Probabilistic Benefit-Cost Analysis for Earthquake Damage Mitigation: Evaluating Measures for Apartment Houses in Turkey

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In the wake of the 1999 earthquake destruction in Turkey, the urgent need has arisen to evaluate the benefits of loss mitigation measures that could be undertaken to strengthen the existing housing stock. In this study, a benefit-cost analysis methodology is introduced for the comparative evaluation of several seismic retrofitting measures applied to a representative apartment building located in Istanbul. 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. 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. It is hoped that this work can serve as a benchmark for more realistic and systematic benefit-cost analyses for earthquake damage mitigation.

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INTRODUCTION

The city of Istanbul has been a major population center with a prominent role in commercial and cultural activities for almost two millennia. It is situated on the northern shores of the Marmara Sea and across the Bosphorus waterway between the Black Sea and the Marmara Sea. The latter is also connected to the Mediterranean Sea via the Dardanelles. Despite the wealth of surviving historical buildings in Istanbul, the exceptionally complete and long historic record reveals that the city has been subjected to many damaging earthquakes due to its proximity to a very active continental transform boundary (e.g, Ambraseys and Finkel 1995).

The North Anatolian Fault (NAF) separates the Asian Plate north of this boundary from the much smaller Anatolian Plate or "block" to the south. The relative westward motion of the Anatolian block is accommodated by right-lateral slip ranging from 20 to 25 mm/year along the NAF (Barka 1996, Sengor et al. 1985, Armijo et al. 1999, LePichon et al. 2001, McClusky et al. 2000). This plate boundary traverses northern Turkey including the inland Marmara Sea. A single major fault accounts for most of the relative motion along much of the boundary, but toward the west and within the Marmara Sea region, the fault system broadens and becomes more complex.

The system of active faults through the Marmara Sea has been intensely investigated, especially since 1999. Many important characteristics of these submarine faults are coming to light, including the role of each fault segment in accounting for the tectonic strain and for specific historic earthquakes, but critical tectonic issues and implications for hazard remain unclear and will be debated for some time.

Concern for earthquakes in Istanbul has drastically increased since the 1999 earthquakes that caused more than 18,000 deaths as well as severe damage to housing and reduced production capacity in northwest Turkey, including some recently developed parts of Istanbul. The severity of that disaster accounts for an increased perception of earthquake risk on the part of the public and for an interest on their part and the government's in taking steps to mitigate future losses. The 1999 earthquakes also highlighted the potential for severe damage to Istanbul from future major seismic events, as it is one of the world's largest and fastest growing cities. These earthquakes have also pointed to widespread deficiencies in design and construction, which can in part be ascribed to the extremely high demand for new housing at affordable prices (USGS 2000).

Scientifically the greatest concern about earthquakes in the Istanbul area is the increased probability that a serious event will occur in the near future. The 1999 sequence of main shocks and the NAF in the Marmara Sea have been targeted by an impressive array of international earthquake and tectonic investigations. Following established methodologies, the hazard can be quantified with increasingly reliable confidence limits (e.g., Atakan et al. 2002). These hazard assessments are now commanding more attention from administrators in Turkey and from the general public, thus contributing to a gradual transition from a fatalistic attitude to one of self-reliance in dealing with hazards. Indeed, the Metropolitan Municipality of Istanbul has recently initiated a comprehensive study that will develop an earthquake master plan for the city.

Most of the NAF has ruptured in a series of large and destructive earthquakes progressing from east to west during the twentieth century. The last in this series are the two large earthquakes in 1999, the M_w 7.4 Izmit (or Kocaeli) and the M_w 7.2 Duzce earthquakes, both of which ruptured 160 km of the NAF just east of the Marmara Sea. West of the Marmara Sea, the NAF ruptured in a M_w 7.4 earthquake in 1912. In contrast, much of the 150-km-long portion of the NAF through the Marmara Sea and nearest to Istanbul has not ruptured since the mid-eighteenth century (e.g., Parsons et al. 2000, Ambraseys and Finkel 1995). The general validity of this statement does not change even if one considers the July 1894 M 7.3 event that caused substantial damage in Istanbul (Ambraseys and Jackson 2000). Thus the NAF across the Marmara has been identified as a "gap" (Toksoz et al. 1979, Stein et al. 1997), a fault segment, or series of segments that could rupture in a single earthquake. Its power has been highlighted by the recent epicenters on a portion of the NAF, suggesting a relatively quiescent segment flanked by enhanced seismicity.

The classical and empirically derived concept of "gap" accounts qualitatively for stress increase from both tectonic strain and neighboring fault ruptures. This concept is now expressed quantitatively in terms of probability of a rupture conditional on both the time since the last rupture (e.g., Nishenko and Buland 1987) and on stress interactions with neighboring ruptures. From the rate of historic earthquakes, Parsons et al. (2000) calculate a 15–25% time-independent probability of strong shaking in Istanbul during the next 30 years. They define "strong shaking" as peak ground accelerations (PGAs) in the range of 0.34–0.65 g, which is equivalent to modified Mercalli intensity VIII and is within the range measured in the meizoseismal area of the 1999 main shocks (e.g., Akkar and Gulkan 2002).

By taking into account the current advanced loading of the Marmara segment, the probability for the next 30 years rises to 34–54%. By further accounting for the stress increase on the Marmara segment caused by the 1999 rupture, Parsons et al. (2000) and Hubert-Ferrari et al. (2000) produced a model that yields a 47–77% probability that during the first 30 years of this century Istanbul will be subjected to strong shaking. Most of the current citizens of Istanbul are likely to experience this event and may wish to prepare for it. Whether they invest in risk-reducing measures is likely to depend on whether they can assess the benefit of such an action.

Much of the current building stock in Istanbul is also likely to experience strong shaking. Damage and casualties in some districts in Istanbul from the relatively distant 1999 Izmit (or Kocaeli) earthquake were still substantial. Stronger shaking is expected from closer earthquake ruptures in the Marmara Sea leading to dire damage scenarios (Pudilo et al. 2002). Retrofitting existing buildings is an option to substantially reduce the expected losses. The design of a mitigation program depends on the benefits and costs of different loss reduction measures to the relevant interested parties.

Decisions are urgent as to what next steps should be taken in Istanbul. 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 Istanbul. 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.

This work should be viewed as a first step that can be refined and expanded so it becomes more realistic. We consider a representative building in Istanbul, as is and hypothetically reinforced with three levels of retrofit, *braced*, *partial* shear wall, and *full* shear wall solutions. We then numerically subject this building in each of these four states to a suite of simulated shaking experiments over a wide range of PGAs. The nonlinear response of the building is then calculated, the damage is estimated by the interstory drift criterion and classified in four categories: slight, moderate, major damage, and collapse. The probability of exceeding each of these damage levels for each of the four states of the building is expressed in terms of the PGA by fragility curves.

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

NATURE OF BENEFIT-COST ANALYSIS FOR ALTERNATIVE MITIGATION MEASURES

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 incor-

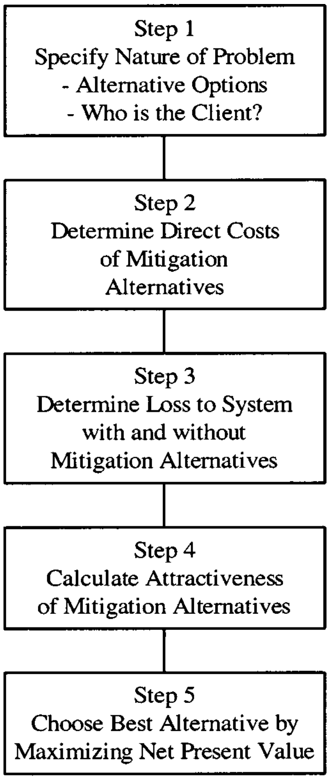

Figure 1. Simplified benefit-cost analysis.

porating the relevant scientific and engineering data that are quantified in the "Probabilistic Seismic Loss Estimation Methodology" section that follows later.

NATURE OF THE PROCEDURE

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.

