

CHAPTER 4: THE VALUE OF LIFE

Value of Life

Benefit-cost analysis (BCA) can be used to assess public-sector resource allocation decisions. However, to identify and objectively measure all benefits of public projects can be very difficult if not impossible (Bentkover, 1986). One of the principal benefits of seismic rehabilitation of hazardous buildings is reducing the expected number of fatalities resulting from an earthquake. Methods of measuring the value of reducing the risks to life and health in BCA are diverse and until recently, controversial (Broome, 1985, and Cochrane, et al. 1987).

Four principal methods have been used to derive the value of life in BCA. They are the human capital approach, the court awards approach, the risk-cost method, and the willingness-to-pay approach. These approaches will be briefly described and evaluated. Finally, a suggested procedure to measure the value of a statistical life for the Benefit-Cost Model (BCM) will be outlined.

Human Capital Approach

Initially the value of health was estimated by measuring the lost wages, medical expenses and indirect costs resulting from the loss of life or injuries (Rice and Cooper, 1967, and Buehler, 1975). This approach is easy to conduct since only the deaths that can be prevented and the expected lifetime earnings need to be estimated. But Viscusi (1986a) concludes that this is a poor proxy for the value of reducing health risks. The benefit of a government program is the reduction of the probability of death or some other health aspect for a large number of individuals rather than the prevention of a certain number of deaths that might be identified after the fact.

This approach suffers from other deficiencies. Persons with low expected future income are under-represented (valued) under this approach. A very old person has a small amount of future earnings and a very young person's earnings are sufficiently distant that current discount rates reduce them to almost nothing in a BCA (Keech et al. 1989). This approach assumes that income determines individual utility and the value of life, and as a result, ignores all non-market goods consumed by individuals.

Court Awards Approach

Courts awarded damages for wrongful deaths are usually based on potential future earnings, which could serve as a proxy for the human capital approach, but they may include punitive damages and bereavement of the family or related consequences (Keech et al. 1989). Since it would be difficult to separate all of the influences that were included in the amount of the judgment, it probably cannot be used to evaluate the reduction.

Court awards are also based on specific historical cases but reducing earthquake hazards saves future lives which are statistical in nature and not individual-specific. Therefore, the use of court awards to evaluate risk reduction in public projects would not be a valid measure of the value of life.

Risk-Cost Approach

Another method used to value life is simply dividing the amount of project expenditures by the number of deaths that will be reduced by the project (Baecher et al. 1980). This approach transfers the responsibility of placing an explicit value on life from the analyst to the political level.

This approach does not value human life but provides decision makers with criteria for comparing programs dealing with safety and health related issues. The variation in the cost of lives saved for various public programs was found to be high which indicates that the procedure does not estimate the correct value of reducing risks to human safety (Broder and Morral, 1983).

Willingness-To-Pay Approach

Willingness-to-pay is a valid methodology for determining the value of risk reduction in BCA (Cochrane et al. 1987, Viscusi, 1986a, and Keech et al. 1989). The theoretical foundation for this method is that individuals will maximize their own utility by trading-off wealth or income for reducing the probability of death (Linnerooth, 1979). Cochrane et al. (1987) summarized why willingness-to-pay is the most correct method available of estimating the value of human life (page 21):

1. The value of life is embedded in the concept of willingness-to-pay for improved safety.
2. The concept provides a framework of establishing tradeoffs between wealth and greater safety.
3. The tradeoffs can be measured.

4. The concept is consistent with benefit-cost analysis because it poses the choice process that would enhance welfare.
5. The concept provides a pecuniary index of safety which is additive to other damages.
6. The willingness-to-pay for safety is a function of age, income and the perception of risk.

Willingness-to-pay assumes that individuals are rational (maximize utility), and correctly perceive the wealth-risk trade-off. These assumption may not be entirely met in all of the different empirical applications of the willingness-to-pay approach. Three basic procedures to measure willingness-to-pay have been developed and accepted as valid methods for valuing reductions in risk (Zeckhauser, 1975). These are: the survey approach; the labor market approach; and the consumer expenditure approach.

