Benefits and Costs of Earthquake Resistant Buildings*

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I. Introduction

The benefits of constructing earthquake resistant buildings are the savings in property damage, injuries, and lives that accrue in the event of an earthquake. The costs are the additional resources required to ensure that buildings are resistant. In certain regions of the U.S., particularly in California, earthquake resistant buildings are commonplace. As we will show, the cost of adding this resistance to buildings is about seven billion dollars in Los Angeles County alone. The purpose of this paper is to present a methodology for estimating these costs as well as the benefits of resistance. The methodology draws upon the economic approach to valuing risks to life, as well as recent engineering and geological studies of earthquakes and the damage they cause. Our results should be useful both to policy makers concerned with whether the current level of precautions taken to mitigate earthquake losses are adequate, and to economists confronted with evaluating the precautions taken by society against natural hazards in general.

Currently, the level of resistance to buildings in most of California is dictated by seismic building codes. The justification for mandatory codes as opposed to a market oriented

*Research support was provided by a grant from the U.S. Geological Survey entitled "Methods Development for Benefit Cost Analysis of Natural Hazards Information" #14-08-0001-20458. Thanks go to Richard Bernknopf, Robert Williams, Carl Wentworth, Roger Noll, Doug Gegax, Fred Sterbenz, James Murdoch and John Filson for thoughtful suggestions and encouragement. All opinions, conclusions and errors are the sole responsibility of the authors.

approach for protection is tied to arguments about information and efficiency. Most consumers cannot adequately process information about safe versus unsafe structures, and if each consumer had to acquire this information by employing his own expert, there would be much duplication of effort.¹ Seismic building codes are part of the general Uniform Building Code (UBC) [30], and they are probably the most developed institution incorporating earthquake hazards information generated by the scientific community. These provisions have been developed in great part on the basis of ground shaking information and engineering motion studies. The U.S. Geological Survey is the primary federal agency for conducting basic research on earthquake hazards, and the research results are eventually disseminated to professional organizations and local and state governments for planning purposes.²

We do not address the issue of whether or not seismic building codes are the best approach for attaining structural integrity and safety. Without knowing the institutions and consumer behavior that would have developed over the past fifty years under a market approach to protection and in the absence of codes, the efficiency of building codes is indeterminant. Our focus is on the effectiveness of the resistance currently being promulgated by the codes now in place.

Our methodology for estimating the expected benefits and costs of resistance begins with an expected utility model that derives an individual's willingness to pay for the increased safety and reduced property losses afforded by resistance. We recognize in the analysis that the benefits from resistance are of a joint product nature, because buildings resistant to earthquakes are also resistant to wind damage. Because benefits from earthquake resistivity are only realized if an earthquake occurs, knowing the probability of an earthquake is essential.³ The probability of a large damaging earthquake on the Southern San Andreas fault is estimated utilizing a geologic record of past events. We use a Weibull distribution to predict the fault's time-to-failure, given that the last major earthquake was in 1857. Our results show that the expected benefits of resistance will be greater or less than the costs of compliance depending upon the real discount rate used. However, the expected benefits increase every year that an earthquake does not occur, since the probability of an earthquake increases. This is a phenomenon not observed with other natural hazards such as tornadoes and hurricanes. Therefore, this increasing probability has an offsetting effect on the discounting of future benefits. Moreover, the probability distribution implies that for many years after an earthquake, the expected benefits drop sharply below the costs.

A few attempts have been made by engineers to evaluate the resistance of buildings to earthquakes [10; 5; 34]. But they have not used the probability of an earthquake which is essential for a benefit/cost analysis in an expected utility framework. Cohen and Noll [4] take a more sophisticated approach by viewing resistance as a problem in optimal investment planning when returns are risky. They analytically solve for a firm's optimal investment in resistance and compare this with society's optimal investment. They do not attempt to value the benefits of wind resistance or of the increased safety which we derive from the expected utility framework and which we find to be large. In addition, the geological data

1. A more detailed justification for building codes and an interesting account of why codes are sometimes adopted can be found in Oster and Quigley [22].

2. The U.S. Geological Survey runs an Earthquake Hazards Reduction Program designed to develop a "... basic understanding of fundamental seismological, geophysical, tectonic and soil mechanics principles [32, 21]."

3. We do not consider any benefits that might accrue to those individuals having greater peace of mind as a result of resistance.

for Los Angeles which we use to determine the probability of an earthquake were not utilized by them. Our goal is also different in that we take current resistance as given, and then determine whether or not it is justified.

The remainder of the paper is comprised of six sections. In section II, the expected utility framework is used to derive an expression for an individual's willingness to pay for resistance, thus identifying appropriate measures of benefits. The probability of an earthquake is developed in section III, and in section IV estimates are made of the value of property saved and risk to life reduced if an earthquake occurs. Section V contains estimates of the joint benefits from wind resistance, and section VI contains the cost estimates for codes. Finally, in section VII, the expected benefits are tallied using a simulation model, and then compared to costs. Several caveats are also included in this last section.