STEP 1: SPECIFY NATURE OF THE PROBLEM

To initiate a BCA, one needs to specify the options that are being considered and the interested parties in the process. Normally, one alternative is the *status quo*. In the case of the current analyses, the status quo refers to the current vulnerability of the structure without a mitigation measure in place. The status quo is likely to be the reference point for evaluating how well other alternatives perform. In general, if there is sufficient political dissatisfaction with the proposed mitigation options and/or the perceived benefits (i.e., reduction in losses) are less than the expected costs to mitigate the risk to the structure, then the status quo will be maintained. The status quo (no mitigation to the structure defined as Alternative 1), will be compared with three other alternatives for retrofitting the property in this study.

In evaluating the benefits and costs of alternative mitigation measures, it is important to determine who is the client. In the context of this problem, the client is the Turkish 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, the Turkish 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.

STEP 2: DETERMINE DIRECT COSTS OF MITIGATION ALTERNATIVES

For each mitigation alternative one needs to specify the direct cost to implement the mitigation measure. For an apartment building in Istanbul, the owners, whether or not they live on the premises, will have to incur these expenditures unless the government partially subsidizes a program of retrofitting residential property. Currently there are surveys being undertaken in different parts of Turkey to better understand how residents feel about alternative mitigation measures and their willingness to pay their share of the cost (Onculer et al. 2003, Fisek et al. 2003). In Turkey, if some of the owners in an apartment building are not willing to pay their share of the mitigation costs, then the other property owners will either have to agree to cover these costs, or the measure will not be pursued. In essence, this amounts to a unanimity rule with the option of those who want to undertake a mitigation measure being willing to buy out those who are unwilling to pay their share.

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.

STEP 3: DETERMINE THE BENEFITS OF MITIGATION ALTERNATIVES

Once the costs are estimated for each mitigation alternative, one needs to specify the potential benefits that impact each of the interested parties. In the case of seismic risk, one considers either a scenario earthquake event or a set of scenario earthquakes of different magnitudes, location, duration, and attenuation that can affect the system. In the context of this analysis the severity of the earthquake is expressed in terms of peak ground acceleration (PGA). The damage to the building from earthquakes of different PGAs is then estimated for the status quo and each of the alternative mitigation options. In addition to reducing the physical damage, there are additional significant benefits of mitigation in the form of fewer fatalities and injuries from an earthquake.

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 a mitigation measure 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.

STEP 4: CALCULATE ATTRACTIVENESS OF MITIGATION ALTERNATIVES

In order to calculate the attractiveness of a given mitigation measure, one compares the expected benefits to the residents in the apartment building and other interested parties to the expenditures associated with the proposed measure. These benefits are normally expressed in monetary terms but this poses a set of challenges. For example, in the case of a reduction in fatalities due to the adoption of a mitigation measure, the benefit is measured by quantifying the value of a human life and multiplying this dollar figure by the number of lives saved.

Since these benefits and costs are expected to accrue over the life of the building, one utilizes a discount rate to convert future returns and expenditures into net present value (NPV). If the $NPV>0$, then the alternative is considered attractive. Since the principal client of this BCA is the Turkish government, then the social discount rate (SDR) converts future costs and benefits into present value units. A key question that needs to be addressed is what discount rate to utilize. There has been a lively debate among economists over the years as to the appropriate SDR to utilize in evaluating alternative projects undertaken by the government.[1] There is now widespread agreement that the real rate of social time preference should be used, as detailed by Bradford (1975), unless the project is large enough to affect interest rates in the capital market. In the analysis that follows we will utilize a constant SDR so that the same discount rate is used to evaluate costs and benefits between years t and $t+1$ for any value of t.

STEP 5: CHOOSE THE BEST ALTERNATIVE BY MAXIMIZING NET PRESENT VALUE

Once the attractiveness of each alternative is calculated through an appropriate discounting procedure, one chooses the option with the highest NPV. This criterion is based

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[1] We thank an anonymous referee for helpful comments on the determination of the social discount rate.

on the principle of allocating resources to its best possible use so that one behaves in an economically efficient manner. There may also be equity considerations that need to be considered if certain interested parties (e.g., owners of apartment buildings) are viewed as being unduly harmed by a particular policy. In that case, special consideration may be given to them in the form of government grants, subsidies, or tax relief.

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.

PROBABILISTIC SEISMIC LOSS ESTIMATION METHODOLOGY

OVERVIEW

At the heart of this study is Step 3 of the BCA methodology: *Determine the Benefits of Mitigation Alternatives*. This step requires estimating losses to the building with and without specific retrofitting measures in place over a range of different time horizons. In this study, seismic loss estimation is performed using fragility curves. The fragility curves of a particular building provide the probability of exceeding different levels of damage (e.g., slight, moderate, major, collapse) as a function of the level of ground shaking.

Fragility curves can be determined either empirically using damage data from past earthquakes[2] or by numerical analysis. For the purposes of this study, fragility curves for a representative structure are established analytically, as an empirical approach is extremely difficult, if not impossible, due to lack of appropriate damage data from previous events in Istanbul. Specifically, a number of response-spectrum-compatible earthquake ground-motion time histories are simulated for a range of different PGAs and then used as input in a series of nonlinear structural dynamic analyses of the structure. The resulting structural responses are expressed in terms of maximum values of the interstory drift that are then used to determine the probability of exceeding different levels of structural damage.

GROUND MOTION DESCRIPTION

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

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[2] In general, an empirical approach would require extensive information on measured site ground motions, detailed structural characteristics, and the resulting damage data.

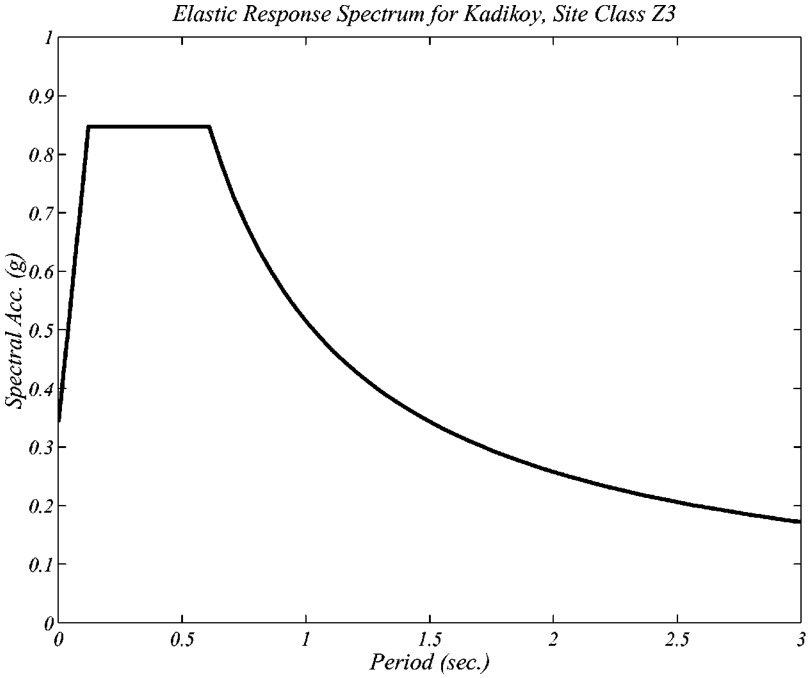

Figure 2. The site-specific elastic response spectrum for Kadikoy, Turkey. The soil type is Turkish Code Site Class Z3. This spectrum was used to synthetically create spectrum-compatible ground-motion time histories for the Monte Carlo simulation study and fragility curve generation.

analyses. The simulation of spectrum-compatible earthquake acceleration time histories is performed using a methodology developed by Deodatis (1996). The response spectrum used in this study is shown in Figure 2.

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 in structural 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 (as is the case here).

To consider a wide range of ground motion shaking levels in this study, PGA values from 0.01 g to 1.4 g are considered when simulating the input acceleration time histories. In total, 400 ground-motion acceleration time histories are generated to establish a complete set of fragility curves (involving all four damage states described below).