The Survey Approach -- for deriving willingness-to-pay is also called the contingent valuation method (CVM). The survey simulates a "market" of the public or nonmarket goods. This analogy, or continent market, is presented to the subject as providing public goods in return for one's payment. Summing across all individuals provides an estimate of value of the public good. In initial CVM studies, individuals were simply asked to value the reduction of the risk in question (Acton, 1973, and Jones-Lee, 1976). Those studies were criticized because of flaws in the design procedure. First, the free rider issue was ignored, and second, the individual's inability to perceive small differences in risk was not recognized (Cochrane, 1987). In addition, the individual subject to a CVM survey may perceive the environmental or social value rather than the individual's intended behavior (Bishop and Heberlein, 1979). Randall et al. (1983) have since offered a number of requirements to properly frame the situation to the subject to avoid these biases. This approach has also produced a wide variance of estimates (Blomquist, 1982).

The Labor Market Approach -- is the willingness of workers to accept additional wages for riskier jobs. This approach has been offered as an indirect indication of the value of life (Keech et al 1989). Econometric models are used to estimate the wage differential earned by workers in risky jobs. This approach assumes that labor is mobile and that labor markets are competitive. These conditions are rarely achieved, which results in an underestimation of the risk differential in wages. In addition, most models use gross wages rather than after tax income which also produces biased results.

Labor market studies also produce high variations in estimates if voluntary versus involuntary risks are not specified. High risk jobs are voluntary and attract risk adverse labor that require small risk premiums. However, very small involuntary risks may produce high value estimates (Viscusi, 1986b). This method has the advantage of re-estimating existing econometric equations using different assumptions or new data to

produce new estimates (Miller, 1986). The use of union or non-union workers (Gegax et al. 1985, Dillingham and Smith, 1985, Olson, 1981, and Viscusi, 1980), before versus after tax wages, and fatal versus non-fatal risks have been tested by changing and re-estimating existing models (Keech et al. 1989). Variations in these assumptions are responsible for the high variations in labor market study estimates (Blomquist, 1982).

The Consumer Analysis Approach -- is observing the way consumers feel about risk. It is proposed that the value of relative risks of certain products can be measured by the willingness-to-pay for safer products. Econometric models are used to estimate the willingness-to-pay for products with better safety records. This approach assumes that consumers have perfect information on the relative safety of each product, and that estimates represent equilibrium demand-supply conditions that are seldom met (Keech et al. 1989). Using past societal decisions that imply health or life values also assumes that those decisions were optimal, which may not be true. As with previous approaches, most studies used very different assumptions and discount rates, and the results are quite variable and incompatible without modification (Viscusi, 1986a).

Attempts have been made to combine the human capital approach and the consumer expenditure approach Landefeld and Seskin (1982) studied the willingness-to-pay for life insurance and estimated the value of life at \$873,000 in 1985 dollars. The authors claim this was the first empirical estimate of human capital values, reformulated using a willingness-to-pay criterion, to produce the only clear, consistent, and objective value for use in BCA of policies affecting risks to life.

The use of safety items such as seat belts are also considered as indications of the value of life (Blomquist, 1979). The value of life has also been derived from automobile speeds (Ghosh et al. 1975, and Jondrow et al. 1983) and cigarette smoking (Ippolito and Ippolito, 1984).

Keech et al. (1989) derived the value of life for the Federal Aviation Administration using willingness-to-pay studies that had been done during the 1970's and 1980's. Miller (1986) had reviewed recently published willingness-to-pay studies and critically evaluated the analytical procedures used, risk variables, model specifications, and results. He found several studies that were judged appropriate and adopted those studies as a basis for determining the value of life.

Thirteen labor market studies were modified to assume after-tax wages, or to separate fatal from nonfatal risks. Nine consumer behavior studies were changed to reflect similar discount rates and other assumptions relating to value of time and family size. Three survey studies done on cancer risks, highway safety, and labor markets were also declared valid. Values from all 25 studies were adjusted to reflect 1985 dollars.