II. Methodological Basis for Valuing Building Codes

An expected utility theoretical framework for valuing building codes is utilized because benefit-cost analysis is a normative as opposed to positive approach for analysis of public policy issues. We note that the expected utility model has had considerable difficulty as a positive explanation of human behavior both in a laboratory experimental environment and in predicting purchases of earthquake insurance [24; 15]. However, some positive evidence exists that real estate values do capitalize the expected value of potential earthquake damage consistent with expected utility theory [2].

Earthquake resistant buildings provide benefits through reduced property losses and safety. We confine our analysis of safety to preventing deaths only; preventing injuries is omitted. Including injuries would require some changes in our theory, but the primary reason for their omission is the lack of data for our empirics. We will derive an expression for an individual's willingness to pay for the reduced property losses and safety in a static framework, and then aggregate this willingness over all individuals and over time. The following notation will be used:

- P_E = probability of an earthquake;
- P_V = probability of high velocity winds;
- Π = nonearthquake related probability of death;
- C = an index of the stringency of resistance;
- W = initial wealth;
- $\Pi_E(C)$ = probability of death due to an earthquake;
- $D_E(C)$ = dollar value of property losses due to an earthquake;
- $D_V(C)$ = dollar value of property losses due to high velocity winds;
- $U(W)$ = a von Neumann-Morgenstern utility function assumed to be strictly concave (i.e., the individual is risk averse).

Increased stringency of resistance reduces both the probability of death and property losses; therefore, Π_E , D_E , and D_V are decreasing functions of C . We assume these functions to be continuously differentiable with first derivatives $\Pi'_E < 0$, $D'_E < 0$, and $D'_V < 0$.

The individual's expected utility can be written as

$$E(U) = (1 - P_E)(1 - P_V)(1 - \Pi)U(W) + P_E(1 - P_V)(1 - \Pi - \Pi_E)U(W - D_E) \\ + (1 - P_E)P_V(1 - \Pi)U(W - D_V) + P_EP_V(1 - \Pi - \Pi_E)U(W - D_E - D_V) \quad (1)$$

where the function argument C has been omitted, and where the utility associated with nonsurvival is assumed to be zero. The four terms on the right-hand side of (1) represent the four possible states of the world. In order, they are: 1) neither an earthquake nor high velocity wind occur; 2) an earthquake occurs but no high velocity wind; 3) high velocity wind occurs but no earthquake; and 4) both an earthquake and high velocity wind occur. In the second and third states, wealth is diminished by losses attributable to an earthquake and wind, respectively, while in the fourth state wealth is diminished by losses attributable to both an earthquake and wind. We assume the individual takes the stringency of resistance as given; it is not a variable in his choice set.⁴ To derive a compensating variation measure of the marginal willingness to pay for resistance, we hold $E[U]$ constant and totally differentiate (1) with respect to W and C . After rearranging terms this yields:

$$\begin{aligned} dW/dC = & P_E[(P_V U_4 + (1 - P_V)U_2)/\alpha]\Pi'_E \\ & + P_E[(1 - \Pi - \Pi_E)(P_V U'_4 + (1 - P_V)U'_2)/\alpha]D'_E \\ & + P_V[(1 - P_E)((1 - \Pi)U'_3 + (1 - P_E)U'_2)/\alpha]D'_V \end{aligned} \quad (2)$$

where $\alpha = P_E(1 - \Pi - \Pi_E)[P_V U'_4 + (1 - P_V)U'_2] + (1 - P_E)(1 - \Pi)[P_V U'_3 + (1 - P_V)U'_1]$ and where subscripts have been added to the utility function to denote the four states of the world. Equation (2) shows that the marginal benefits due to a change in resistance on the right-hand side (rhs) are offset by the marginal willingness to pay (i.e., to forego wealth) on the left-hand side. The first term on the right side is the marginal benefit from increased safety, and the second and third terms on the right side are the marginal benefits from reduced property losses due to an earthquake and wind, respectively.

In more detail, the first bracketed term on the rhs is the marginal value of safety with regards to the risk of death in an earthquake.⁵ We will denote this marginal value of safety by S , so that the entire safety benefit becomes $P_E S \Pi'_E$. The second bracketed term on the rhs of (2) is approximately equal to one. To see this, we can rewrite this bracketed term, after dropping the subscripts on U , as

$$\begin{aligned} & 1/\{P_E + [1 - P_E]\}\{[1 - \Pi][P_V U'(W - D_V) + [1 - P_V]U'(W)] \\ & [1 - \Pi - \Pi_E][P_V U'(W - D_V - D_E) + [1 - P_V]U'(W - D_E)]\} \end{aligned} \quad (3)$$

which is equal to one if $\Pi_E = D_E = 0$. As Π_E and D_E increase from zero, $[1 - \Pi] > [1 - \Pi - \Pi_E]$ and $P_V U'(W - D_V) + [1 - P_V]U'(W) < P_V U'(W - D_V - D_E) + (1 - P_V)U'(W - D_E)$ by strict concavity of U . These two inequalities are offsetting in the denominator of (3). Therefore if Π_E is small and D_E is small relative to W , the fraction in the denominator of (3) will be approximately equal to one, hence, (3) will also be approximately equal to one. The data provided below support the requirement that Π_E is small and