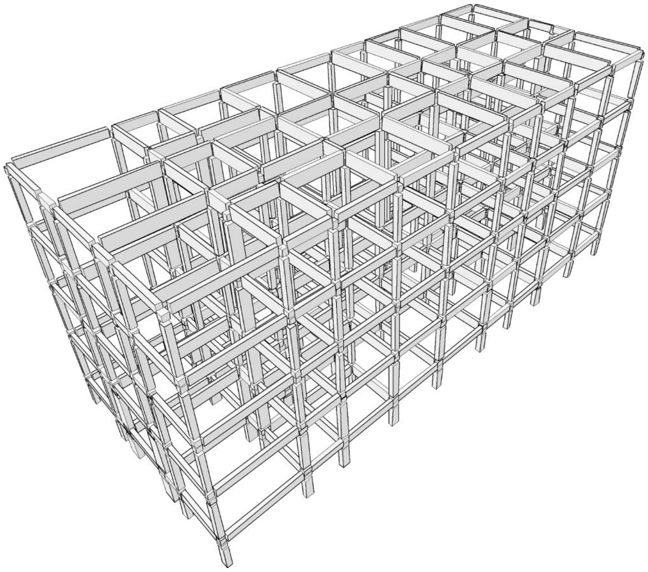

Figure 3. 3-D illustration of the reinforced concrete moment-resisting frame of the original apartment structure.

STRUCTURAL MODELING

The representative structure selected here is an actual building located in Caddebostan, a suburb of Istanbul on the Asian side of the Bosphorus. Built in 1968, it is a typical reinforced concrete five-story building founded on Z3-type soil (relatively stiff soil) according to the description in the current Turkish seismic design code. In plan, the structure's footprint is 28.14 m×11.3 m, and in elevation it is 13.5 m tall. The original structure is a moment-resisting reinforced concrete frame without shear walls (Figure 3). The concrete of the existing structure has a characteristic yield limit of 16 MPa while the concrete used for the different retrofits has a yield limit of 25 MPa (the corresponding Young's Moduli are 27,000 MPa and 30,250 MPa, respectively). The structure was chosen because it was deemed to be highly representative of many residential apartment buildings in and around Istanbul and its design was probably based on the 1967 code that prescribed much smaller seismic loads than the current code.

A three-dimensional finite element model of the candidate apartment building was established in the SAP2000 computer package Computers and Structures, Inc. 2000. For this study, the structure was actually modeled in four different states:

1. The *original* unretrofitted structure,
2. A *braced* retrofitted version of the structure,
3. A *partial* shear wall retrofitted version of the structure, and
4. A *full* shear wall retrofitted version of the structure.

These four states, referred to in the following as *original*, *braced*, *partial*, and *full*,

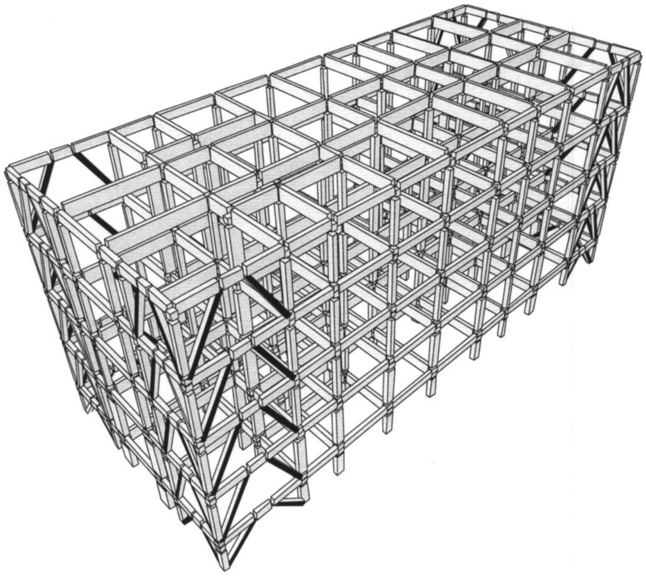

Figure 4. *Braced Retrofit*: The four corners of the building are retrofitted by building steel braces in the exterior bays along both the weak and the strong directions. This pattern is reproduced throughout all floors, resulting in eight braced bays per floor.

were selected to compare the consequences of the three different retrofitting schemes on the expected damage sustained by the structure. They are described and illustrated in figures 3–6.

The 3-D finite element models of the aforementioned four states include nonlinear behavior of beam-column connections modeled by potential plastic zones described by bilinear rotational springs, without strength degradation.

For the current study, the direction of the earthquake is always assumed to be perpendicular to the weak axis of the structure, i.e., only uni-axial 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.

COMPUTATION OF STRUCTURAL RESPONSE

Using SAP2000, the response of the structure was computed for each of the 400 input ground-motion acceleration time histories (corresponding to a wide range of different PGAs), and the response statistics were used to establish the fragility curves. The response parameter used was the peak interstory drift. It is defined as the maximum relative horizontal displacement of one floor relative to the adjacent floor. The value of the drift δ is normalized by the column height h, so it is actually the percentage of interstory

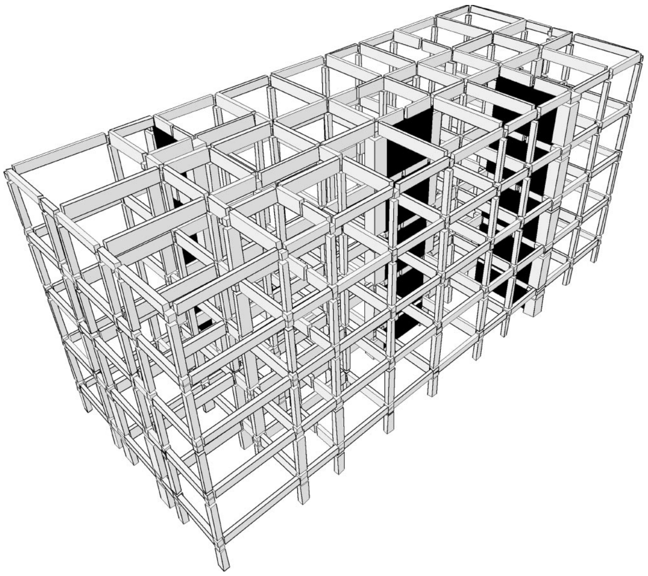

Figure 5. *Partial Retrofit*: Two bays along the weak direction, situated at the third and eighth axes of columns, are retrofitted with shear walls throughout the whole height of the building. Similarly, one bay along the strong direction, on one of the sides of the elevator shaft, is retrofitted also with shear walls throughout the whole height. These make for a total of three shear walls of retrofit per floor.

drift (δ/h) that is used as the response parameter, rather than the drift itself. It is generally accepted today that the maximum δ/h is a solid basic indicator of the level of damage a structure experiences (HAZUS99-SR2 Technical Manual). While in reality there would be a continuum of levels of damage, the full range was divided for practical purposes into four discrete levels or events E_i, whose threshold values are

1. E_1: slight damage $\delta/h > 0.13\%$
2. E_2: moderate damage $\delta/h > 0.33\%$
3. E_3: major damage $\delta/h > 0.80\%$
4. E_4: total collapse $\delta/h > 1.87\%$

These four threshold values are suggested by the HAZUS99-SR2 Technical Manual for pre-code reinforced concrete structures of height similar to that of the structure considered here.

The fragility curves are established using the 400 values of maximum interstory drift obtained from the 400 nonlinear dynamic structural analyses performed using the 400 simulated response-spectrum-compatible ground-motion acceleration time histories. The methodology proposed by Shinozuka et al. (2000) is used to establish all four fragility curves (for slight, moderate, major damage, and total collapse) in one step. This is done in the following way as demonstrated in Figure 8 for the case of total collapse. There are 400 pairs of PGA and corresponding maximum interstory drift. If for such a pair, the

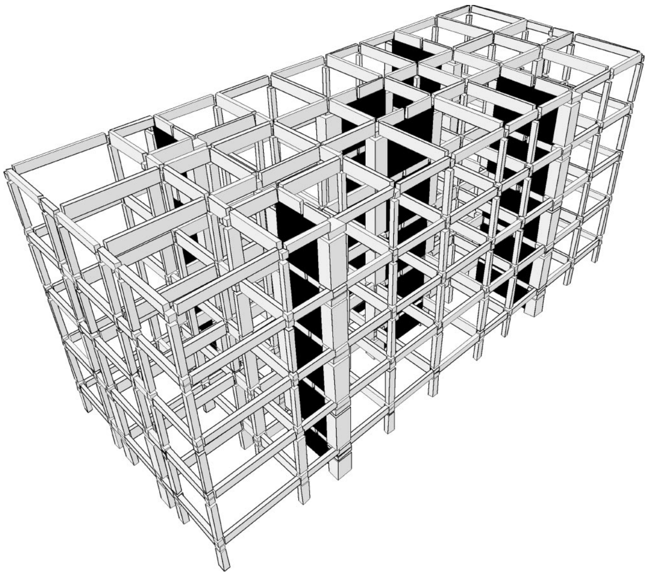

Figure 6. *Full Retrofit*: Four bays, symmetrically placed with respect to the longitudinal axis of the building along the weak direction, again situated on the third and eighth axes of columns, and two bays on both sides of the elevator shaft along the strong direction are retrofitted with shear walls throughout the whole height of the building. These make a total of six shear walls of retrofit per floor.

