SEISMIC DESIGN DECISION ANALYSIS

by

Robert V. Whitman, John M. Biggs
John Brennan III, C. Allin Cornell
Richard de Neufville, Erik H. Vanmarcke

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PREFACE

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R.V. Whitman, J.M. Biggs, J. Brennan III, et al.

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16. Abstract (Limit: 200 words)
This paper describes and illustrates a procedure for organizing into a useful format the information required to arrive at a balance between the cost of earthquake resistant design and the risk of damage and death vs. future earthquakes. The procedure, Seismic Design Decision Analysis (SDDA), is illustrated in the presentation of a pilot application involving buildings of moderate height in Boston. The heart of the methodology is examination, in probabilistic terms, of the damage which one earthquake will cause to a particular building system designed according to a particular design strategy. This evaluation is repeated for different levels of earthquakes, different design strategies, and for different types of buildings. The lateral force requirements for 5- to 20-story apartment buildings in Boston are studied. This paper discusses the results for reinforced concrete buildings. All designs have to resist the wind loading required by the Boston Building Code: 20 psf. Drift requirements under both wind (1/600) and earthquake (1/300) were considered as well as permissible stresses. Five different design strategies were considered. Four of these are the requirements for seismic zones 0, 1, 2, and 3 of the UBC, 1970 edition. The fifth design strategy, designated as superzone S, required forces twice as great as for zone 3.

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Robert V. Whitman,[1] F. ASCE; John M. Biggs,[1] M. ASCE;
John E. Brennan III,[2] M. ASCE; C. Allin Cornell,[3] M. ASCE;
Richard L. de Neufville,[3] M. ASCE; and Erik H. Vanmarcke,[3] A. M. ASCE

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INTRODUCTION

It is generally agreed that a building should be designed so as (a) not to collapse during a major earthquake, and (b) not to incur significant damage from moderate or minor earthquakes. While both of these principles are widely accepted as a basis for seismic design, it is difficult to be precise in their implementation. The second principle clearly implies a balancing of the risk of future loss against the initial cost of providing a stronger building. Even the first principle implies some risk, since the definition of a major earthquake is always a compromise. The earthquake design requirements developed in California have represented a very serious attempt to implement these principles. Engineers used the available facts to recommend a reasonable balance between increased initial cost and risk of future loss, although seldom has the balance been stated in an explicit way.

Recently, the adequacy and appropriateness of these codes has come under questioning. Following the 1971 San Fernando earthquake, many people have suggested that more severe design requirements should be adopted, at least for hospitals and other important public buildings. On the other

[1]Professor of Civil Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts.

[2]Vice President, LeMessurier Assoc. Inc., Cambridge, Massachusetts

[3]Associate Professor of Civil Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts.

hand, there has been considerable local resistance against national pressures to increase earthquake design requirements in eastern parts of the country. Certainly it makes little sense, as suggested in the 1970 edition of the Uniform Building Code (UBC),[4] to require the same level of seismic resistance for buildings in Boston as in Los Angeles. However, it is not immediately clear whether the requirements for Boston should be decreased or whether those for Los Angeles should be increased.

In order to respond satisfactorily to such questions concerning code requirements, it is necessary to have a more explicit procedure for balancing cost and risk. The overall problem has many diverse aspects with complicated interrelationships. Hence, it is essential to have an organized systematic framework for assembling the available facts and for expressing the complex interrelationships. It also is essential to provide clear statements of the costs and risks that are to be balanced.

This paper describes such a procedure, called Seismic Design Decision Analysis (SDDA). While the procedure potentially has a broad range of application, this paper focuses specifically upon building code requirements. To illustrate the procedure, a pilot application is presented involving buildings of moderate height in Boston. The aim of the paper is primarily to present and illustrate the procedure; however, some tentative conclusions concerning design requirements applicable to Boston are indicated.

THE METHODOLOGY

Figure 1 outlines the methodology by means of a flow diagram. The heart of the methodology is examination, in probabilistic terms, of the

[4] The abbreviations used in this paper are listed in Appendix A.

damage which one earthquake will cause to a particular building system designed according to a particular design strategy. This evaluation is repeated for different levels of earthquakes, different design strategies and, where appropriate, for different types of buildings. For each different design strategy, the initial cost required by that strategy is combined with the losses from future earthquakes.

In simplest terms, a particular building system might be defined, for example, as: all buildings having 8 to 13 stores. In a more refined study, a building system might be defined as 8- to 13- story reinforced concrete buildings with ductile moment resisting frames. Other building systems are then defined by different ranges of stories, different construction materials and different lateral force resisting systems.

The simplest statement of a design strategy is: design in accordance with the UBC for earthquake zone 2 (or 0 or 1 or 3). More refined variations on the design strategies may also be considered, such as requirements concerning ductility, allowable drift, mechanical equipment, etc. The initial cost premium is a function of the design strategy. This cost may be expressed, for example, as the extra cost to design for zone 2 requirements as compared to making no provision for earthquake resistance.

One key step is determining the seismic risk. This is the probability that a ground motion of some stated intensity will occur during, say, one year, at the site of interest. Intensity may be expressed by the modified Mercalli scale, or better yet, by the spectral acceleration for the fundamental dynamic response period of the building system.

The effect of ground motions upon the building system is expressed by a family of damage probability matrices (DPM). Each DPM applies to a particular building system and design strategy, and gives the probability that various levels of damage will result from earthquakes of various intensities. By combining seismic risk with the information in the DPM, the probability that the building will receive various levels of damage may be determined. The expected future repair costs may then be determined.

For each damage state, there is an incident loss. Such incident losses include loss of function or loss of time during repairs and, in extreme cases, injury and loss of life and impact on community. In general, not all of the incident losses can readily be expressed in dollars.

If it were possible to express all losses in dollars, then the criterion for selecting the optimal design strategy would be minimum present total expected cost. That is to say, the design strategy would be selected that minimizes the sum of initial cost plus the discounted value of expected future losses. Actually, since future losses can be only partly expressed in dollars, alternate criteria for decision making must be considered.

Any such methodology can only provide systematic and rational information concerning risks and benefits; where building codes are concerned, public bodies must still make the final decision concerning the proper balance between these conflicting considerations. The proposed methodology can never (and should never) be a substitute for judgement and experience, but rather provides for a systematic organization of such experience and judgment.

Criteria for Decision Making

The various steps indicated in Figure 1 will be discussed in more detail in the course of the illustrative pilot application that follows. However, it is necessary to say more at the outset concerning the criteria that may be used in judging the proper balance between cost and risk. With the danger of some over simplification, three approaches to making this judgment may be identified: (a) cost/benefit analysis, (b) risk of death, and (c) multi-attribute decision theory.

In cost/benefit analysis, which has been used for many types of studies for many years, all losses--including fatalities, injuries and social costs --are expressed in monetary units. This means, in particular, that a monetary value must be assigned to human life, and various methods for arriving at this value have been proposed. Application of cost/benefit analysis also requires a decision as to the value of losses that may occur well into the future as compared to the value of costs incurred "now" during construction of a building; this decision generally takes the form of a choice of a discount rate.