Updated estimates from these 25 studies were summed and an average value calculated. The estimate was then adjusted to 1987 dollars which yielded a "consensus" value of life of \$1,577,129. This estimate was defined as the "private

value of a statistical life" which is just part of the "social value of a statistical life". Keech et al. (1989) defines the social value of early death as also including foregone taxes, and medical, emergency, legal, court, and public assistance administration costs. The total of these costs, which is the social value of a statistical life, was estimated at \$1,740,000 in 1987 dollars.

A "consensus" procedure was also used by Schulze et al. (1987) to derive a value of life of \$1 million. The studies used in this procedure were reported by Violette and Chestnut (1983).

The use of willingness-to-pay to estimate the value of life has been accepted by many Federal agencies. Viscusi (1986a) concludes:

Indeed as of 1984, the valuation of life has become a generally accepted component of the debate over risk regulation. The recent debate over an OSHA construction industry standard epitomizes this change. Rather than claiming that the value-of-life issue was too sensitive to be discussed, there was an open policy debate over the appropriate value of life. OSHA used a value of life of \$3.5 million in its regulatory analysis based on results for the average blue-collar worker. OMB took a different approach, citing evidence regarding the heterogeneity in the value of life. After noting the high and well-known risks associated with construction jobs, OMB urged that OSHA use a lower value of life of \$1 million. One Congressman viewed both of these estimates as too low, advocating a \$7 million figure in line with results for the Panel Study of Income Dynamics. In each case, the willingness-to-pay approach was accepted, as was the importance of using labor market studies as a reference point. (page 207)

Cochrane et al. (1987), however, offer a more guarded endorsement:

Despite the significant gains that have occurred over the past decade in refining survey instruments and honing theoretical constructs, the essential ingredients for incorporating risk into BCA are still clearly lacking. It appears that although market data provide a useful glimpse of what society at large is willing to tolerate in terms of risks, it is still no more than a glimpse. The use of expected values in these analyses tends to obscure the losses that result when the less probable events materialize. Perhaps the primary criticism that has been leveled at risk-cost methods is the lack of appreciation for the process of valuation. It is clear from the work of Starr (1985) and others that risk wealth tradeoffs may be nonlinear. Hence, the social losses may not be a simple additive adjustment to project net benefits as Baecher et al. suggests. These concerns have led to the development of alternative technical means (multiobjective and partitioned risk) of deriving an optimum strategy for those situations involving more than economic efficiency. (page 27)

Value of a Statistical Life

The "consensus" estimate of the private value of a statistical life derived by Keech et al. (1989) draws on the work of many scientists specializing in the value of life. The studies were reviewed by Miller (1986), adjusted or revised when possible, and judged to be adequate as value of life estimates. It seems reasonable to use the estimates as derived and reported by Keech et al. (1989) in this study. As stated before, Keech et al. (1989) has derived a "social" value of life based on the sum of the "private" value of life, foregone taxes and other direct costs of early death. This also seems appropriate for this study.

Foregone taxes are discounted present value of expected future earnings multiplied by the applicable state, local and federal tax rates. This value represents the lost tax revenues that the government will not collect as a result of early death. To estimate foregone taxes for this study, an age, sex, occupation, and income profile of potential death victims will need to be derived for the earthquake site.

A study by the National Highway Traffic Safety Administration (1986) included medical and emergency costs, legal and court costs (the cost of carrying out court proceedings, not the cost of settlements), and costs associated with the administration of public assistance insurance. The total direct costs using just these parameters was estimated to be \$33,093 in 1987 dollars. Taxes foregone and other direct costs can be estimated for each individual test site.

