed to prevent total collapse, and hence loss of life, but which may not protect the structure from significant damage requiring its complete replacement.

The study of a prototype apartment building has relevance to the design of earthquake policy for the city of Istanbul and perhaps a wider region of Turkey. The vast majority of Turkey’s urban population lives today in multistory apartment blocks constructed of reinforced concrete similar to the one considered in this paper. Statistics onurban housing indicates that in the three largest cities. Over 50 percent of the buildings are of reinforced concrete frame construction; over 75 percent of these are more than three stories tall. Recent earthquakes have demonstrated that this type of construction is more vulnerable to damage or collapse in an earthquake than low-rise construction.

In designing mitigation measures, one needs to consider ways of reducing the risk to new buildings as well as retrofitting existing structures. For the new buildings, adherence to the current Turkish earthquake code would limit future earthquake losses to acceptable levels. Further, the knowledge of the earthquake hazard and local ground conditions in many cities now enables areas of particularly high earthquake risk to be identified and avoided in future development. The challenge is to ensure enforcement and compliance with the code on the part of designers and builders and to enforce urban hazard zoning.

Conclusion:

While this study clearly raises some critical questions and suggests a general methodology towards selecting an appropriate retrofitting scheme for any type of building, it should be noted that it is also a demonstration piece indicating the kinds of policy questions and assessments which can be made from this coordinated collaborative endeavor between seismologists, engineers, and economists. As has been acknowledged through out the paper, the study has been conducted using certain simplifying assumptions, some of which are due to lack of better information, and others so as to keep the study manageable. There are several avenues for future research to refine and expand the benefit-cost analysis (BCA) introduced here so it becomes even more realistic.

The analysis undertaken in this paper assumed that the annual accordance probability of various PGAs associated with future earthquakes in the Istanbul area was constant over time. In reality, it is almost certain that there will be an increase in the likelihood of a severe earthquake in this region of Turkey as a function of time T, if a severe earthquake has not occurred in the Marmara area since the last major earthquake in 1999 for T,2029.

Given that the occurrence of the forecasted severe earthquake is associated with the rupture of the branch of the North Anatolian Fault that traverses the Sea of Marmara some 20 km to the south of the city where the seismic gap is located, then this expectation of increased odds is realistic.

Future benefit-cost analyses need to take into account the time dependency of severe earthquake occurrence in evaluating the desirability of undertaking different types of mitigation measures and the timing of their adoption. More specifically, one needs to undertake an analysis as to the desirability of recommending measures today or waiting one or more years to do so. If mitigation is attractive now, it should be even more attractive a year from now if the probability of an earthquake in the area increases. It would be worthwhile to determine the difference in NPV if one undertook these measures now or waited another year. This information is likely to make an even strong for finding ways to develop implementable strategies for loss mitigation now.

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