There are many difficulties in the practical use of cost/benefit analysis. Many people find it very difficult to accept the notion of placing any sort of value on human life. Yet today communities that impose earthquake design requirements already make such a judgment implicitly. For example, these communities are in effect deciding that it is better to make the owner of a new building pay extra for added resistance to earthquakes instead of contributing the same sum toward a transit system that will reduce highway deaths. It can effectively be argued that cost/benefit analysis, with consistent values assigned to human life and other social costs, may properly be used to choose from among various ways of spending fixed total resources to alleviate the risk of death and suffering.

As an alternative to placing a monetary value on human life, Starr (1969)[5] evaluated the risk of death from various causes. These risks can

[5] References are listed in Appendix B.

be grouped into two general categories: those associated with voluntary activities and those associated with involuntary activities.

In the case of "voluntary" activities, an individual uses his own value system to evaluate his experience, and adjusts (usually subconsciously) his exposure to risk accordingly. There is a general consistency in the average risk associated with every day accidents of various kinds, and these risks appear to represent a societal norm for such voluntary activities. As interpreted by Wiggins and Moran (1970) from Starr's original work, these risks fall in the general range of 10^{-4} fatalities per person-exposed per year. "Involuntary" activities differ in that the criteria and options are determined not by the individuals affected but by a controlling body. The risks from such activities are determined by regulations adopted by governmental agencies in response to public pressures. Starr indicates that the public typically is willing to accept voluntary risks roughly 1000 times greater than involuntary risks. On this basis, Wiggins and Moran suggested that 10^{-7} fatalities/person-exposed/year might be used as a target for seismic design requirements.

Whereas the first two approaches to decision making involved either exclusively monetary units or exclusively lives lost, multi-attribute decision theory strives to evaluate alternatives in terms of several characteristics (de Neufville and Marks, 1974). In simplest terms, this might mean examining the trade-offs between total discounted expected costs (initial cost plus discounted expected future repair costs, but without costs of human life or other social costs) and lives lost. This approach has been used in the M.I.T. study, but will not be discussed in this paper.

Related Studies

Other investigations have used portions of the methodology outlined in

Figure 1: Whitham et al.(1970), Liu and Neghabat (1972), Shah and Vagliente (1972), Jacobsen et al (1973), Steinbrugge and others (USCGS, 1969), Blume and Munroe (1971) and Grandori and Benedetti (1973). As contrasted to these other studies, Seismic Design Decision Analysis combines all of the elements shown in Figure 1, and also strives to assemble detailed, credible data concerning the various elements.

A PILOT APPLICATION

To provide focus for the study, a specific design situation was selected: the lateral force requirements for 5- to 20- story apartment buildings in Boston. While both steel and concrete design were considered in the study, this paper will discuss the results for reinforced concrete buildings. Shear walls were used to resist lateral forces in the transverse direction while longitudinal forces were resisted by moment resisting frames in the exterior walls. All designs have to resist the wind loading required by the Boston Building Code: 20 psf. Drift requirements under both wind (1/600) and earthquake (1/300) were considered as well as permissible stresses. Masonry block walls were assumed for the exterior walls and interior partitions in accordance with usual practice in Boston. Five different design strategies were considered. Four of these are the requirements for seismic zones 0, 1, 2 and 3 of the UBC, 1970 edition. The fifth design strategy, designated as superzone S, required forces twice as large as for zone 3. The question was: which design strategy would be most appropriate?

INITIAL COST PREMIUM

Designs for the five design strategies were carried to the point where costs could be reasonably estimated. As the design lateral forces increased, it in general became necessary to increase the number of transverse shear walls and to increase the size and reinforcing steel for the members of the longitudinal frames. With the zone 0 and zone 1 seismic requirements, wind loading was found to prevail and the designs were structurally identical for these two design strategies. For zones 2, 3 and S, it was necessary to consider the design of joints to permit placement of the reinforcing steel required by the code. For zones 1, 2, 3 and S, it was assumed that the code required reinforcement of the masonry walls and partitions. It was further assumed that the walls and partitions should be isolated from the frames by the amount of the computed wind or earthquake drift, and yet must be able to withstand the lateral forces required by the code for the various zones.

Using the designs, the increase in cost over that for no seismic design (zone 0) was estimated, based upon current experience with the construction costs in Boston. Assuming that the total cost of the building with zone 0 requirements would be $28/sq. ft., initial cost premiums were computed as a percentage of the cost with seismic requirements. The results are given in Figure 2 for three different heights of building.

The increase for the zone 1 design stems from the requirement that masonry walls be reinforced. The further increase for the zone 2 design comes largely from the additional reinforcement to meet the ductility provisions of the code. The additional increase for zones 3 and S reflect the increased member sizes and reinforcement required to resist the increased lateral forces. It should be remembered that the structural system contributes only about one-quarter of the total cost of a building. Hence, the overall percentage increases shown in Figure 2 correspond to much larger percentage increases in the cost of the structural system.

These initial cost premiums are consistent with the very scant literature concerning such costs (SEAOC, 1970).

SEISMIC RISK

The likelihood of ground motions of different intensities was determined using the procedures developed by Cornell (1963).

The first step is to establish a set of source areas distinguished by identifiably different seismic histories and different geology and tectonics. This is difficult to do for the region of Boston, since the causes of past earthquakes are so poorly understood. The earthquake of 1755, which is often cited as the basis for concern about earthquakes in the region of Boston, is believed to have had its epicenter in a source about 50 miles northeast of Boston. Recent studies indicate that the epicentral intensity of this earthquake was about MMI VIII, while the intensity in Boston itself was MMI V or VI on firm ground and MMI VI or VII on poor soil. A large random source is used to represent the background earthquakes not covered by any of the specific sources.

Recurrence rates for earthquakes in each of the sources are based upon a study of the historical record. The ratio of the recurrence rates for earthquakes of two different epicentral intensities is known to be very similar for many different parts of the earth, and this same ratio was found to apply in the Boston region. Thus, the frequency at which moderate or strong earthquakes would be expected in any source area can be estimated from the rate at which small earthquakes are occurring in the source.

It generally is presumed that the character of earthquakes in the northeast states region is such that there are inherent limitations on the epicentral intensity that can occur. Thus, upper bound epicentral intensities as low as MMI VI, VII and VIII were selected for each of the sources. These estimates on upper bounds are perhaps the most uncertain and most controversial part of the entire analysis, as will be seen subsequently.

All of the foregoing information is combined together into an analytical procedure which also incorporates an empirical law giving the attenuation of intensity with distance from an epicenter. This analytical procedure calculates the probability that in any year there will be a ground motion, at the site of interest, equal to or greater than some specified intensity. This result proved to be the same for all locations in Boston and Cambridge.