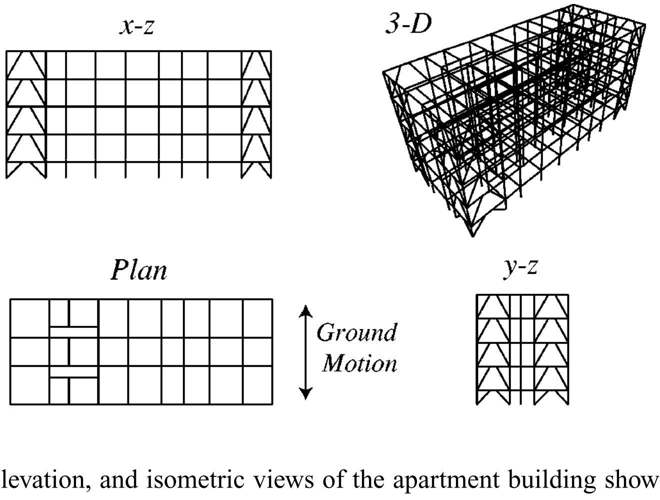

Figure 7. Plan, elevation, and isometric views of the apartment building showing the direction of ground motion considered in this study. The building is shown here with the bracing retrofit.

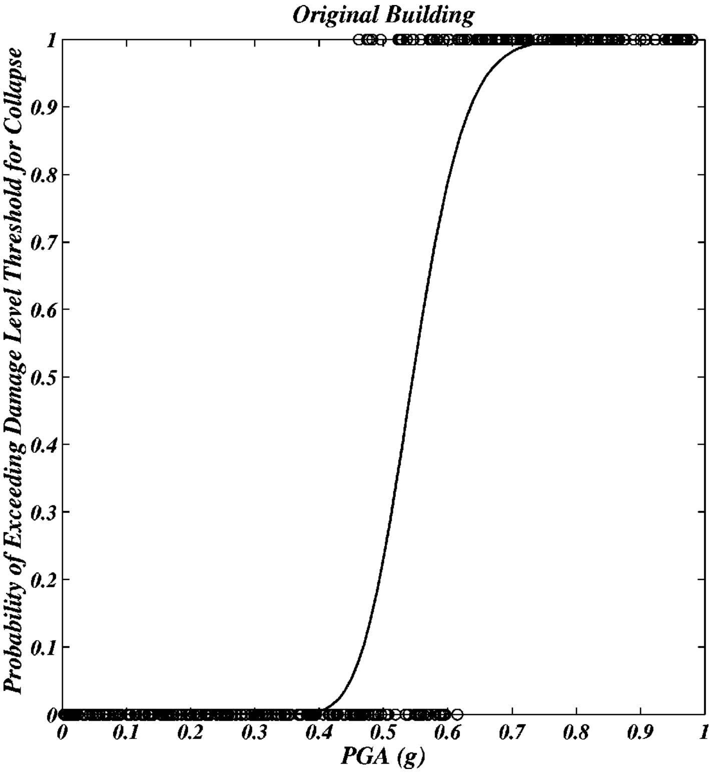

Figure 8. Lognormal distribution fit of the binomial outcomes of the Monte Carlo trials for total collapse for the original structure. This curve is the fragility curve for that damage level.

value of maximum interstory drift exceeds the threshold for total collapse (1.87%), then the pair is plotted as a "1" at the corresponding PGA value. If, on the other hand, the value of maximum interstory drift does not exceed the threshold for total of 1.87%, then the pair is plotted as a "0" at the corresponding PGA value.

The 400 plotted pairs for the case of total collapse are shown in Figure 8 as circles either at the zero probability level, or unity probability level. A lognormal curve is then fitted to these 400 binomial outcomes using the maximum likelihood approach suggested by Shinozuka et al. (2000). This lognormal curve constitutes the fragility curve for the damage level under consideration. It provides the probability of exceeding that damage level for a given value of PGA.

The fragility curve for damage level E_i is denoted by $F_i(a)$ and defined as

$F_i(a)$=the probability of exceeding the interstory drift threshold corresponding to damage level E_i for a PGA value equal to a.

In figures 9–12, fragility curves of the four damage states considered are plotted together for the original unretrofitted structure and for the three retrofitted versions of the structure. As the structure is progressively strengthened through the three retrofitting

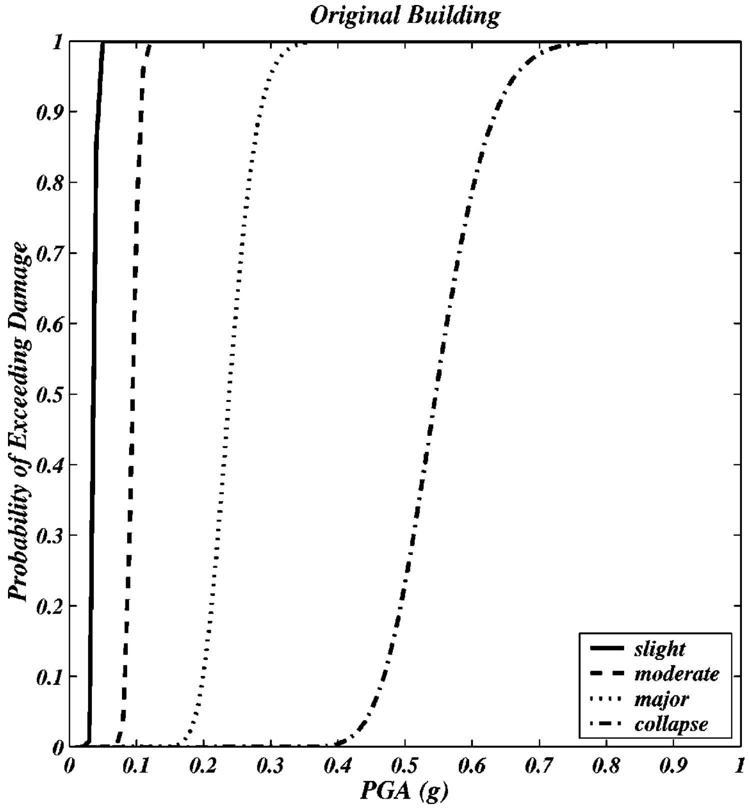

Figure 9. Combined plot showing the fragility curves for various damage levels for the original building structure.

schemes, one can clearly see the fragility curve corresponding to a given damage level shift to the right. In other words, for a given PGA value, the probability of achieving that damage level decreases. This is a direct quantification of the effect of the three increasingly effective retrofitting schemes. The four figures indicate quite dramatic improvements in the behavior of the structure as it is retrofitted. The most dramatic improvement is observed with the full retrofit using shear walls, followed by the partial retrofit and the braced solution.