4. If the individual could choose C to maximize expected utility, then (1) could be rewritten with wealth as a function of codes, $W(C)$. This would reflect the cost of adopting codes with $W' > 0$. Then (1) could be maximized over C , and we could analytically solve for the optimum stringency. However, in this paper our objective is not to determine optimality, but rather to determine whether the benefits of resistance currently enforced in the Los Angeles area outweigh its costs.

5. Early contributions to using the marginal value of safety and willingness to pay approaches for valuing life can be traced to Drèze [6], Shelling [27] and Mishan [20]. See Jones-Lee [13] for recent contributions to valuing human life, Schulze and Kneese [25] for a review of the appropriate concepts in valuing safety, and Violette and Chestnut [36] for a review of the empirical estimates of the marginal value of safety.

that D_E is small relative to W . A similar argument can be used to show that the third bracketed term in (2) is also approximately equal to one. Thus, (2) can be rewritten as

$$dW/dC = P_E S \Pi'_E + P_E D'_E + P_V D'_V. \quad (4)$$

In order to estimate (4) in section IV, we approximate the marginal changes in Π'_E , D'_E , and D'_V by the discrete changes $\Delta \Pi_E$, ΔD_E , and ΔD_V , respectively. These latter values measure the changes in risk and property losses when moving from no resistance to the current level of resistance. For example, $\Delta D_E = D_E(C^*) - D_E(0)$ where the asterisk indicates the current stringency of resistance. Total benefits to the individual are, therefore,

$$P_E S \Delta \Pi_E + P_E \Delta D_E + P_V \Delta D_V. \quad (5)$$

To aggregate these benefits over a population of N individuals, we simply multiply (5) by N . This is valid if the individuals are identical, or if (5) is the average benefit over the population. Finally, the benefits accrue only in the event of an earthquake or high wind, and the probability of these events vary over time. Moreover the useful life of most buildings may be fifty, one hundred, or even more years, and all future benefits must be discounted. Therefore, noting that P_E and P_V are functions of time, we rewrite (5) as

$$\int_0^T e^{-rt} \{P_E(t) [S \Delta \Pi_E + \Delta D_E] + P_V(t) \Delta D_V\} dt \quad (6)$$

where r is a discount rate and T is a future time period designated below. In the following sections, we develop estimates for the benefit terms in (6) for Los Angeles. Of particular importance is $P_E(t)$ which behaves very differently from probabilities associated with other natural hazards.

III. The Probability of a San Andreas Earthquake

As indicated in (6), a critical element in a benefit-cost analysis of earthquake resistant buildings is the estimate of the probability of an earthquake. In our search for the appropriate modeling procedure for estimating the probability of an earthquake, we turned to the theory of plate tectonics. Major earthquakes are explained as sudden movements or ruptures along faults, where faults are the boundaries of the earth's great crustal plates. The San Andreas fault is the boundary between the Pacific Plate and the North American Plate.

The process leading up to an earthquake is one of strain accumulation. At depths of 10 to 12 kilometers, the slippage along the boundary proceeds without the build-up of significant strain accumulation relative to that which occurs in the surface region. There the rocks are brittle and movement along the zone is controlled by friction. Given that the plates are constantly moving, this zone must accommodate slippage or strain accumulates. In the case of the San Andreas fault, the necessary accommodation is 3.5 centimeters per year. Thus, strain accumulates as the geological nature of the surface zone precludes slippage.

Eventually the strain accumulates to the point that a sudden slippage occurs resulting in an earthquake. Models that accurately detail the accumulation of stress *and* predict the exact moment the accumulated strain will be released do not exist. As such, we are unable to learn more about the earthquake function over time.

Thus, the appropriate modeling of the probability of an earthquake involves recog-

nizing the time to failure aspect of the phenomena. That is, given the accumulation of stress, an earthquake will eventually occur. Critical to the prediction of the earthquake is the existence of data that details the recurrence interval of the phenomena.⁶

We confine our procedures for estimating the probability of an earthquake to potentially large ones on the Southern San Andreas Fault, i.e., in the Los Angeles area.⁷ We do not consider other, lesser faults, since the necessary recurrence data is far less developed than the data for the Southern San Andreas. The bias introduced into our analysis by this approach will be an understatement of benefits. Details on estimating the probability of a large earthquake in the Los Angeles area can be found in Schulze et al. [26]. The estimate is based upon evidence documented by Sieh [28] regarding the seismic history of the Southern San Andreas Fault. We present a summary of the results here.