Figure 3 gives results for several different assumptions concerning various parts of the analysis. Curve 1 represents the best professional estimate of the seismic risk in Boston; this curve is based upon the estimated upper bounds for epicentral intensities for all sources. In computing curve 3, it was assumed that there were no upper bounds to the epicentral intensities in the sources in the vicinity of the epicenter of the 1755 earthquake, but that the estimated upper bounds applied to the other sources. In computing curve 4 no upper bounds were assumed for any of the sources. Curves 3 and 4 represent possible but unlikely interpretations of the seismic risk to Boston. Curve 5 was computed using only the random source with a recurrence rate based upon all historical earthquakes that had occurred anywhere within this source area, and assuming that there is no upper bound to the epicentral intensity. According to these assumptions, an earthquake equal to or larger than the 1755 earthquake is as likely to have its epicenter directly under downtown Boston as at any other point near Boston. This is the most conservative possible interpretation of the seismic history of the Boston region, and in the professional view of the study group staff it is a very unrealistic and unlikely interpretation. Curves 3, 4 and 5 all extend to MMI X, the largest intensity considered, with constant slope.

Curves 1, 3, 4 and 5 all give the intensity for firm ground such as dense glacial till and outcroppings of rock. The historical record for the region of Boston contains ample evidence that damage during historical earthquakes was greater on soft ground than on firm ground. The specific effect of softer ground is still to be analyzed as part of the study. For purposes of this pilot application, it was assumed that soft ground increases the intensity by one unit on the modified Mercalli scale. Thus curve 2 gives the best estimate of the seismic risk for soft ground in Boston.

It is recognized by all earthquake engineers that the modified Mercalli scale is a poor representation of the intensity of ground motion. For SDDA, it would certainly be desirable to utilize a more quantitative measure of intensity based upon some characteristic (such as peak acceleration, peak velocity, spectral acceleration, etc.) of strong ground motion. However, unfortunately there are no strong motion records from the eastern United States and the entire seismic history of this region can be expressed only in MMI. Much of the available information concerning damage during earthquakes also can be related only to MMI. Hence, in this pilot application, MMI has been used as the basic measure of the strength of ground shaking.

DAMAGE PROBABILITY

The general form of the damage probability matrix (DPM) used for this study is shown in Figure 4. Damage to buildings is described by a series of damage states (DS), while the intensity of ground motion is described by the modified Mercalli intensity scale. Each number P_{DSI} in the matrix is the probability that a particular state of damage will occur, given that a certain level of earthquake intensity is experienced. The sum of the probabilities in each column is 100%. There are several reasons why there is a spread in the damage resulting from a particular intensity of ground shaking:

1. Individual buildings, all meeting the same general design requirements, will have different resistances to earthquake damage.

2. The details of the ground motion will differ significantly at different locations all experiencing the same general intensity.

Hence the damage to be expected in future earthquakes must be expressed in probabilistic terms.

Each damage state is defined in two ways: (a) by a set of words describing the degree of structural and non-structural damage, and (b) by a ratio of the cost of repairing the damage to the replacement cost of the building. If the actual cost of damage is known, then the damage ratio (DR) is the best method for identifying the damage state. However, the record of damage during past earthquakes often does not indicate the actual costs of damage, and in these cases the alternate word description must be used to characterize damage states. For the work of the study, the brief one-word damage descriptions appearing in Figure 4 were supplemented by more detailed descriptions.

For many applications, it suffices to replace the full set of probabilities in each column of a DPM by a mean damage ratio (MDR), defined as:

$$MDR = \sum_{DS} (P_{DSI})\ (CDR_{DS})$$

where CDR_{DS} is the central damage ratio for damage state DS. The summation is made over all damage states, and the resulting MDR is a function of MMI. In the few cases where the actual damage ratio (DR) is known for each building a more accurate value of MDR may be obtained by simply averaging the individual DR.

Evaluation of Damage Probabilities

The best way to evaluate damage probabilities is from experience during actual earthquakes. For this reason, a considerable portion of the study has been devoted to documenting the damage (and non-damage) to buildings shaken by the San Fernando earthquake of 1971. Damage ratios were documented for about 370 buildings out of a total of about 1600 buildings having 5 stories or more. Many of these buildings had been built prior to 1933 when the codes contained no requirements for design against earthquakes; many others had been built since 1947 under code requirements similar to those for zone 3 of the current UBC. More complete details of the study are given by Whitman et al (1973a, 1973b).

Several other past earthquakes have also been analyzed so as to develop DPM: the Caracas earthquake of 1967, two earthquakes in Japan during 1968, the damage in Anchorage during the Alaskan earthquake of 1964, the San Francisco earthquake of 1957 and the Puget Sound earthquake of 1965. In all of these cases, only descriptions of the damage, and not actual damage ratios, were available.

The MDR from all of these past earthquakes have been plotted in Figure 5. Most of these earthquakes involved shaking of predominantly concrete buildings. Overall, there is an encouraging degree of consistency, especially since some of the data for MDR are relatively crude and MMI is only a crude indicator of the intensity of ground shaking.

However, the sum total of such empirical data proved inadequate for the purpose of determining DPM for the pilot application of SDDA. The data were especially scant for the higher intensities. Moreover, the empirical data are not necessarily applicable to buildings in a particular city, such as Boston, without further interpretation. Hence, the empirical data were supplemented by theoretical studies (Anagnostopoulos, 1972; Biggs and Grace, 1973; Czarnecki, 1973). The designs described in the section on initial cost premiums were modelled mathematically and dynamic response analyses were carried out. These theoretical studies provided considerable insight into the effect of strengthening a building upon expected dynamic response of the building. The buildings designed without seismic requirements were found to yield at MMI VI. Because strengthening a building also causes stiffening which in turn means greater induced forces during an earthquake, designing for seismic forces led to only modest increases in the intensity of ground motion that would first yield a building (see Figure 6) and in the damage predicted at various intensities.

Theoretical analyses by themselves do not reflect all of the subtle ways in which designing for seismic forces improves the resistance of a building. For example, increasing design forces undoubtedly lead to better details at joints between members, simply because the designer is forced to pay more attention to these joints. Hence, in order to supplement the empirical data and theoretical results, a structural engineering firm from Los Angeles was asked to evaluate DPM for these same buildings, using their subjective judgment.

These efforts led finally to the curves of MDR shown in Figure 5 and the corresponding DPM in Table 1. The reader should keep in mind that these results apply to concrete buildings as they might be designed and constructed in Boston today. By more attention to the detailing of non-structural portions, the damage to buildings at the lower intensities might be reduced. By giving great attention to the reinforcement of shear walls and columns, the probability of great damage and collapse at higher intensities might be reduced.

The total effort of assembling the damage estimates is described by Whitman (1973).

INCIDENT LOSSES

Incident losses include all of the consequences of an earthquake beyond the cost of repairs to the building. These consequences include: damage to building contents, disruption of normal users' activities both during and after the event, injuries, lives lost, cost of rescue and victims assistance operations, impact on local economy and other similar factors. These consequences may be subdivided into those where an economic value may reasonably be assigned (damage to contents, disruption of normal activities), and those where it is very difficult, and perhaps even meaningless, to assign an economic value (loss of life, impact on economy).