Updating the Value of a Statistical Life

Keech et al. (1989) suggested that the value of a statistical life be updated using the GNP Implicit Price Deflator for Total Personal Consumption Expenditures for the following reasons:

1. The private willingness-to-pay estimates are based upon individual assessments which in turn are based upon income, consumption of a wide variety of goods and services in the economy, and the consumption of other non-pecuniary activities. The resulting monetary values probably closely correspond with the typical mix of goods and services available in the economy.
2. The other elements of the valuation of a statistical life are expenses or income measures which should increase in approximate proportion to economy-wide inflation.

These procedures to estimate the value of life for the BCM used in this study represent the least cost alternative which is defensible to the economics profession. The procedure is simple, the data needed for calculations are readily available, and the results are reasonable.

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CHAPTER 5: TECHNICAL ISSUES

Seismic Risk Assessment

Introduction

Seismic risk assessment is one of the most critical steps in benefit-cost analysis of seismic rehabilitation projects because seismic risk varies markedly with location, and seismic risk has a major impact on benefit-cost results. The type of seismic risk information required for benefit-cost analysis differs significantly from that required for engineering design purposes.

For design purposes, seismic risk is usually expressed in terms of a design earthquake (or earthquakes) with the design earthquake defined in terms of an exceedance probability for some stated time period. For example, a 10% exceedance probability in 50 years is used in the Uniform Building Code (UBC). This type of seismic risk is usually expressed as a single value of effective peak ground acceleration, PGA, such as 30% of g (the acceleration of gravity). When a detailed, site-specific geotechnical analysis is conducted, the result is also a single value. For example, for a given site the level of effective peak acceleration with a 10% chance of exceedance in 50 years might be calculated as 17% g . At such a site, 20% g might be used as the design earthquake.

For benefit-cost analysis, however, an explicit statement of the annual probabilities of the full range of damaging earthquakes must be made. Seismic risk assessment for benefit-cost analysis must be expressed in probabilistic terms because the timing and severity of future earthquakes is unknown. The benefit-cost program uses the expected annual probability of earthquakes in each "bin" or level of seismic ground motions (expressed as Modified Mercalli Intensity, MMI, and effective peak ground acceleration, PGA) to perform an expected value calculation. For example, if at a site under consideration, the annual probability of earthquakes of MMI VIII is 1%, then there is a one percent chance per year of such an earthquake. If each such earthquake causes \$1,000,000 in damages, then on average (over a long time period) there will be \$10,000 per year in damages. The \$10,000 per year in average damages is the "expected" or statistical average damages per year. If these damages are avoided by a rehabilitation project, then the expected or statistical average damages avoided (i.e., the benefits) are \$10,000 per year. To count fully the benefits of a seismic rehabilitation, the expected benefits of avoiding damages from the full range of damaging earthquakes must be counted, rather than simply considering one scenario or design earthquake.

Modeling Seismic Risk: Principles

Quantitative seismic risk assessment requires four steps:

- a) identification of all active faults or fault zones,
- b) estimation of the recurrence interval and magnitude of earthquakes expected on each fault,
- c) determination of an appropriate attenuation relationship for the local geologic conditions, and
- d) modeling site effects (amplification or attenuation) at the site under consideration.

Identification of the active faults affecting a given area and estimation of the recurrence intervals and magnitudes of earthquakes on each of the faults is ordinarily done through assessment of historical seismicity in the area. Inferences from historical seismicity are supplemented by knowledge of the tectonic setting of the faults and by analogies to other similar fault systems. The extent of current knowledge about regional seismicity varies substantially depending on the level of seismic activity. For example, highly active areas, such as portions of California near the San Andreas fault system, are much better understood than are seismically active regions in the Midwest or East, where the record of historical seismicity is much thinner because the recurrence intervals for earthquakes are much longer. For completeness, estimates of regional seismicity usually include "background seismicity" or "area sources" to account for earthquakes on faults not currently mapped or faults without surface expressions.

Determination of an attenuation relationship for the local geologic conditions is necessary to account for the diminution of ground motion with increasing distance from the causative fault. Finally, the intensity or level of ground shaking experienced in a given earthquake at a specific site depends on the site conditions. For example, soft soils may amplify ground motions so that soft soil sites experience higher levels of ground shaking than do nearby firm soil or rock sites. In some cases, especially at high levels of ground motion, site effects can also attenuate ground motions.