THE EXPECTED DAMAGE COSTS

Every one of the four discrete damage levels E_i has an associated cost C_i^D consisting of the percentage loss of the value of the 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 (E_4). In this case, a prespecified (deterministic) number of lives N_L will be assumed to be lost. The value of a human life is specified as V, so that the expected cost associated with fatalities, should the structure collapse, is given by $N_L \times V$. The replacement value of the structure is given as variable S, and the loss due to structural damage in the

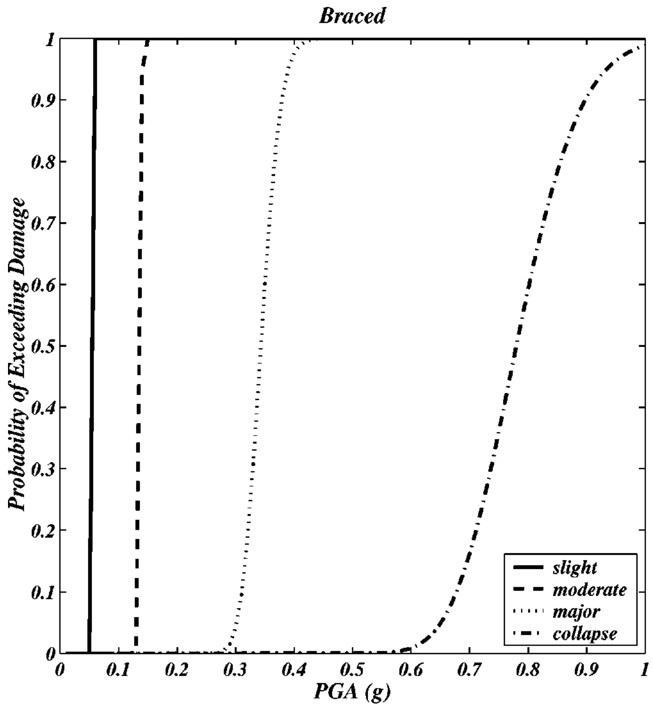

Figure 10. Combined plot showing the fragility curves for various damage levels for the braced retrofitted building structure.

moderate and slight damage cases is given by a percentage s_i of S. It is also assumed that for both major and total collapse cases s_3 and s_4 are 100%, while for slight damage s_1 was set equal to 1% and for moderate damage s_2 was set equal to 10%. This information is summarized in Table 1.

It should be pointed out that the main objective in this study is to demonstrate the potential and capabilities of the methodology, rather than to focus on determining precise values of the various parameters involved in specifying the cost. Some of the cost parameters are therefore defined as variables in order to perform sensitivity analyses later when going through the cost-benefit study for the various retrofitting measures. These parameters include N_L and V. The cost of the building replacement value S is taken however as a fixed constant throughout this study, as it was obtained from a construction contractor specializing in earthquake retrofitting in Istanbul and is believed to be a reliable estimate. The specific value for S is estimated to be \$250,000.

ANNUAL PROBABILITY OF STRONG GROUND MOTION

Elements that contribute to a seismic hazard curve can be broadly grouped into earthquake sources, seismic attenuation, and site response. Many issues in all three cat-

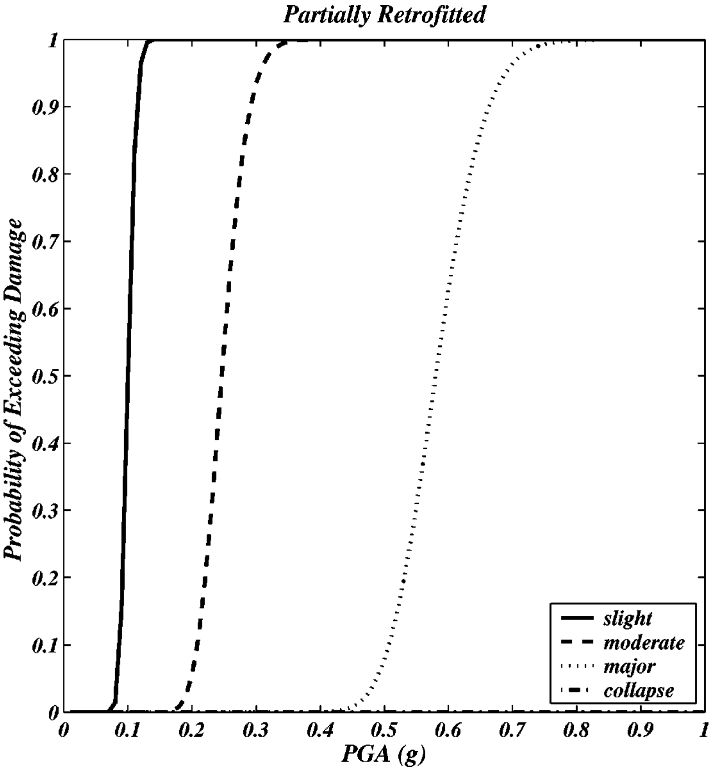

Figure 11. Combined plot showing the fragility curves for various damage levels for the partially retrofitted building structure.

egories relevant to Istanbul are being investigated (e.g., Atakan et al. 2002, Akkar and Gülkan 2002, Kudo et al. 2002) and conclusions derived from current information will need frequent updates as new results become available. Our strategy is to adopt a simple hazard model and to bias on the conservative side.

We have obtained the annual exceedance probability for a range of accelerations from work in progress in a collaboration between Kandilli Observatory and the U.S. Geological Survey (Petersen 2002). This hazard curve (Figure 13) is pertinent to Istanbul (41.0N and 29.0E) in terms of the source distribution, and is appropriate for a firm-rock site (shear wave velocity of 620 m/s in upper 30 m). It was derived from a source model that considers 10 segments along a 250-km-long portion of the NAF centered south of Istanbul.

The assumption and procedures used to obtain the hazard curve in Figure 13 are similar to the ones used for the hazard maps (models 2 and 3) in Atakan et al. (2002). Their alternative choices of seismic attenuation relations, except the one leading to the highest ground motion, were combined into an average. The distribution of events about

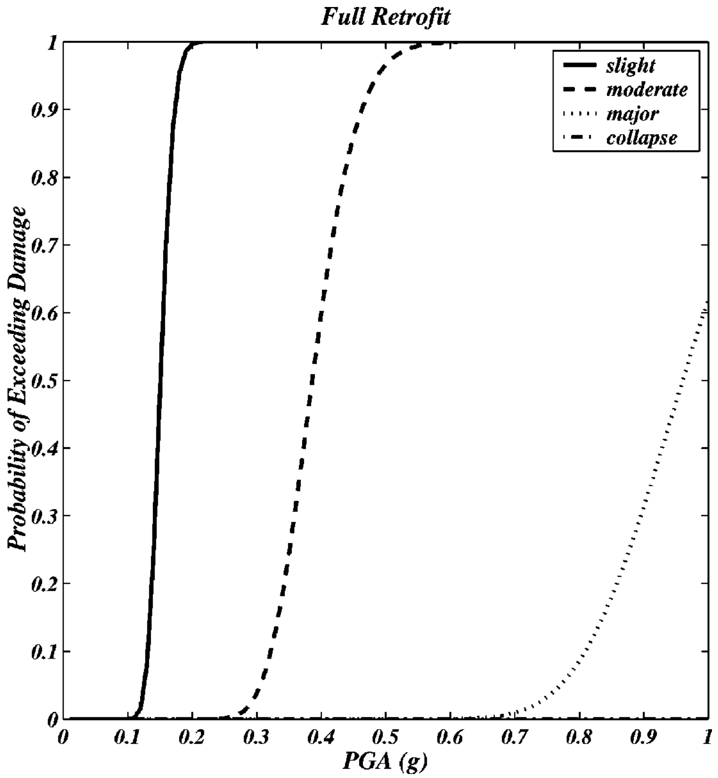

Figure 12. Combined plot showing the fragility curves for various damage levels for the fully retrofitted building structure.

the recurrence time was modeled by a Brownian passage-time distribution with a 0.5 a-periodicity parameter. This time-dependent model accounts for the time since last rupture and the rate of tectonic loading on each of these segments and applies to the year 2000.