Sieh determined that twelve large earthquakes occurred on the Southern San Andreas over approximately the past seventeen centuries. Given this along with geological knowledge concerning the nature of the fault, statistical failure theory relying upon the Weibull distribution was utilized to estimate the probability of an earthquake. The Weibull distribution has been widely used in connection with the lifetime of manufactured items such as vacuum tubes [14], with biomedical applications such as the time to occurrence of tumors in humans [35], and with economic applications such as labor search models [8] and retirement times for workers in risky careers [1]. The distribution for the Weibull has the form

$$F(t) = 1 - e^{-(\alpha(t-t_0))^\beta} \text{ for } t > t_0 \quad (7)$$

where $F(t)$ is the fraction in a given sample which has failed at time t , α and β are parameters affecting the scale and shape of $F(t)$, respectively, and t_0 is the starting time. The rate at which failure occurs, $f(t)$, is given by the probability density function (pdf)

$$f(t) = dF/dt = \alpha\beta(\alpha(t-t_0))^{\beta-1} e^{-(\alpha(t-t_0))^\beta} \text{ for } t > t_0. \quad (8)$$

Note $F(t) = f(t) \equiv 0$ for $0 \leq t \leq t_0$. Parameters α , β , and t_0 were estimated using a maximum likelihood technique. The estimates are

$$\alpha = .01194, \beta = 1.1128, \text{ and } t_0 = 64.33. \quad (9)$$

The estimated pdf is shown as a solid line in Figure 1 and is interpreted in the following manner. The last major earthquake on the Southern San Andreas occurred at Fort Tejon in 1857 which is time zero on the horizontal axis. Viewed from 1857, the probability of a large earthquake occurring 128 years later in 1985 is approximately .61 percent. However, since a large earthquake has not occurred since 1857, the probability in 1985 is actually greater than .61 percent. Following Bayes's Theorem, the approximate probability of an event in the year T^* , given that no event has occurred prior to T^* , is

$$P_E(T^*) = f(T^*) / \int_{T^*}^{\infty} f(t) dt. \quad (10)$$

This function is referred to as the failure rate function. For the Weibull distribution with β

6. This discussion draws upon R. L. Wesson and R. E. Wallace [33].

7. We define a large earthquake as one with magnitude of at least 8.3 on the Richter Scale. This Scale is logarithmic and it measures the release of energy during an earthquake.

Figure 1

> 1 , the failure rate function is monotonically increasing [16] as shown by the dotted line in Figure 1. The implication is that in 1985, 128 years after the last event, the annual probability of an earthquake on the Southern San Andreas is about 1.29 percent. By the year 2000, 143 years after the Fort Tejon earthquake, if no new earthquake occurs, the probability will rise slightly to 1.32 percent. In order to evaluate the discounted present value of benefits as defined in (6), we will use (10) to estimate the probabilities of an earthquake in years subsequent to our starting year of 1980.

IV. Estimating Property Losses and Lives Lost

Our next step in estimating benefits is to determine the extent to which resistance reduces risk to life during a large earthquake and reduces property losses during a large earthquake or high winds. That is, we must determine $S\Delta\Pi_E$, ΔD_E , and ΔD_V in (6) for N individuals. Considering a large earthquake first, we account for different building categories by re-writing the terms in (6) as follows:

$$NS\Delta\Pi_E + N\Delta D_E = \sum_{i=1}^3 [NS\Delta\Pi_{Ei} + \gamma\Delta D_{Ei}B_i]w_i \quad (11)$$

where

- $i = 1$ for single family structures;
- $= 2$ for public schools;
- $= 3$ for commercial buildings;
- $\Delta\Pi_{Ei}$ = reduced risk of death for the individual in structure category i , $i = 1, 2, 3$;
- γ = an adjustment factor, greater than one, that accounts for reduced losses in buildings' contents;
- ΔD_{Ei} = reduced seismic property losses as a percent of building value for structures in category i , $i = 1, 2, 3$;
- B_i = total value of all structures in category i , $i = 1, 2, 3$;

Figure 2

w_i = proportion of structures in category i , $i = 1, 2, 3$, that are built according to seismic building codes;

and where all other terms are as previously defined. Note that for property losses we consider the total value of all buildings and contents rather than using N and assigning property to each individual.

Reduced Seismic Property Losses

Structural damage to buildings from a large earthquake can range from minor interior and exterior cracks or slight movement off the foundation to a partial collapse of the walls, roof, floors and masonry chimneys. The extent of these damages will depend upon the age of the structure, the construction materials, and upon the intensity of ground shaking.

Single family dwellings, category 1, are predominately of wood frame construction, whereas public schools, category 2, and commercial buildings are usually constructed of materials other than wood. Included in the commercial building category are low-to-medium rise and high-rise office buildings and multi-family dwellings. Generally, the structural design of both single family dwellings and commercial buildings built prior to 1940 make them more susceptible to damage than those built after 1940, owing to the more stringent codes adopted in California following the 1933 Long Beach earthquake. Therefore, in calculating damages, 1940 is used as a dividing line for “old” versus “new” structures. New structures are assumed to meet current seismic codes as defined by the UBC, while old structures are assumed not to meet the UBC.