The principles of modeling seismic risk, as briefly summarized above, are well understood and have been applied to estimate seismic risk in numerous areas for planning purposes or for the design of individual structures. However, it is important to recognize that limitations of data, especially in low or moderate seismicity areas, may impart significant uncertainty to seismic risk estimates.

Modeling Seismic Risk: The Benefit-Cost Model

There are two methods for estimating seismic risk in the benefit-cost model. First, the default method, which is built into the model, uses the spectral acceleration contour maps prepared by the United States Geological Survey for the 1991 Edition of the NEHRP (National Earthquake Hazards Reduction Program) Recommended Provisions for the Development of Seismic Regulations for New Buildings (Appendix). Second, if they are available, the user may enter site-specific geotechnical seismic risk assessments into the model.

Default Method

The default method uses the 0.3 second period spectral acceleration contours from the 1991 NEHRP Appendix maps or ground motions with 10% chance of exceedance in 50 years and 250 years. The 0.3 second data is used as being applicable to low and midrise buildings which constitute the vast majority of the building stock in the United States. Effective peak ground accelerations are obtained from the spectral acceleration values by dividing by a factor of 2.5, as per the NEHRP Appendix. Exceedance probabilities for other levels of ground motion are obtained by a log-log¹ fit of the 10% in 50 year and 10% in 250 year data points available from the NEHRP maps. Interval probabilities for the MMI/PGA bins are obtained by difference from the exceedance probabilities. For example, the annual probability for events between 8 and 16% of g is the annual exceedance probability for 8% g minus the annual exceedance probability for 16% g.

For the convenience of users, tabulated values of the NEHRP spectral acceleration contour values are compiled in Volume 1 of the User's Manual (Table 5.1 on page 5-24) for most of the major cities in the United States. Alternatively, for smaller cities or rural areas, users may read values directly from the contour maps, which may be obtained from the Building Seismic Safety Council, 1201 L Street, N.W., Washington, D.C. 20005.

The default method seismic risk assessment estimates depend directly on the NEHRP maps. These maps were developed using the general principles of seismic risk assessment outlined above. However, because these maps were intended to represent broad regional variations in seismic risk, only major faults were included. Therefore, for specific local sites, these maps may not include faults which may produce strong local ground motions. Therefore, while these maps do approximately represent regional seismic risk and thus clearly demarcate high seismicity areas from moderate or low seismicity areas, they may not accurately reflect the full seismic risk at all specific localities. For this reason, use of site-specific geotechnical seismic risk assessments is strongly recommended whenever such assessments are available.

¹ A log-log fit is used because plots of earthquake probabilities versus magnitude typically fall on a straight line when log scales are used, in accordance with the well-known Gutenberg-Richter relationship between the size and number of earthquakes.

Uncertainty in the NEHRP spectral acceleration contours is greater for the 250-year maps than for the 50-year maps and greater for lower seismic areas than for higher seismic areas. Values from these maps should be used with caution. As noted on the 250-year maps:

The estimation of low values of probability of ground motion (250-year exposure time) may give unrealistic values of spectral acceleration because of uncertainty in attenuation of spectral values in fault rupture length. The uncertainty is increased in the central and eastern United States because of the difficulty of defining earthquake source zones and the infrequency of earthquake occurrence. Thus, any values on this map should be considered advisory and treated with caution. (NEHRP 250-year map)

The probabilities of given levels of ground motion at a specific site depend not only on location relative to active faults, but also on site conditions. The default seismic risk assessment in the benefit-cost model includes a methodology for including site effects, using the 5-level NEHRP soil classification scheme:

SITE EFFECTS

SOIL TYPE	MULTIPLIER FACTORS AS A FUNCTION OF GROUND SHAKING ²			
	25% g	50% g	75% g	100% g
S0 Hard Rock	0.6	0.6	0.7	0.8
S1 Rock	0.7	0.8	0.9	1.0
S2 Very Dense Soil	1.0	1.0	1.0	1.0
S3 Stiff Soil	1.2	1.1	1.0	1.0
S4 Soft Soil	1.5	1.3	1.1	0.9

The default method of seismic risk assessment, discussed above, is based on an S2 soil type. For sites with soils other than S2, site effects are incorporated into the seismic risk assessment by using the multiplier factors shown in the above table.