As part of the overall study, an attempt was made to ascertain the cost of the first class of incident losses: those to which economic value could reasonably be assigned. A first step was to determine the type of incident loss typically associated with each of the damage states. Toward this end, a set of photographs taken inside buildings affected by the San Fernando earthquake was assembled; the overall damage state for these buildings had already been established. These photographs were shown to engineers and building owners who were then asked to estimate the incident costs suggested by these pictures. Owners and managers of buildings shaken by the San Fernando earthquake were interviewed to determine the actual incident costs, if any. Finally, cost estimates were made by the staff of the study project. All of these efforts led to the incident cost ratios in the 3rd column of Table 2. Except for damage state L, these incident costs are small compared to the repair costs, and hence they were ignored in the subsequent analysis.

In order to make some study of the role of injury and loss of life, experience was used to estimate the fraction of the building occupants who might be killed and injured corresponding to the several damage states. These fractions, which are given in columns 4 and 5 of Table 2, are influenced by a number of considerations: the fraction of the total occupants that are, on the average, present in a building at any time; that collapse may be partial rather than total; and that passersby may be killed and injured by falling objects or by collapse. By using typical data for the cost of an apartment building per occupant, and by assigning values to death and injury ($300,000 per life and $10,000 per injury), the percentages in the last column of Table 2 were determined. This column gives the cost of injury and life lost as a percentage of the replacement cost of a building.

As discussed earlier, cost/benefit analyses incorporating a monetary value on human life are unpalatable to many people. However, it has seemed desirable to pursue this approach at least to the point of seeing its implications. From the results in Table 2, it is evident that the human factor will be of great importance no matter what value one might choose to place on life.

By combining the damage probabilities in Table 1 with the ratios in Table 2, two additional mean ratios may be computed. Table 3 gives the life loss ratio as a function of MMI and design strategy; this ratio is based upon the fractions in column 4 of Table 2. Table 4 similarly gives the total cost ratio, based upon the sum of columns 2 and 6 in Table 2. Each of these two new loss ratios is computed in the same way as the mean damage ratio.

RESULTS

Having assembled all of the necessary information, it is a relatively simple matter to calculate the costs and expected benefits associated with the different design strategies. Calculations have been made using all of of the seismic risk curves in Figure 3. In the computation of the present value of future dollar losses, it has been necessary to assume a discount rate: 5% per year has been used. Where appropriate, an average of the initial cost curves in Figure 2 has been introduced.

Damage Repair Costs

The second column in Table 5 shows the present value of expected future repair costs, expressed as a percentage of the replacement cost of a building, for multi-story reinforced concrete buildings with no design against earthquake forces (i.e., designed for UBC zone 0). Comparing these losses with the initial cost premiums in Figure 2, it may be seen that, even for the most conservative estimate of seismic risk, the net discounted cost (the sum of the initial cost plus the discounted expected losses) is smallest when no seismic design is required. This result is shown in Figure 7.

Total Costs

When the above-mentioned values for human life and injury are introduced, the total discounted expected costs are given ty the 3rd column in Table 5. For the most conservative seismic risk curve, design for UBC zone 3 requirements appears to lead to minimum net cost, as is shown in Figure 7. However, for all other seismic risks the cost of providing seismic resistance is found to increase more rapidly than the reduction in losses brought about by the increased seismic resistance. Of course, this last conclusion would change if a greater value were to be assigned to a human life.

Loss of Life

Table 6 summarizes the computed annual fatality rate for the five seismic risk curves, assuming no seismic design requirements. For comparison, the fatality rate from "normal" accidents and the average earthquake-caused fatality rate for all of California during the present century are also given.

The results in Table 6 suggest that the fatality rate may be unacceptably large, compared to the proposed limit of 10^{-7} fatalities/person exposed/year, for several of the seismic risk curves. This outcome has several possible implications: (a) the involuntary risk acceptable to the public apparently implies a very large value on human life (Grandori and Benedetti, 1973), and (b) the assumption of no upper bounds to epicentral intensities (curves 3, 4 and 5) may be much too conservative.

Recurrence of 1755 Earthquake

The foregoing results are based upon average annual losses. Such results should be meaningful to a person who likes to gamble with long term odds. However, it is also meaningful to ask: what would happen if the 1755 earthquake were to reoccur tomorrow?

This question can also be answered using the information that has been assembled. To make the question more specific, assume that MMI VI occurs on firm ground in Boston. According to the best estimate seismic risk curves in Figure 3, such an intensity might be expected to occur once every 167 to 900 years.

According to Table 3, there is zero probability of loss of life in concrete buildings on firm ground, even if such buildings have not been designed for seismic resistance. However, this same earthquake can be assumed to cause MMI VII on soft ground. Now the mean life loss ratio becomes 10^{-4}. Thus, if 50,000 people are living in multi-story apartments built over soft ground, 5 deaths might be expected on the average--which means that the actual number of deaths in a particular earthquake might range from zero to perhaps 50 or 100. The possibility of these deaths would be entirely eliminated by going to UBC zone 3 requirements.

IMPLICATIONS FOR BOSTON

Each reader should reach his own conclusions based upon his own personal reaction to risk. However, two points should be emphasized. First, in all of this study, it has been assumed that the typical reinforced concrete building has at least a nominal amount of ductility and will not collapse as soon as it starts to yield. A much more pessimistic picture would result if reaching yield point indicated imminent collapse. Second, this paper has introduced the effect of soil conditions in a very crude fashion. Further study may indicate that the effect of poor soil may be greater than increasing MMI by one unit.

The following conclusions of the writers, based upon the work to date, are given here to illustrate the types of conclusions that may be reached using SDDA. First, it appears that normal concrete buildings located on firm ground (and probably on soft ground) in Boston do not need to be designed for seismic resistance. On the other hand, considering the uncertainty in the estimates of seismic risk Boston should not totally ignore the danger of earthquakes. Buildings which may not have nominal ductility, such as buildings using prefabricated elements, buildings with relatively few vertical load carrying members or buildings with unusual shapes should receive special attention. This is particularly true when such buildings are located over poor ground.

CLOSING REMARKS

As stated at the outset, the primary purpose of this paper has been to describe and illustrate a procedure for organizing into a useful format the information required to arrive at a balance between the cost of designing to give earthquake resistance and the risk of damage and loss of lives vs. future earthquakes. The illustration selected involved a particular type of building in a specific city. However, the methodology developed by the study hopefully is applicable to other types of buildings in other locations.

The methodology potentially can be extended to include engineered facilities other than just buildings.

The illustrative example has looked at only part of the earthquake problem in Boston, and has served primarily to indicate the types of conclusions that may be reached by such a study. As has been indicated, SDDA is intended as a tool for engineers, building officials and public bodies, and much more interaction is required with such people before firm recommendations can be given.