Figure 2 illustrates expected damages as a percent of single family dwelling replacement value relative to ground shaking intensity in an earthquake. The intensity, plotted on

Figure 3

the horizontal axis, is measured using the Modified Mercalli Scale, which relates ground shaking to its effect on people and structures.⁸ For example, an intensity equal to IX indicates extreme shaking. Figure 3 provides similar information for commercial buildings where the upper bound for expected damages is represented by unreinforced buildings built prior to 1940 and the lower bound of expected damages is represented by reinforced or steel buildings built after 1940. Using an average ground-shaking intensity of VII [21] and subtracting the percent on the pre-1940 curve from the percent on the post-1940 curve yields estimates for single family dwellings (ΔD_{E1}) and commercial buildings (ΔD_{E3}) of 3.5 percent and 7 percent, respectively. The estimates are probably conservative, because the relationship between percent damage and ground shaking intensities becomes nonlinear for higher intensities.

Based on private property data from the Los Angeles County Assessor's Office, the dollar values of single family dwelling units and commercial buildings in Los Angeles County in 1980 are approximately \$103.1 billion and \$73.6 billion, respectively. The proportions of single family dwellings and commercial buildings meeting seismic codes in Los Angeles County are 74 percent and 83 percent, respectively, according to a building inventory conducted by the Federal Management Agency in Los Angeles.

Public schools have received special attention with regards to seismic codes. The 1933 Field Act [7] was an attempt by the state legislature to upgrade safety standards in California public schools. Later the Garrison [9] and Greene [11] Acts increased planning and

8. For example, an intensity equal to VII would mean "Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars."

code enforcement requirements for public schools. For instance, school board members became personally liable for earthquake related damages or injuries due to unsafe conditions in any public school. Furthermore, all buildings which were not brought up to the specifications of the Field Act were to be demolished or rehabilitated and put into uses other than education by June 30, 1977. Thus, effectively all public school buildings in use in Los Angeles County have been brought up to code requirements which are generally stricter than the UBC. For this reason, benefits due to decreased property damage and increased safety are higher per building than for UBC-governed buildings; likewise, the costs of more stringent requirements under the Field Act may be higher for public schools than for single family dwellings or commercial buildings. Based on Mann [19] and the 1981 California Public School Directory [3], a value of \$3.3 billion is used to represent the value of school buildings. The estimate for reduced damages in public schools, ΔD_{E2} , is 49 percent, an average taken from Mann.

Some adjustment for the contents in all building categories must be made. The contents factor adjustment used is $\gamma = 1.53$. This implies that the value of reduced structural damages is inflated by 53 percent to reflect content losses in all building categories [29].

Substituting these data into (11) yields an estimate of the reduction in property losses in buildings and contents in Los Angeles County if a large earthquake occurred on the Southern San Andreas in 1980 relative to a world without resistant buildings. This amount is \$13.11 billion. In 1980 there was a probability of 1.27 percent that a large earthquake would occur; thus, expected 1980 benefits due to decreased property losses were \$166.5 million. Expected benefits for all subsequent years are calculated in Section VI.

Reduced Lives Lost

In order to derive Π_{E1} , Π_{E2} , and Π_{E3} in equation (11), the expected deaths from an earthquake must be known. The risk of death varies with the time of day, since the location of large segments of the population varies over the day. The expected number of deaths per 100,000 population for a large earthquake on the Southern San Andreas is 32.74 if the earthquake occurs at 2:30 a.m. and 141.35 if the earthquake occurs at 2:00 p.m. [29]. At the early morning hour the estimates reflect the fact that two-thirds of the population in Los Angeles County would be in single family dwellings, and about one-third of the population would be in higher risk, multi-family dwellings. For the afternoon period we assume that only 40 percent of the population would be subject to the risk associated with family dwellings, and 60 percent of the population would be found in commercial buildings and public schools.

Adjustments to expected deaths reported above are necessary because the two time periods represent extreme points. These adjustments, which will move the final expected death calculation downward, account for the length of time the population is at various risk levels, the percent of population in single family, multiple family, commercial buildings, and public schools at different times of day, and the percent of population residing in new and old buildings. The population was assumed to be exposed for 16 hours per day to the 2:30 a.m. risk levels and 8 hours per day to the 2:00 p.m. risk. Utilizing 1980 U.S. Census data [31], an allocation of the 7,477, 657 people in Los Angeles County was made between single family dwellings (2/3) and multiple family dwellings (1/3) for the 16-hour period. For the 8-hour period, 40 percent of the population was assumed to be at home and was allocated

Table I. Deaths with and without Resistance

	Deaths, No Resistance	Deaths, Current Stringency of Resistance
Single Family Dwellings	1206 (16.13 / 100,000)	724 (9.69 / 100,000)
Commercial Buildings & Multi- family Dwellings	8359 (111.78 / 100,000)	4312 (57.66 / 100,000)
Public Schools	4252 (56.86 / 100,000)	119 (1.59 / 100,000)
Total	13817 (184.77 / 100,000)	5156 (68.94 / 100,000)

by dwelling category in the same ratio as used for the 16-hour period (i.e., 2/3, 1/3). The 60 percent of the population not at home during the day was allocated between commercial buildings (35 percent) and public schools (25 percent). Furthermore, in public schools the occupants are assumed to be subject to only 10 percent of the 2:30 a.m. risk levels. All of these allocations and assumptions are based upon estimates of risk to life provided in NOAA [21] and Steinbrugge et al. [29]. For lack of data, we did not account for the number of people in transit.