² Multiplier factors are from preliminary unpublished data (April 1993) from the Design Values Panel which is preparing updates of the NEHRP seismic provisions.

Site-Specific Geotechnical Method

The best method for obtaining the seismic risk estimates required for benefit-cost analysis is through a detailed, site-specific, geotechnical risk assessment. The site specific analysis can include all of the local faults and thus most accurately model the site-specific seismic risk. Moreover, by including as much detail as available about site conditions, a site-specific analysis can more accurately model site amplification as well. A site-specific analysis can also quantify the probabilities of liquefaction and/or lateral spreading which may significantly impact engineering judgement about a building's seismic performance.

A building's seismic performance depends, in detail, on the frequency content (i.e., period of motion) of ground motions and on duration, as well as on the level of ground shaking. For example, a short building may be more vulnerable to high frequency motions (e.g., 0.3 sec period), while tall buildings may be more vulnerable to lower frequency motions (e.g., 1.0 sec period). A full geotechnical analysis would include frequency and duration information as well as ground shaking information. Ideally, this full information should be incorporated into the engineering evaluation of the building's seismic performance and then incorporated into the mean damage functions used as input into the benefit-cost analysis.

MMI/PGA Relationship

The Modified Mercalli Intensity (MMI) scale is qualitative, antiquated and may not adequately reflect the seismic performance of many modern building types. Nevertheless, the MMI scale has been used for many decades and a great deal of the historical seismic damage information is formulated in MMI. In particular, the two major sources of damage data for US buildings (ATC-13 and ATC-36), which are used in the benefit-cost model, both formulate building damage data in MMI.

Effective peak ground acceleration (PGA) is a quantitative, modern measure of the level of ground motion. However, PGA does not fully capture the seismic parameters which relate ground motion to building damages. In detail, building damages depend not only on the level of ground shaking but also on the duration and frequency content of the ground motions.

In the benefit-cost model, both MMI and PGA are used. The earthquake "bins" in which intensity-dependent information such as building damage function are entered are labeled in both MMI and PGA. MMI is used because of the wealth of historical damage data formulated in MMI. PGA is used as a good single quantitative measure of ground motion which is obtainable from site-specific geotechnical seismic risk assessment studies. More complex, multi-dimensional measures of ground motion (e.g., including duration and frequency content) were not used because of the paucity of damage data expressed in this form and the heavy burden of data collection which such analysis would place on the users of the benefit-cost program.

The relationship between MMI and PGA assumed in the model is shown below.

MMI/PGA Relationship

MMI	VI	VII	VIII	IX	X	XI	XII
PGA (% g)	4-8	8-16	16-32	32-55	55-80	80-100	>100

There have been many attempts, only partially successful, over the years to determine quantitative relationships between MMI and other more quantitative measures of ground motions such as PGA. None of these efforts have been compellingly successful, because of the multidimensional measures necessary to describe ground motions quantitatively and the qualitative, subjective nature of the MMI scale. Nevertheless, a broad correspondence between MMI and PGA is well established in the literature. A brief review of the MMI/PGA relationship is given in ATC-13 and is not repeated here.

Sensitivity Analysis

The benefit-cost analysis model has been extensively reviewed and is believed to be conceptually correct. However, results calculated by the model are, of course, subject to uncertainty and inaccuracies in the input data. The purpose of this section is to review the sensitivity of calculated results to uncertainties in the input data.