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Appendix A

LIST OF ABBREVIATIONS

CDR_{DS}	Central damage ratio for damage state DS
DPM	Damage Probability Matrix
DR	Damage ratio
DS	Damage state
MDR	Mean damage ratio
MMI	Modified Mercalli intensity
P_{DSI}	Probability that intensity I will cause damage state DS
SDDA	Seismic Design Decision Analysis
UBC	Uniform Building Code

Appendix B

REFERENCES

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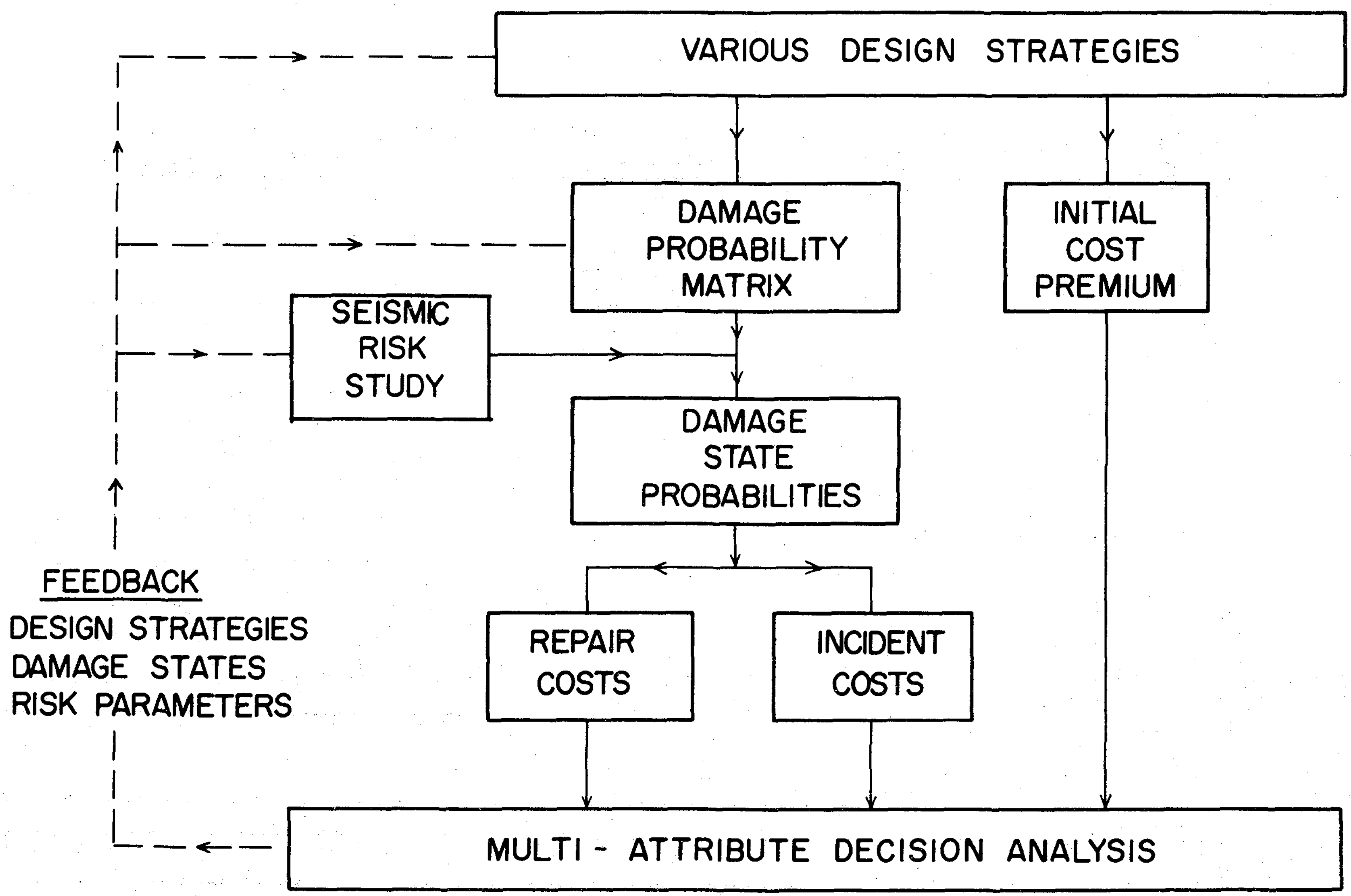