Table 1. Assumed direct losses corresponding to the four damage levels

Damage Level	Cost (C_i^D)	Comments
E_1: slight damage	$C_1^D=(s_1 \times S)+(0 \times V)$	$0\% \leqslant s_1 \leqslant s_2 \leqslant 100\%$ $(s_1=1\%)$
E_2: moderate damage	$C_2^D=(s_2 \times S)+(0 \times V)$	$0\% \leqslant s_1 \leqslant s_2 \leqslant 100\%$ $(s_2=10\%)$
E_3: major damage	$C_3^D=(s_3 \times S)+(0 \times V)$	$s_3=100\%$
E_4: total collapse	$C_4^D=(s_4 \times S)+(N_L \times V)$	$s_4=100\%$

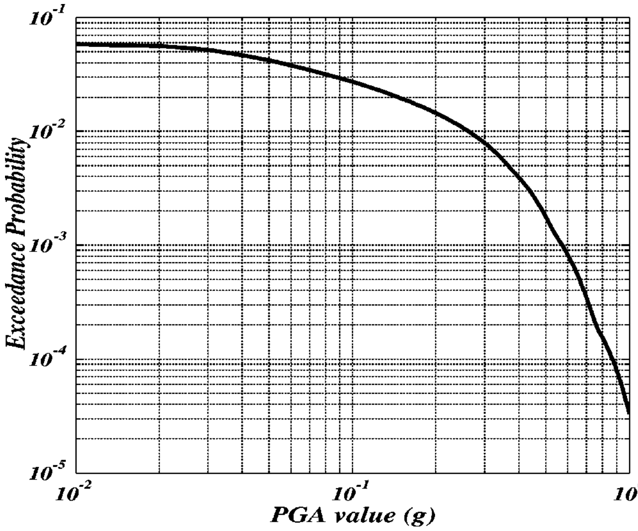

Figure 13. Seismic hazard curve: annual probability for exceeding various PGA levels for a stiff soil site in Istanbul. (Curve provided by Mark Petersen of the USGS.)

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 exceedance 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 earthquake hazard and thus greater benefit from retrofitting. Unfortunately, such a time-dependent model is not currently available.

COMBINING THE HAZARD AND FRAGILITY INFORMATION TO OBTAIN LOSS ESTIMATES

The following basic assumption is made for the loss estimation calculation: the structure will only be repaired or rebuilt once in the time horizon being considered. In other words, costs will be incurred only at the first occurrence of a destructive earthquake during the time horizon being considered. Therefore this is a lower-bound estimate of the possible losses.

The basic equation to calculate the present value of losses using a real (social) discount rate d is given by the following equation:

Total loss in present value for a given time horizon T^* (in years) =

$$\sum_{T=1}^{T^*}\sum_{i=1}^{4}\int_{a_{\min}}^{a_{\max}}[\hat{R}(a+da,T)-\hat{R}(a,T)]P(E_i\ \text{only}|a)\frac{C_i^D}{(1+d)^{T-1}}da \qquad (1)$$

where

$\hat{R}(a,T)$ = the probability of exceeding the PGA value a given that no earthquake has occurred in the previous $(T-1)$ years.

=(the probability of exceeding the PGA value a in year T) × (the probability that no earthquake has happened in the previous $T-1$ years)

$=R(a)\times e^{-R(a_{\min})(T-1)}$

This last term $e^{-R(a_{\min})(T-1)}$ represents the probability that no earthquake has occurred in the previous $(T-1)$ years based on the assumption of a Poisson distribution of earthquake occurrence. The term $a_{\min}$ denotes the lower limit of PGAs considered, so if this value is not exceeded, then a (significant) earthquake will not have occurred. In this study this lower limit $a_{\min}$ is set equal to 1% of g.

The additional probability in the expression above is given by

$P(E_i \text{ only}|a)$ = the probability of only event E_i occurring for a given PGA value a. This is needed so as not to count damage levels twice that are lower than (or fall within the set of) more severe damage levels. This expression is easily related to the fragility curves as follows:

$P(E_1 \text{ only}|a)=F_1(a)-F_2(a)$
$P(E_2 \text{ only}|a)=F_2(a)-F_3(a)$
$P(E_3 \text{ only}|a)=F_3(a)-F_4(a)$
$P(E_4 \text{ only}|a)=F_4(a)$

SUMMARY OF CRITICAL ASSUMPTIONS AND LIMITATIONS IN LOSS ESTIMATION PROCEDURE

- Only ground motions in the weak direction of the structure were considered. In this sense the fragility of the structure may have been exaggerated.
- The structure is modeled based on drawings and does not include construction deficiencies. In contrast to the previous simplification, this would tend to underestimate the structural fragility.
- No uncertainties were considered in the building parameters. (The reader may refer to a study by Porter et al. (2002) exploring the effects of structural uncertainties on the seismic loss estimation.)
- C_i^D only includes direct structural and fatality losses.
- Only one soil type was considered (Z3) that coincides with the actual building site conditions. For broader application many soil types should be considered so that this analysis could be extended to similar structures throughout Istanbul.
- A Poisson distribution on the frequency of occurrence of earthquakes was assumed. Based on recent studies, this is almost certainly not an accurate reflection

Table 2. Costs C_i^M of mitigation alternatives

Alternative (A_i)	Mitigation Cost (C_i^M)
A_1: Status Quo (original)	\$0
A_2: Braced	\$65,000
A_3: Partial (shear wall)	\$80,000
A_4: Full (shear wall)	\$135,000

of the area's actual seismicity. This assumption was made because at this time there were no time-dependent hazard curves available over the time horizon of interest.

APPLICATION OF BENEFIT-COST ANALYSIS TO THE APARTMENT BUILDING IN ISTANBUL

We are now in a position to undertake a benefit-cost analysis (BCA) for evaluating alternative mitigation measures for the prototype building in Istanbul. More specifically, we utilize the five-step procedure depicted in Figure 1 to compare the status quo with the three mitigation alternatives for the prototype apartment building and determine which one of the options is most attractive based on the criterion of maximizing net present value (NPV).

STEP 1: SPECIFY NATURE OF THE PROBLEM

There exists a well-documented prediction that there is a relatively high probability that a severe earthquake may strike Istanbul in the next 30 years. One would therefore like to take steps to mitigate the damage to structures and reduce the number of fatalities should such a disaster occur. The following question to earth scientists, engineers, and policy analysts naturally arises: *Should apartment buildings in seismically active regions of Istanbul be required to be retrofitted against earthquakes, and if so what standard should be met?*

STEP 2: DETERMINE DIRECT COSTS OF MITIGATION ALTERNATIVES

To address this question, the mitigation costs (C_i^M) (in U.S. dollars) shown in Table 2 are utilized for each mitigation alternative A_i ($i = 1$, 2, 3, and 4), based on information provided by a well-known retrofitting contractor in Istanbul.

If the government requires one of these measures to be implemented then there is the implicit assumption that they will impose some type of tax on all the residents to finance the retrofitting hazard mitigation costs.

STEP 3: DETERMINE THE BENEFITS OF MITIGATION ALTERNATIVES

By incorporating the seismological hazard data with the engineering fragility curves developed in the previous section the benefits of different mitigation alternatives are determined by evaluating the expected damage to the building and the reduction in fatalities from earthquakes of different magnitudes in the Istanbul area.

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. For one thing, there is some chance that the building will be torn down a few years from now to be replaced by another structure (especially for older structures). 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 $d=3\%$ for the analysis that follows and then show how to determine the maximum discount rate for which mitigation will still be cost effective.
- *Number of Fatalities* (N_L): 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 (N_L) 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). It is unclear to us how one converts this value into estimates of V for Turkey. Rather than enter this debate we have arbitrarily chosen two figures $V=\$1$ million and $V=\$4$ million for our CBA analysis.

Table 3 depicts the expected damage and benefits for the prototype apartment building from the overall earthquake hazard as one varies the time horizon from $T^*=1$ to 50 years for an annual discount rate of $d=3\%$. For this case we are assuming that there are no fatalities ($N_L=0$) if the building collapses. Columns 2 through 5 of Table 3 depict the expected discounted damage (in U.S. dollars) for the four alternatives. The last three col-

Table 3. Expected discounted damage and expected benefits of mitigation with no fatalities (in thousands of dollars)

	Expected Discounted Damage				*Expected Discounted Benefits*		
Alternative (A_i)	$i=1$	$i=2$	$i=3$	$i=4$	$i=2$	$i=3$	$i=4$
***Time Horizon* (T*)**	***Status Quo***	***Braced***	***Partial***	***Full***	***Braced***	***Partial***	***Full***
1	\$3.4	\$2.0	\$0.7	\$0.2	\$1.4	\$2.7	\$3.2
2	\$6.4	\$3.7	\$1.2	\$0.3	\$2.7	\$5.2	\$6.1
3	\$9.3	\$5.4	\$1.8	\$0.5	\$3.9	\$7.5	\$8.8
4	\$11.8	\$6.9	\$2.3	\$0.6	\$5.0	\$9.5	\$11.2
5	\$14.2	\$8.2	\$2.7	\$0.8	\$6.0	\$11.5	\$13.4
10	\$23.3	\$13.6	\$4.5	\$1.3	\$9.8	\$18.8	\$22.1
25	\$35.5	\$20.6	\$6.9	\$1.9	\$14.9	\$28.6	\$33.6
50	\$39.4	\$22.9	\$7.6	\$2.1	\$16.5	\$31.8	\$37.3

umns indicate the expected discounted benefits of adopting each mitigation alternative (A_i, $i=2, 3, 4$) for different values of T*. These are obtained by subtracting the expected discounted damage associated with each mitigation measure (i.e., A_i, $i=2, 3, 4$) from the expected discounted damage if one maintains the status quo (A_1).