To determine the reduced risk of death due to resistance, we used Figures 2 and 3. We assumed that because earthquake-related building damages at intensity level VII in Figures 2 and 3 are somewhat more than twice as great in old buildings as in new buildings under current resistance, then risk to life would be reduced by slightly more than 50 percent if the same resistance were incorporated in all structures. The estimates of lives lost shown in Table I for single family dwellings reflect this assumption, where lives lost under current resistance have been adjusted upward to account for the presence of some pre-1940 structures. For public schools, the risk to life without resistance is much greater than currently, because all school buildings were brought up to stringent Field/Garrison/Greene Act code requirements by 1980. Subtracting column 2 from column 1 in Table I results in an estimated 482 deaths avoided in single-family dwellings, 4,133 deaths avoided for schools, and 4,047 deaths avoided for commercial structures, for a total of 8,662.

Using a marginal value of safety factor of \$1 million per life saved, the safety benefit in terms of lives saved due to current resistance is \$8.662 billion. The \$1 million per life represents an average value derived from a number of studies on valuing risk [36]. Multiplying by the probability of an event in 1980 of 1.27 percent, the expected value of safety due to resistance for 1980 is \$109.99 million. The expected value of safety for all subsequent years is calculated in section VI.

V. Benefits from Wind Resistance

Though earthquake resistant buildings provide benefits to the population in the form of both reduced property losses and lives saved in the event of destructive earthquakes, additional property and safety benefits accrue from the increased wind resistance provided by

Table II. Expected Present Value of Wind Resistance Benefits in Los Angeles (1980 \$ billions)

Discount Rate	Time Horizon				
	20 Years	40 Years	60 Years	80 Years	100 Years
.02	2.508	4.195	5.331	6.095	6.610
.03	2.304	3.579	4.286	4.677	4.894
.05	1.968	2.709	2.988	3.094	3.133
.06	1.704	2.145	2.258	2.288	2.295

these buildings. In general, wind resistance requirements will be met in Los Angeles County when structures are designed and built in compliance with the seismic building codes. This will not necessarily be the case, however, in other regions of the nation where wind risks exceed earthquake hazards.

The conjunctive benefits attributable to the earthquake resistant buildings are examples of jointly supplied goods [23]. The theory of jointly supplied goods provides a basis for making an appropriate benefit-cost comparison. Summing the benefits of earthquake resistance and of wind resistance in structures will yield the relevant estimate of total benefits. However, total costs will be only those costs associated with implementing the seismic codes.

The benefits for wind resistance are shown in (6) along with the seismic benefits, but the former are developed in a very different manner. We are primarily concerned in this paper with developing the seismic benefits; therefore, we appeal to previous work by Hageman [12] for the wind benefits. Hageman's estimation of wind damages avoided due to earthquake resistance was limited to an analysis of single family dwellings which comprise about 57 percent of total building value in Los Angeles County. Although potential wind damages to commercial structures, especially high-rise buildings, would be substantial without adherence to seismic building codes, lack of data forced this limited estimation. Furthermore, only property losses avoided were estimated; the issue of benefits due to safety (i.e., reduced risk of injury and death) was not addressed.

Using wind speed data from Lew and Hart [18], Hageman estimates a wind velocity frequency distribution for Los Angeles County. Applying this distribution to a wind damage function derived from the work of Leicester et al. [17] yielded an estimate of \$150.4 million in expected annual benefits due to wind resistance in the single family dwellings of Los Angeles County. The present values of expected benefits shown in Table II are calculated by summing annual wind damages avoided in dwellings built to codes using various time horizons and discount rates.

VI. Costs of Earthquake Resistance

Earthquake resistant buildings require such precautionary measures as extra bracing in the structure frame (either cross-bracing or sheathing of the inner walls), extending the studs to the foundation, and extra care and reinforcement in chimney and fireplace construction. In split-level dwellings, extra wide walls are needed in the garage to reduce the possibility of collapse.

No generalized estimates have been published on the increased construction cost due to

building dwellings and commercial structures up to seismic code requirements. Consequently, we obtained a range of cost estimates from engineers and appraisers in California. Construction costs for a single family are increased by approximately 2–3 percent when UBC earthquake codes are met. Because structural requirements under the UBC become stricter with increased building height, adherence to seismic codes is more costly for apartment buildings and many commercial structures. To estimate compliance costs for multi-family dwellings and commercial buildings, we applied a higher factor of 3–7 percent of construction costs. This is probably an over-estimate since the majority of commercial structures are probably not multi-story buildings. (For example, warehouses are frequently large metal buildings with little or no need for earthquake resistant elements in construction.)