FIGURE 1 FLOW DIAGRAM FOR GENERAL METHODOLOGY

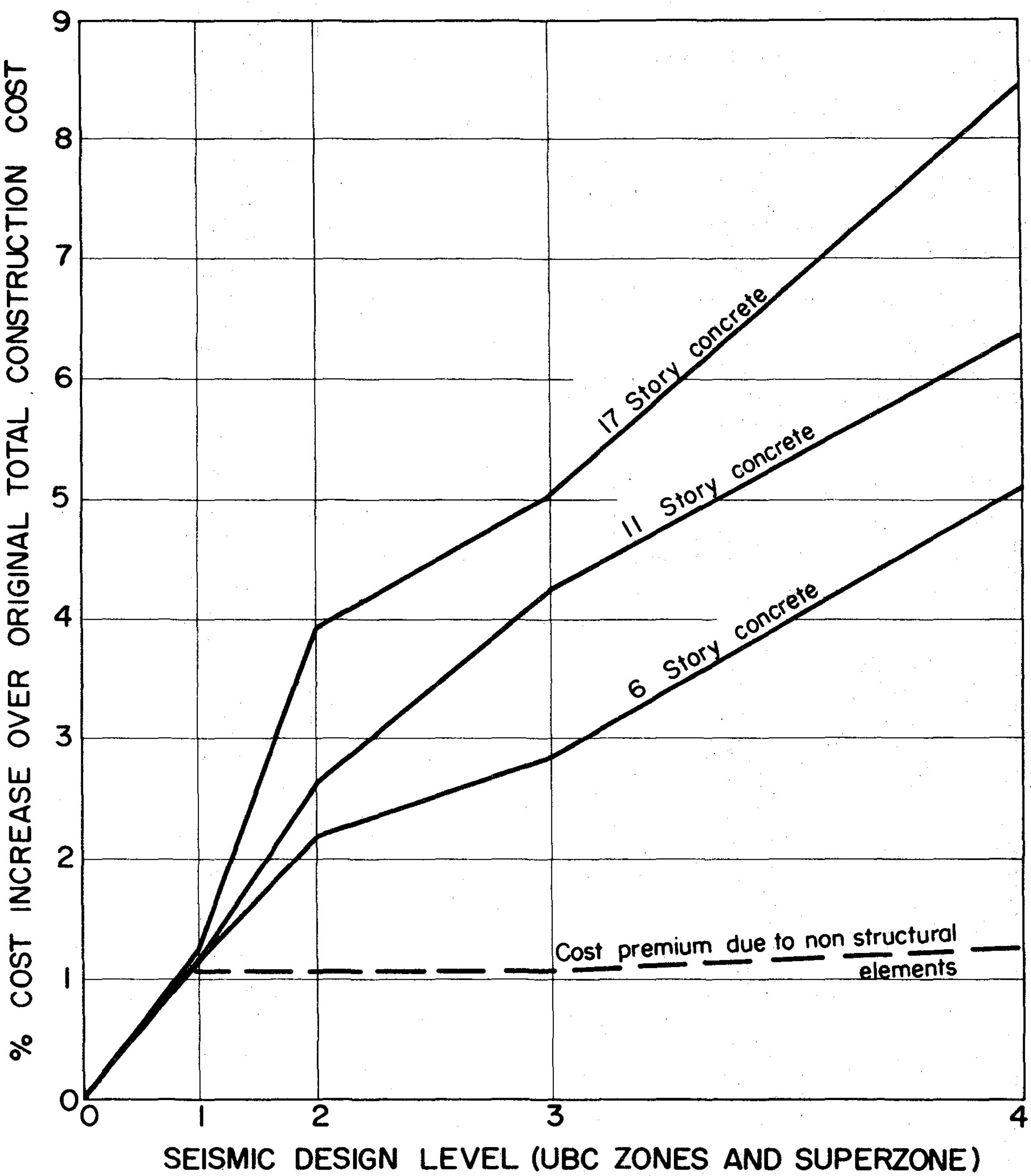

FIGURE 2 INITIAL COST PREMIUMS FOR TYPICAL CONCRETE APARTMENT BUILDINGS IN BOSTON

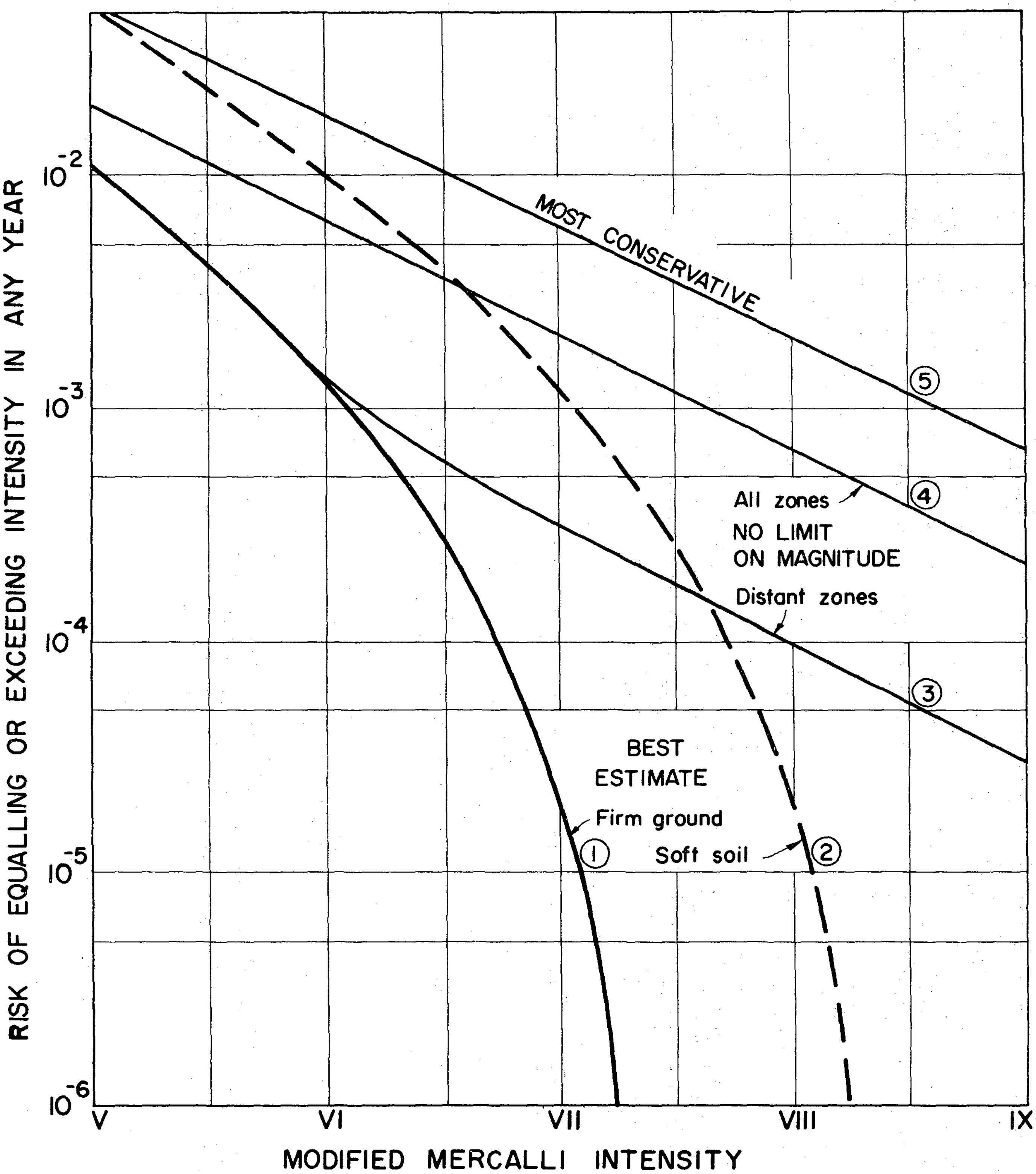

FIGURE 3 VARIOUS ESTIMATES OF SEISMIC RISK IN BOSTON

DAMAGE STATE	CENTRAL DAMAGE RATIO, %	MM INTENSITY				
		VI	VII	VIII	IX	X
O - NONE	0					
L - LIGHT	0.3		P_{DSI}			
M - MODERATE	5					
H - HEAVY	30					
T - TOTAL	100					
C - COLLAPSE	100					