Let $B_{iT*}(N_L)$ denote the expected discounted benefit over a T*-year horizon from adopting alternative i, when there are N_L fatalities from the earthquake. The last three columns of Table 3 provide estimates of $B_{iT*}(0)$. For example, $B_{32}(0)=\$5{,}200$ is the expected discounted benefit of partially retrofitting the apartment building for a two-year time horizon (assuming of course that there are no fatalities if the building collapses). Naturally full-mitigation (A_4) is the most effective mitigation measure and hence has the highest discounted expected benefits for any value of T*. Note that we have not yet considered the costs of mitigation C_i^M.

If it is possible to reduce N_L from a severe earthquake significantly by undertaking certain mitigation measures, then this will make these mitigation alternatives much more attractive than if only the physical damage were considered. Furthermore, as one puts a higher estimate on the value of a human life (V), the benefit-cost ratio of such measures increases even further.

Rather than attempting to estimate precise values on the number of fatalities N_L and V, we examine the following scenario: Suppose that a severe earthquake that destroys a building results in N_L fatalities. By undertaking different mitigation measures one can reduce the chances that the building will collapse and hence will reduce the expected number of fatalities. The expected cost of fatalities will then be determined by specifying a value of V.

Based on this scenario, we depict in Table 4 the expected annual damage plus the cost of fatalities for a one-year time horizon (i.e., $T^*=1$) for the following four cases:

- Case 1: $N_L=10$, $V=\$1{,}000{,}000$
- Case 2: $N_L=20$, $V=\$1{,}000{,}000$
- Case 3: $N_L=10$, $V=\$4{,}000{,}000$

Table 4. Expected damage and costs of fatalities as one varies N_L and V for $T^*=1$ (in thousands of dollars)

Case	$i=1$ ***Status Quo***	$i=2$ ***Braced***	$i=3$ ***Partial***	$i=4$ ***Full***
1	\$21.8	\$6.1	\$0.7	\$0.2
2	\$40.3	\$10.3	\$0.7	\$0.2
3	\$77.2	\$18.6	\$0.7	\$0.2
4	\$151.1	\$35.2	\$0.7	\$0.2

- Case 4: $N_L=20$, $V=\$4{,}000{,}000$

If the status quo is maintained, then there will be a relatively high probability that the building will collapse from a severe earthquake and some fatalities would result. The costs are naturally lowest when $N_L=10$ and $V=\$1$ million (Case 1) and highest for Case 4. If the structure is braced, then these expected costs are lower than the status quo. For both partial and full retrofitting, we show in figures 11 and 12 that the building has an extremely low probability of collapsing in the relevant range of peak ground accelerations considered for earthquakes in Istanbul.[3] Given our assumption that fatalities only occur when the building is totally collapsed, there are no expected fatalities for these two mitigation measures.

STEP 4: CALCULATE ATTRACTIVENESS OF MITIGATION ALTERNATIVES

Based on the costs of alternative mitigation measures shown in Table 2 and the data presented in Table 1, one can now compare the relative attractiveness of the four alternatives in terms of expected discounted benefits and costs for various time horizons T^*. We will analyze each of the three alternative mitigation measures relative to the status quo (A_1).

Let NPV(N_L) represent the net present value if there are N_L fatalities due to a structural collapse. Let us first consider the case where there are no fatalities due to a collapse so that $N_L=0$. Table 5 presents the net present value $\mathrm{NPV}(0)=B_{iT^*}(0)-C_i^M$ for each A_i ($i=2$, 3, and 4) over different time horizons T^*. If there were cases in which the $\mathrm{NPV}(0)>0$, then these values would be written in bold in Table 5. These would be the cases where retrofitting the building is cost effective.

None of the three mitigation strategies is cost effective when considering only the direct economic loss due to building damage or collapse. All of the NPVs are negative because the expected benefits do not outweigh the expenditures for the retrofitting measures.

If there are fatalities, then mitigation starts to make sense. To illustrate this point consider Case 1 ($N_L=10$, $V=\$1{,}000{,}000$). Table 6 depicts NPV(10) for this case. As one can see, all three mitigation measures are now cost effective (i.e., $\mathrm{NPV}(10)>0$) for a

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[3] In fact, in 400 Monte Carlo trials, the partially retrofitted and fully retrofitted structures did not collapse. A few trials were conducted up to highly improbably PGA values of 1.4 g and still no collapses were observed.

Table 5. Expected net present value with no fatalities [NPV(0)] (in thousands of dollars)

Alternative (A_i)	$i=2$	$i=3$	$i=4$
Time Horizon	***Braced***	***Partial***	***Full***
1	−\$63.6	−\$77.3	−\$131.8
2	−\$62.3	−\$74.8	−\$128.9
3	−\$61.1	−\$72.5	−\$126.2
4	−\$60.0	−\$70.5	−\$123.8
5	−\$59.0	−\$68.5	−\$121.6
10	−\$55.2	−\$61.2	−\$112.9
25	−\$50.1	−\$51.4	−\$101.4
50	−\$48.5	−\$48.2	−\$97.7

time horizon of 9 years. For $T^*=5$, it is still beneficial to brace the building or partially retrofit it. Naturally, as N_L and/or V increases, the benefits of mitigation will be enhanced even further.

STEP 5: CHOOSE BEST ALTERNATIVE BY MAXIMIZING NET PRESENT VALUE

In determining the best mitigation alternative, there are a number of considerations that need to be taken into account under the assumption that one knows the costs of each mitigation alternative (C_i^M):

- the length of the time horizon (T^*)
- the discount rate (d)
- the expected number of fatalities (N_L)
- the value of a human life (V)

In addition, there may be budget constraints that restrict the choice of mitigation al-

Table 6. Expected net present value with 10 fatalities and $V=\$1{,}000{,}000$ (NPV[10] in thousands of dollars)

Alternative (A_i)	$i=2$	$i=3$	$i=4$
Time Horizon	***Braced***	***Partial***	***Full***
1	−\$49.3	−\$58.8	−\$113.4
2	−\$34.9	−\$39.4	−\$93.5
3	−\$21.7	−\$21.7	−\$75.4
4	−\$9.6	−\$5.4	−\$58.8
5	**\$1.4**	**\$9.5**	−\$43.5
6	**\$11.5**	**\$23.1**	−\$29.6
7	**\$20.8**	**\$35.6**	−\$16.8
8	**\$29.3**	**\$47.0**	−\$5.1
9	**\$37.1**	**\$57.5**	**\$5.6**
10	**\$44.2**	**\$67.1**	**\$15.4**
25	**\$100.9**	**\$143.6**	**\$93.5**
50	**\$119.3**	**\$168.4**	**\$118.9**

ternatives that can be considered. For example, full retrofitting costs C_4^M=\$135,000 while braced retrofitting costs only C_2^M=\$65,000. If the tenants in an apartment have a choice between different measures, they may choose the lowest cost option even though it may not be as cost effective as those that are more expensive.

The criterion that is normally used for choosing between alternatives is to maximize the NPV. From Table 6, we conclude that the "partial" retrofit is the most economically attractive option for Case 1 ($N_L=10$, V=\$1,000,000) if the relevant time horizon is five years or more. For $T^*\geqslant 5$ the NPV(10) is positive when the structure is partially retrofitted. The net present value of this measure also exceeds that of the other two retrofitting options considered for any $T^*\geqslant 5$. Should $T^*<5$ then it would *not* be cost effective to retrofit the building with any of the three alternatives considered given the assumptions on which this BCA is based.