A detailed breakdown of actual construction costs for school buildings is provided in Mann [19]. His study evaluates all cost components of a typical one million dollar school facility. Of this, he estimates that at most 5 percent of the total can be allocated to meeting Field Act requirements. Further, Mann states that the more stringent Field Act requirements increase construction costs 1–2 percent over those incurred under normal UBC seismic codes in non-residential buildings, a fact that provides further support for our use of a 2–7 percent range for non-school structures.

Mann reports finding only one Field Act school structure which needed any major repair after an earthquake in over forty years. At most, repairs have amounted to less than 1 percent of replacement cost. However, pre-Field Act schools, many on the same sites as Field Act structures, were severely damaged, with damage ratios of 25–75 percent. This is attributed to the pre-1940 construction of masonry structures with very little reinforcement. As a result, Mann found that bids on rehabilitation costs to bring pre-Field Act schools up to code have ranged from 50 to 75 percent of replacement cost. Frequently, extra costs may run 15–20 percent more than initial bids, since records do not exist on original plans and specifications. Therefore, though we apply a 5 percent factor to the construction cost for Field Act schools, a 50–90 percent factor is used to estimate the cost of bringing pre-Field Act school facilities up to code.

To calculate the cost of seismic codes in Los Angeles County, the factors of 2–3 percent for single family dwellings, 5 percent for Field Act schools, 50–90 percent for pre-Field Act schools, and 3–7 percent for all other buildings were applied to the respective structural values for all buildings which meet UBC requirements. The estimated range for the total cost of constructing earthquake resistant buildings in Los Angeles County amounts to \$5.25 – \$8.91 billion in 1980 dollars.

There are some enforcement costs encountered; however, county officials indicate that the incremental cost of enforcing seismic codes over the cost of enforcing all other building codes is insignificant. Some costs are also omitted. Engineers and geologists have been active over the past five decades in gathering data on earthquake related building damages, and then developing building techniques based on this data.⁹ Further, federal, state, county, and city governments employ geologists and engineers who devote at least part of their time to monitoring seismic hazards and implementing ways of mitigating damages. The costs of these various activities are not well documented, and are not included in the analysis.

9. As an example, Bell Laboratories has an ongoing program for designing earthquake resistance into the telephone system. As part of their program, hydraulic shakes are used to test designs for relays, frames, racks, and other equipment. Public utilities such as electric, gas, and water companies, apply very strict design standards and usually exceed the stringency of the Uniform Building Code by two.

Figure 4

VII. Expected Benefits of Earthquake Resistant Buildings and a Comparison with Costs

Utilizing the probability of a large Southern San Andreas earthquake from section III, the reduced property losses and reduced risk to lives from section IV, the wind benefits from section V, and the resistance costs from section VI, this section contains the expected dollar benefits for various discount rates and compares them to the range of costs. Our approach can be illustrated in Figure 4 which depicts possible future scenarios regarding large earthquakes on the Southern San Andreas fault. Each node in the figure is labelled *E* for earthquake or *NE* for no earthquake. The last large earthquake was in 1857, and from 1858 (year 1) to 1980 (year 123) only *NE*'s appear. The first uncertain year is 1981 where there are two states of the world, the second uncertain year is 1982 where there are four states of the world, and so on. Benefits of resistance are realized only when an earthquake occurs, and to calculate expected benefits, we need to determine the probabilities of being in any of the *E* nodes for each year (i.e., for each row). Note, however, that many of the *E* nodes have probability zero. This follows because once an earthquake does occur, the probability of another occurring over the next $t_0 = 64.33$ years is zero. Consequently, only the solid lines from the 1980 node represent feasible paths.

A Monte Carlo simulation was used to assess the likelihood of following the various feasible paths. The procedure was as follows. For year 124, equation (10) was used to determine $P_E(124)$, the probability of being at the *E* node on the right. Given that the probabilities of being at either the *NE* or *E* nodes sum to one, a random number between zero and one was generated from a uniform distribution. If the random number was less than or equal to $P_E(124)$, the *E* node was realized and the simulation run ended. If the

random number exceeded $P_E(124)$, the NE node was realized and the simulation proceeded to year 125 where (10) was used to determine $P_E(125)$ which is the probability of being at the leftmost E node. From Figure 4, this is the only E node for which a probability needs to be calculated. A random number was then generated and compared to $P_E(125)$ to determine if the simulation should end because an E node was encountered, or if the simulation should continue to year 126. Whenever an E node was encountered, say in year Y , the benefits were calculated as

$$[1/(1+r)^{Y-123}]P_E(Y) \sum_{i=1}^3 [NS\Delta\Pi_{Ei} + \gamma\Delta D_{Ei}B_i]w_i \quad (12)$$

where the first bracketed term is a discrete version of the discount factor and the last bracketed term represents the property losses and lives saved benefit from (11). If the simulation did not encounter an E node after year 174, 50 years from 1980, the run ended and no benefits were realized.