FIGURE 4 FORM OF DAMAGE PROBABILITY MATRIX

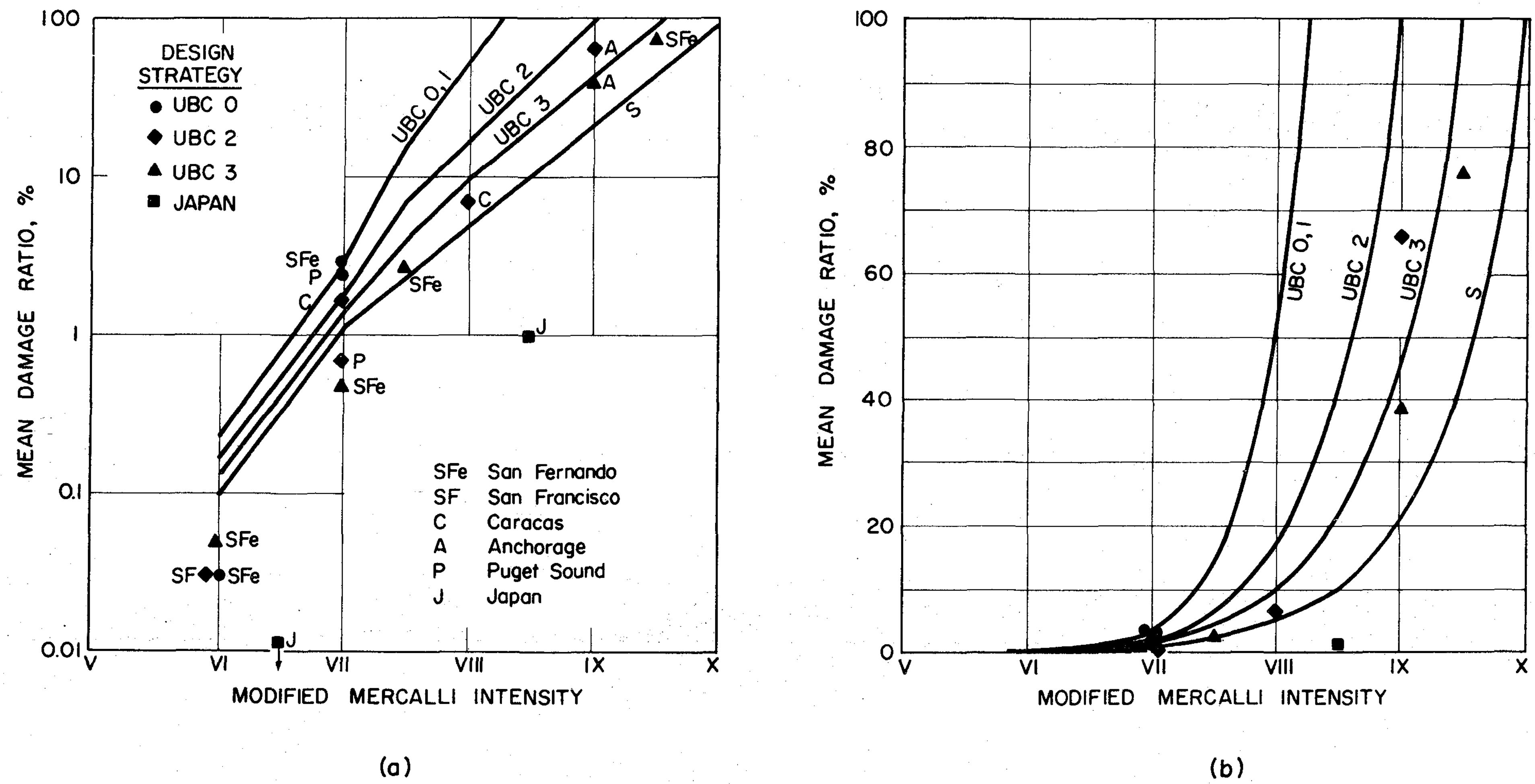

FIGURE 5 MEAN DAMAGE RATIOS FROM HISTORICAL EARTHQUAKES AND CURVES FOR PILOT APPLICATION

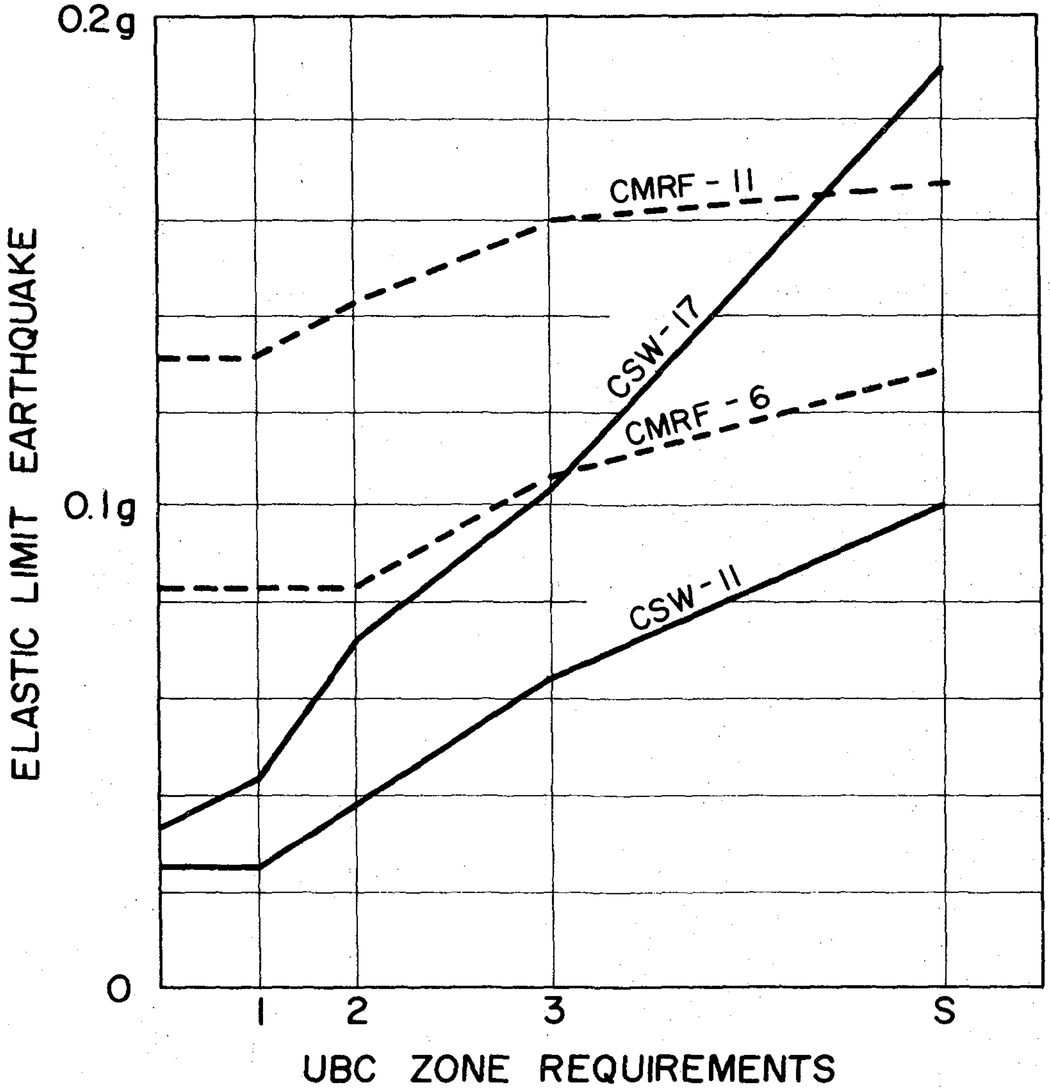

FIGURE 6 EFFECT OF DESIGN STRATEGY UPON INTENSITY OF EARTHQUAKE FIRST CAUSING YIELD

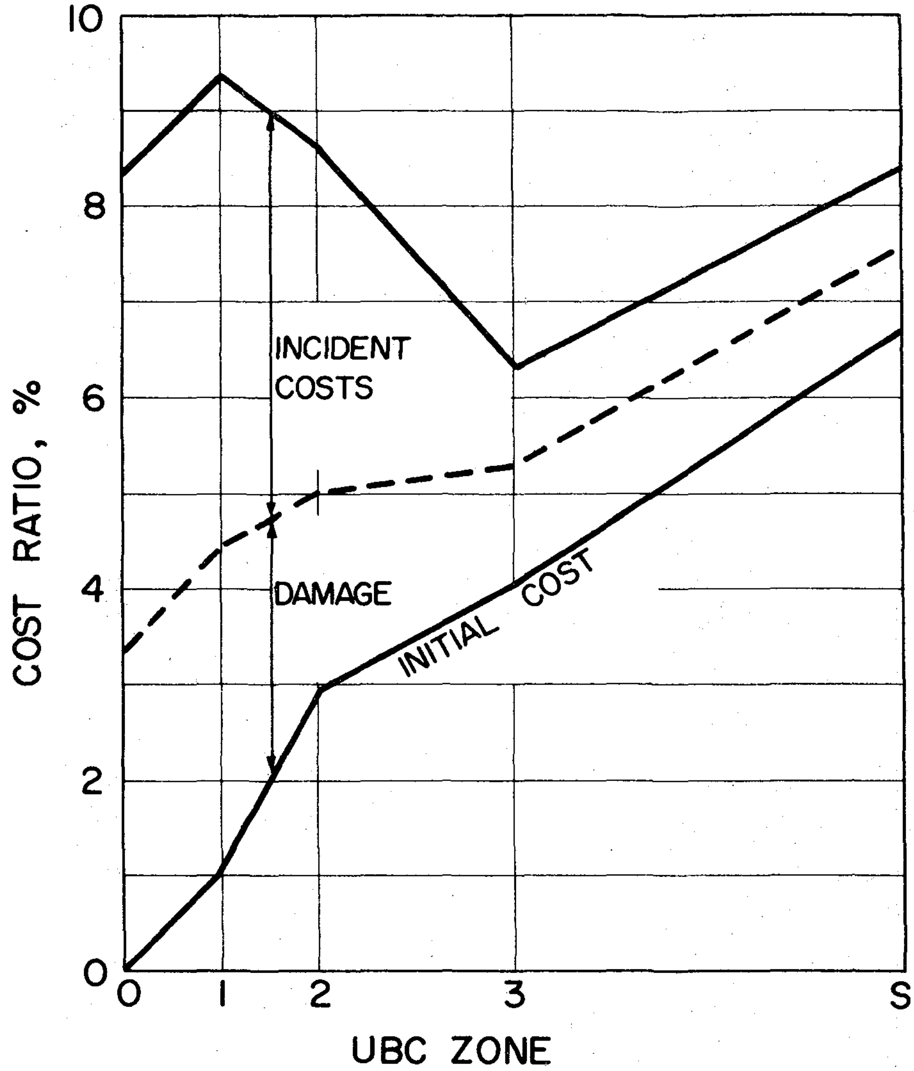

FIGURE 7 COST RATIOS FOR MOST CONSERVATIVE ESTIMATE OF SEISMIC RISK ON FIRM GROUND

Table 1

DAMAGE PROBABILITIES (%) FOR PILOT APPLICATION OF SEISMIC DESIGN DECISION ANALYSIS

Design Strategy	Damage State	MODIFIED MERCALLI INTENSITY V	VI	VII	VIII	IX	X
	O	100	27	15	0	0	0
	L	0	73	48	0	0	0
UBC 0,1	M	0	0	33	20	0	0
	H	0	0	4	41	0	0
	T	0	0	0	34	75	25
	C	0	0	0	5	25	75
	O	100	47	20	0	0	0
	L	0	53	50	10	0	0
UBC 2	M	0	0	29	53	0	0
	H	0	0	1	31	0	0
	T	0	0	0	5	80	60
	C	0	0	0	1	20	40
	O	100	57	25	0	0	0
	L	0	43	50	25	0	0
UBC 3	M	0	0	25	53	20	0
	H	0	0	0	21	52	0
	T	0	0	0	1	23	80
	C	0	0	0	0	5	20
	O	100	67	30	0	0	0
	L	0	33	49	40	10	0
S	M	0	0	21	52	30	0
	H	0	0	0	8	58	0
	T	0	0	0	0	2	90
	C	0	0	0	0	0	10

Table 2

INCIDENT COSTS

Damage State	Central Damage Ratio - %	Incident Cost Ratio - %	Fraction Dead	Fraction Injured	Human Cost Ratio-%
None (O)	0	0	0	0	0
Light (L)	0.3	0.3	0	0	0
Moderate (M)	5	0.4	0	1/100	0.6
Heavy (H)	30	2	1/400	1/50	7