The equations which govern the benefit-cost model are all linear (i.e., calculated results depend on the sum or linear product of inputs). There are no higher order terms (exponentials or power functions) in any of the equations. Because the model is linear, it is very stable: small changes in inputs result in small changes in output (calculated results). There is no place in the model where a small change in any input drastically changes the output.

There are many input parameters in the benefit-cost calculations. However, many of these are known almost exactly (e.g., size of buildings), while others are usually well-determined (replacement value of building, value of contents, occupancy, agency budgets, etc.). Furthermore, many of the inputs have only minor impacts on the final results and thus uncertainties in these inputs do not substantially affect results. For example, the total benefits for a particular rehabilitation project are generally dominated by the building damages avoided and the value of avoided casualties. Other factors such as value of contents damages avoided, avoided relocation costs, avoided rental income losses, and avoided loss of government services, are generally quite small. While these other factors are included for completeness and for the few cases in which they may be unusually important, they are not of major importance for most analyses and, therefore, uncertainties in the input parameters which determine these benefits

are usually not of major significance.

There are, however, several input parameters which do generally have major impacts on calculated benefit-cost results. The typical uncertainties in these parameters and the sensitivity of calculated benefit-cost results to such uncertainties are discussed below for each of these important input parameters. These important input parameters include: seismic risk, building mean damage function, effectiveness of the retrofit, occupancy and casualty rates, death rates, and the economic assumptions (discount rate and project lifetime or planning horizon). The other input data parameters (see Chapter 5 in Volume 1) generally are of lesser importance. These parameters, however, are necessary to include for completeness and because they may be important in some circumstances.

Seismic Risk

Seismic risk, expressed as the annual probability of a given level of ground shaking, varies enormously from location to location within the United States. Benefit-cost results are directly proportional to seismic risk: doubling the annual probabilities of each level of ground shaking doubles the expected (average) damages and other losses and thus doubles the benefits of avoiding these damages. Correspondingly, a given level of uncertainty in seismic risk corresponds exactly to the same level of uncertainty about benefit-cost results. Uncertainty in seismic risk estimates is probably the largest uncertainty in the benefit-cost calculations. There are, however, two mitigating aspects of uncertainty in seismic risk estimates:

- 1) the annual probabilities for low to moderate levels (MMI VI to IX), which are generally better determined, have much greater impact on benefit-cost results, than do the annual probabilities for extreme levels of ground shaking (MMI X to XII).
- 2) the relative ranking of prospective seismic rehabilitation projects within a given geographic area is unaffected by uncertainty in the absolute level of seismic risk.

Because of the first factor above, large uncertainties in the probabilities of extreme earthquakes have limited impact on benefit-cost analysis. Because of the second factor above, comparing benefit-cost ratios among a group of buildings in the same location has much less uncertainty than does comparing ratios for buildings in different locations.

Building Mean Damage Function and Rehabilitation Effectiveness

The seismic vulnerability of a given building is expressed in the model as a mean damage function (MDF) which indicates the average amount of damage (as a

percentage of replacement value) expected for each bin of ground motion (MMI and PGA). Similarly, the seismic vulnerability of the rehabilitated building may be expressed as a MDF or, equivalently, as the effectiveness of the rehabilitation (i.e., the percentage reduction in MDF after rehabilitation).

There may be substantial uncertainty about the seismic vulnerability of an individual building. The uncertainty will be largest if default MDFs are used, which depend only on the building type. Uncertainty will be progressively less as more engineering information is available, ranging from a quick walk-through to detailed calculations and testing of materials. All other factors being equal, benefit-cost results are directly proportional to building MDF, because other damages to contents, loss of functionality and casualties are all closely related to building MDF. Therefore, a given level of uncertainty in building MDF corresponds to a closely similar level of uncertainty in benefit-cost results.