Suppose that the Turkish government wanted to know under what circumstances partial retrofitting (A_3) will be the most attractive option, if the various parameters specified above were not known with certainty. In such a case, it would have to undertake a sensitivity analysis across different parameters to determine at what point the decision regarding the adoption of this specific mitigation measure would change.

To illustrate how one would undertake this type of sensitivity analysis, consider the case where the Turkish government examines the values of different parameters that yield

$$\text{NPV of } A_3=0 \tag{2}$$

In this way, it can determine how wide the range of values of these parameters can be for A_3 to be preferred over not doing anything (but not necessarily over A_2 or A_4 too).

To keep the analysis straightforward, we will vary only one parameter at a time while keeping the others constant at some base case. More specifically, we will arbitrarily specify the base case to be as follows:

$$T^*=10,\ N_L=10,\ V=\$1{,}000{,}000,\ C^M=\$80{,}000,\ \text{and}\ d=3\%$$

For these prespecified values, we will determine where Equation 2 is satisfied as we change each of the above parameters while holding the others constant. Below we present the results of this analysis:

- The minimum time horizon where Equation 2 is satisfied is $T^*_{\min}=5$ years. This means that if we were to consider a time horizon greater than or equal to 5 years ($T^*\geqslant 5$), then the alternative A_3 should be preferred over the status quo (A_1).
- The minimum number of fatalities from a severe earthquake where Equation 2 is satisfied is $(N_L)_{\min}=6$.
- The minimum value of a human life where Equation 2 is satisfied is $V_{\min}$ =\$480,000.
- The maximum cost of mitigation where Equation 2 is satisfied is $C^M_{\max}$ =\$147,100.
- The maximum discount rate where Equation 2 is satisfied is $d_{\max}=25\%$.

POLICY IMPLICATIONS

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, 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 in the Istanbul area does *not* increase over time.

The one striking conclusion that can be made, assuming that the structural and retrofitting 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 on urban housing indicate that in the three largest cities (İstanbul, İzmir, Ankara) 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.

Previous experience with earthquakes in Turkey highlights this point. In five urban earthquakes in Turkey during the past decade approximately 20,000 people have been killed, the vast majority of them through collapses of residential buildings. Altogether in these earthquakes, 70,000 buildings have been damaged, and some 20,000 buildings destroyed. The costs of the damage to the destroyed buildings alone have been estimated at $20 billion.

There is also a logical connection between the adoption of mitigation measures in advance of the next earthquake and the claims costs from insurance should a quake occur in the Istanbul area. The more residential buildings that are retrofitted, the lower the insurance and reinsurance costs will be. This has some significance for Turkey since the Government has recently created the Turkish Catastrophe Insurance Pool (TCIP).[4] All existing and future privately owned property, except for non-engineered rural housing

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[4] For more details on the TCIP and insurance markets in Turkey see Boduroglu (2001) and Yalcin (2001). A discussion of the linkages between mitigation and insurance appears in Freeman and Kunreuther (2002).

and fully commercial buildings are required to contribute to TCIP.[5] Between the launching of TCIP on 27 September 2000 and 14 May 2003, 1.9 million insurance policies have been issued (Kunreuther et al. 2003). This makes TCIP the second largest catastrophe pool in the world. Gulkan (2001a) has proposed that TCIP take the lead in developing guidelines for encouraging the adoption of mitigation measures for existing structures in Turkey because of the stake it has in maintaining its operability. Such a program builds on concepts discussed by Balamir (2001) and Gulkan (2001b) regarding changes in disaster policy in Turkey with respect to urban and land-use planning.

It should be noted, however, that it is not at all clear whether the TCIP in its present form can serve as an incentive mechanism for the adoption of relatively costly retrofitting schemes. Subscription to the TCIP is still relatively weak, and also, given the low maximum coverage of about $20,000 and corresponding small premiums, no adjustment of these small premiums alone can serve as an incentive to strengthen one's property.

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.

CONCLUSIONS AND FUTURE RESEARCH

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 throughout 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.

TIME DEPENDENCY

As previously mentioned, the same hazard curve was used for each year in the time horizon. This is not the best representation of the seismic environment in the Istanbul region. The BCA methodology undertaken in this paper can easily incorporate a time-dependent hazard curve $R(a)$ that will be developed by seismologists in the future to reflect the anticipated earthquake activity in the region. These time-dependent hazard

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[5] It is estimated that of the 14 million households in the country, 10 million will be under TCIP coverage. Rural houses continue to be covered by the Disasters Law, and their tenants will receive government subsidized housing if their homes are demolished by natural disasters. The goal in 2001 was to reach a total of 1.5 million policy holders. This goal has now been surpassed but the sale of new policies has stagnated in 2003, and is currently 1.9 million. It would be fair to assume that the eventual target cannot be reached in less than five years.

curves will probably be defined relative to the time of occurrence of events on different faults. This will add a complexity to the analysis, because several "bounding" scenarios will have to be considered as to when major events occur.

The analysis undertaken in this paper assumed that the annual exceedance 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 stronger case for finding ways to develop implementable strategies for loss mitigation now.

ENGINEERING ANALYSIS

Among the additional considerations that should be addressed in order to extend the usefulness of this type of study to the Istanbul region in general, are (1) additional site soil conditions, (2) accurate modeling and experimental calibration of retrofitting behaviors, (3) additional and state-of-the-art retrofitting schemes, (4) variability in the directivity effects of the site ground motion, and (5) the introduction of some randomness in the structural properties in order to determine confidence intervals on the fragility curves.

EXTENDING BCA FOR EVALUATING MITIGATION MEASURES

Future work in BCA needs to more explicitly specify all the benefits and costs associated with specific alternatives, notably the impact of technological externalities and second-order effects.

The case of *technological externalities* can be illustrated by the following simple example. If a building collapses after an earthquake, it could break an underground pipeline and cause a major fire that would damage other apartment buildings that were not affected by the earthquake in the first place. Suppose that an unbraced apartment building toppled in a severe earthquake and had a 20 percent chance of bursting a gas pipeline and creating a fire that would severely damage ten other retrofitted apartment buildings, each of which would suffer $40,000 in damage. Had the first apartment building been retrofitted this series of events would not have occurred. If the annual probability of such a severe earthquake is .01, then there is an additional expected loss of $800 (.01

×.20×10×$40,000) that needs to be taken into account when evaluating the expected costs of the alternative "Do Not Retrofit" the apartment building.

Second-order effects refer to disruption of businesses and the life of the community as a result of damage to property from a disaster. In the case of the apartment building, the second order effects could be the costs of evacuating and sheltering residents of the building who are now homeless. At a broader level, the destruction of commercial property could cause business interruption losses and the eventual bankruptcy of many firms. The impact on the fabric of the community and its economic base from this destruction could be enormous.

Most BCA studies produce an aggregate NPV without providing different interested parties with information on how they are affected. By identifying the distribution of impacts across individuals and groups, there is more information available to stakeholders as to how they personally will fare if a particular option is chosen as well as the impact that such a choice will have on society as a whole. Furthermore, policy makers have a much clearer idea as to which groups are likely to support each option and who will be opposed to it. They can then make the tradeoff between (1) advocating a policy that maximizes NPV of social benefits but may be difficult to implement due to distributional considerations, and (2) proposing an alternative that is second-best using the NPV criterion but is viewed as more desirable from a political vantage point because of distributional considerations.

Finally, one may want to examine different assumptions regarding the appropriate discount rate to use for analyzing different alternatives. Normally BCA uses a constant discount rate over time adjusted for inflation. One needs to work closely with Turkish economists to determine the appropriate discount rate to use given projected interest rates and rates of inflation. Recently some economists (see Harvey 1994 and Weitzman 1994) have suggested that one should utilize declining discount rates for impacts that occur further in the future to reflect the concern with future generations. Some philosophers have even argued that the social discount rate should be zero (i.e., nondiscounting) so that future events are given the same weight as current events. Boardman et al. (2001, Chap. 10) has a detailed discussion of the issues associated with the use of declining discount rate(s).[6] One needs to examine the sensitivity of alternative mitigation measures if one changes the discount rate over time to reflect these considerations.

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[6] For empirical evidence on declining social discount rates as the time horizon extends into the future, in the context of saving lives today rather than in the future, see Cropper et al. (1992).

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