The simulation model was re-run repeatedly and a running average of the benefits was calculated. The running average is itself a random number and has a distribution described by a mean and standard deviation. By the central limit theorem, as the number of simulation runs approaches infinity, the standard deviation of the running average from the 50-year simulation runs approaches zero. Thus, the mean of the benefit estimate becomes more stable. The standard deviation became statistically insignificant after 100,000 simulation runs; therefore, reported results were derived from sets of simulation runs, where each set of 100,000 runs used a different discount rate.

The 50-year time horizon was chosen because expected benefits leveled off after this point owing to discounting. We verified this and our simulation benefit estimates by using an alternative methodology. Referring to Figure 4, until t_0 (64.33) years after 1980, only the leftmost E node has a positive probability of occurring. Write (10) as $P(E = T^* | E > T^* - 1)$ which is the probability that an earthquake occurs in year T^* given that it occurs in some year after $T^* - 1$. It follows that the probability of being at one of the leftmost E nodes in year $Y > 123$ is

$$P(E = Y | E > Y - 1) \prod_{i=1}^{Y-124} P(E > Y - i | E > Y - i - 1) = P(E = Y) / P(E > 123) \quad (13)$$

by Bayes's Theorem. Calculating (13) for each of the 50 years subsequent to 1980, multiplying the result for each year by the appropriate discount factor, then summing these products over the 50 years and multiplying the sum by the savings in property losses and lives lost, yields the same benefits obtained with the simulation. We also carried out this procedure as far as 100 years beyond 1980 while noting that 64 years beyond 1980 other E nodes have positive probabilities. But the added benefits beyond the 50-year time horizon were very small.

Figure 5 summarizes our results. The curves are the benefits which are vertically added so that a point on the top most curve is the sum of benefits associated with wind, safety, buildings, and contents for a particular discount rate stated in real terms, 1980 dollars. The curves illustrate that if a real discount rate of less than 4.5 percent is appropriate, then discounted benefits will exceed the upper bound of estimated costs. At a discount rate of 8 percent, benefits fall below the lower bound of costs. Each year that passes without an earthquake implies that the base year or starting year (1980 in our analysis) for estimating

Figure 5

expected benefits increases by a year. Given the current stringency of resistance, this would result in an upward shift in the upper three curves, since higher probabilities of an earthquake would be associated with each year. Consequently, barring an earthquake, earthquake resistant buildings become more attractive over time.

If an earthquake does occur, then expected benefits decrease substantially and will not approach the costs of resistance until many years after the earthquake. This suggests that immediately following the next large southern San Andreas earthquake, the need for resistance to protect against future earthquakes on this fault will be small. Buildings that are damaged or destroyed could be replaced with less sturdy structures given the recurrence intervals as currently understood and described in section III. It follows that optimum resistance would change over time and become more stringent as the probability of an earthquake increases. Traditionally, however, severe damages from an earthquake inevitably encourage more stringent codes and resistance immediately, as government responds to the outcry of irate citizens.

At the outset, we indicated that our goal is not to determine an optimum level of building resistance by equating marginal benefits and marginal costs. Instead, we have determined total benefits and total costs of the current situation. (See footnote 4.) If optimum resistance differed substantially from current resistance, changing seismic codes would need to be considered along with alternative private market incentives that would encourage such changes. The analysis would then have to account for consumer and builder response to such changes. If sturdier, safer structures are built, there may be a population shift

toward the earthquake prone areas. Conceivably, the new codes or market incentives could result in greater overall losses in an earthquake, since there would be more lives and property to lose.

As in any large-scale, benefit-cost analysis, numerous assumptions outside the realm of economic expertise were made throughout our work. In making these, we adhered to state-of-the-art engineering and geology studies. Over time our assumptions can be improved as society gains unwelcome experience with earthquakes. Two important benefit categories have been omitted from our analysis for lack of data. First is the avoidance of emergency services, clean-up, and the loss of economic activity after an earthquake. Emergency service includes housing for the homeless where approximately .62 percent of the population would be homeless for at least one week [21]. Second, as indicated earlier, is the savings due to reduced risk of injuries which would add substantially to the safety benefits. Including these would increase the benefit estimates and make resistance more attractive.

Finally, we have not addressed the risks associated with many of the other faults in Los Angeles County because of insufficient information on their activity. None of them are capable of generating an earthquake as high on the Richter Scale as the San Andreas. Nevertheless, they can inflict substantial damages, and including them in the analysis would increase the benefits of resistance. Their inclusion would also add more of a spatial aspect to our analysis, since risks would vary with locations. Designing the optimum stringency of resistance may call for locational variations instead of the uniform approach currently used with building codes.

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