However, as with uncertainty in seismic risk, uncertainty in buildings' seismic vulnerability has less impact on relative benefit-cost results than on absolute results. Some classes of buildings (e.g., unreinforced masonry or non-ductile concrete moment frame buildings) typically have much higher seismic vulnerability than other classes of buildings (wood frame or steel frame buildings with shear walls). Reasonable engineering judgement about whether a given building is better (e.g., good detailing) or worse (e.g., major irregularities) than typical buildings is relatively robust. Therefore, benefit-cost analyses in which a modicum of good engineering judgement is applied are likely to identify correctly the most seismically vulnerable buildings. Because avoided damages (benefits) may be larger in more vulnerable buildings, benefit-cost analyses are likely to correctly identify the most vulnerable buildings as the best candidates for seismic rehabilitation.

Occupancy and Casualty Rates

All other factors being equal, the expected number of casualties in a given building for a given earthquake is directly proportional to occupancy. Therefore, the portion of the benefits of a rehabilitation project corresponding to the dollar values placed on deaths and injuries is directly proportional to occupancy. Average occupancy for buildings is generally very well determined. Therefore, uncertainties in occupancy contributes very little uncertainty to the average or expected value of benefits, even though occupancy may vary markedly depending on day of the week or time of day. Because benefit-cost analysis considers, quite properly, the average occupancy, uncertainties in occupancy contribute very little uncertainty to calculated benefit-cost results.

The expected number of casualties depends not only on occupancy but also on casualty rates per earthquake event. Casualty rates depend primarily on building MDFs - greater building damage will result in greater casualties. Therefore, uncertainties about the number of casualties avoided are subject to similar uncertainties to those discussed above under Building Mean Damage Function and Rehabilitation Effectiveness.

The economic value of casualties avoided is dominated by deaths avoided. Deaths in buildings during earthquakes occur primarily due to partial or full collapse. Therefore, an important aspect of casualty estimation is to determine the level of ground shaking likely to initiate collapse. Thus, as with building MDFs, good engineering judgement about a building's seismic performance is essential to obtaining useful benefit-cost results.

Economic Assumptions (Discount Rate and Project Lifetime)

Benefit-cost calculations require assumptions about discount rates and project lifetimes (or planning periods). Unlike the other input parameters discussed in this section, these economic inputs are policy decisions. Changes in the discount rate or project lifetimes assumed directly affect the benefit cost results. Such changes directly affect the absolute value of benefits (and benefit-cost ratios), but have no impact on relative benefit-cost results because they affect all prospective projects equally. The impact of discount rate and project lifetime combine to yield a "present value coefficient," which is the present value of \$1.00 per year in future benefits. The impact of changes in these factors is shown below.

Present Value Coefficients

PROJECT LIFETIME	DISCOUNT RATE					
	3%	4%	5%	6%	7%	8%
20 years	14.88	13.59	12.46	11.47	10.59	9.82
30 years	19.60	17.29	15.37	13.76	12.41	11.26
50 years	25.73	21.48	18.26	15.76	13.80	12.23
100 years	31.60	24.50	19.85	16.62	14.27	12.49

Benefits and benefit-cost ratios are directly proportional to the present value coefficient shown in the table above. The impact of changing economic assumptions is shown by the changes in present value coefficient. For example changing from assumptions of 7% and 50 years to 4% and 100 years, changes benefit-cost ratios by 24.50/13.80 or a factor of 1.78.

Interpretation of Benefit-Cost Results

Because of the inherent uncertainties, benefit-cost results, like any other calculation, should not be interpreted blindly or in disregard of the uncertainties. Three prospective seismic rehabilitation projects with benefit cost ratios of 0.2, 1.2, and 2.2 are unambiguously distinguishable. Three prospective projects with benefit-cost ratios of 0.95, 1.00, and 1.05 are probably not significantly different. Three projects with

ratios of 0.8, 1.0 and 1.2 may or may not be significantly different, depending on the validity of the input data.

References

Applied Technology Council (1985). Earthquake Damages Evaluation Data for California (ATC-13), Redwood City, CA.

Applied Technology Council (in progress). Earthquake Loss Evaluation Methodologies and Data Bases for Utah (ATC-36), Redwood City, CA.