Total (T)	100	3	1/100	1/10	30
Collapse (C)	100	-	1/5	1	600

Table 3

MEAN LIFE LOSS RATIO

Design Strategy	Modified Mercalli Intensity VI	VII	VIII	IX	X
UBC 0,1	0	1×10^{-4}	0.0144	0.058	0.153
UBC 2	0	0.25×10^{-4}	0.0033	0.048	0.086
UBC 3	0	0	6×10^{-4}	0.014	0.048
S	0	0	2×10^{-4}	16×10^{-4}	0.029

Table 4

MEAN TOTAL COST RATIO

Design Strategy	Modified Mercalli Intensity VI	VII	VIII	IX	X
UBC 0,1	2.2×10^{-3}	3.5×10^{-2}	0.95	2.7	5.6
UBC 2	1.6×10^{-3}	2.1×10^{-2}	0.28	2.4	3.6
UBC 3	1.3×10^{-3}	1.5×10^{-2}	0.12	0.85	2.4
S	1×10^{-3}	1.3×10^{-2}	0.06	0.26	1.9

Table 5

EARTHQUAKE LOSSES FOR BUILDINGS DESIGNED FOR UBC ZONE 0[a]

Seismic Risk[b]	Discounted Losses as % of Replacement Cost: Repair Cost	Total Cost[c]
Curve 1	0.0064	0.0064
Curve 2	0.17	0.20
Curve 3	0.17	0.42
Curve 4	1.2	2.9
Curve 5	3.3	8.3

(a) Computed using 5% discount rate (b) See Figure 3
(c) Includes $300,000 per life and $10,000 per injury

Table 6

RISK OF FATALITIES IN BUILDINGS DESIGNED FOR UBC ZONE 0

Risk Situation	Fatalities/person-exposed/year
Auto accidents	3×10^{-4}
Home accidents	10^{-4}
Boston:risk curve 5	8×10^{-5}
Boston:risk curve 4	3×10^{-5}
Boston:risk curve 3	4×10^{-6}
Calif. earthquakes	10^{-6}
Boston:risk curve 2	6×10^{-6}
Involuntary risk	10^{-7}
Boston:risk curve 1	2×10^{-7}