2148 Nat. Haz. (earthquake)

ASCE National Meeting on
Water Resources Engineering

January 21-25, 1974 Los Angeles, California

$0.75

AMERICAN
SOCIETY OF
CIVIL
ENGINEERS
FOUNDED
1852

RISK-BASED SEISMIC DESIGN CRITERIA FOR LIFELINES

Robert V. Whitman

Meeting Preprint 2148

RISK-BASED SEISMIC DESIGN CRITERIA FOR LIFELINES

by

Robert V. Whitman, F. ASCE*

INTRODUCTION

This paper is a plea for a serious, major effort to apply benefit/risk analysis with regard to the anti-seismic design of engineered facilities. The paper discusses the obstacles to use of such analysis, describes in general terms a methodology for such analyses and a pilot application of this methodology to the choice of lateral force requirements for buildings, and discusses some of the problems that must be faced in applying this methodology in the new field of lifeline earthquake engineering.

Application of benefit/risk analysis in earthquake engineering means quantitative evaluation of the benefits to be achieved by more stringent requirements for resistance to earthquakes, and systematic approaches to assembling and portraying this information so that it may be used as a basis for decision-making. In a general sense, benefit/risk analysis is essential to answer the question:

> *Considering the many risks (disease, transportation accidents, natural hazards, etc.) to which people are exposed, what priority should be given at the national (or state or local) level to expenditure of public funds to alleviate the earthquake hazard?

In a more detailed sense, benefit/risk analysis is needed to answer

---

*Professor of Civil Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts.

questions such as:

*Are the present requirements in building codes in various cities (Los Angeles, Boston, etc.) adequate or too demanding?

*What are the relative merits of various approaches (more resistent design, redundancy, more effective disaster responses, etc.) that might be adopted with regard to earthquake engineering for lifelines?

To emphasize that benefit/risk analysis must, to be useful, be oriented toward decision making, the name seismic design decision analysis will be used.

During recent decades, risk oriented criteria have evolved for the design of buildings against earthquakes. The aim of code provisions now in effect in California is to provide structures which will:

*Resist minor earthquakes without damage

*Resist moderate earthquakes without structural damage, but with non-structural damage.

*Resist major earthquakes, of the intensity of severity of the strongest experience in California, without collapse, but with some structural as well as non-structural damage.

These statements clearly imply that buildings designed to modern standards may well be damaged during very large earthquakes; that is, the risk of damage is recognized and accepted. The difficulty in applying these criteria lies in the interpretation of phrases like "minor earthquake." This difficulty is especially troublesome in parts of the country where the earthquake threat is poorly understood. Seismic design decision analysis is aimed at making such criteria more specific.

It must be emphasized that seismic design decision analysis involves much more than just evaluation of the likelihood of earthquake occurrence.

This one part of the problem is often referred to as seismic risk. The recent development of a seismic zoning scheme for Canada (Whitham et al, 1970) illustrates the application of seismic risk analysis. In that study, Canada was divided into 4 zones on the basis of a very thorough and detailed analysis, using probabilistic methods, of past earthquakes. However, the written descriptions of that study suggest that much less effort went into choosing the absolute level of design requirement for each zone.

In addition to study of seismic risk, seismic design decision analysis requires hard-headed quantification of the benefits to be achieved by improved design and of the costs associated with accomplishing these improvements. This is the area in which earthquake engineers should be experts. Moreover, engineers traditionally have the ability to draw together diverse and incomplete information as the basis for decision making. For those reasons, it is imperative that earthquake engineers assume leadership in seismic design decision analysis.

THE VALUE OF SEISMIC DESIGN DECISION ANALYSIS

It really should not be necessary to plea in 1974 to an audience of earthquake engineers for the desirability of seismic design decision analysis. In 1970, the Task Force on Earthquake Hazard Reduction (chaired by Karl V. Steinbrugge) recommended:

> "Realistic cost-benefit studies in terms of earthquake risk should be made on an interdisciplinary as well as interagency basis".

The report of this Task Force (OST, 1970) went on to argue strongly for this recommendation, which was judged potentially to lead to significant short term benefits. The same recommendation has subsequently been repeated by other task groups (e.g. NBS, 1972)

However, progress toward the effective implementation of this recommendation has been modest at best. As has been mentioned, some sophisticated methods have been developed for estimating in quantitative terms the likelihood of strong ground motion (Cornell, 1968; Algermissen, 1972), but such analyses do not be themselves constitute decision analysis. There have also been detailed studies of the effect of ground shaking upon residences (Steinbrugge et al, 1969; Scholl and Farhoomand, 1973), but these studies have not looked into the effect of improved design upon performance. The seiscal risk/ benefit analyses that have been made (Wiggins and Moran, 1970; Liu and Neghabat, 1972; Shah and Vagliente, 1972; Jacobsen et al, 1973; Grandori and Benedetti, 1973) all are ecxellent beginnings, but have employed very simplified approaches and relatively crude input in at least some part of the analyses. The M.I.T. study to be described in a subsequent section also is only a beginning.

There are a number of obstacles in the way of rapid, meaningful progress toward implementation and use of seismic design decision analysis studies.

First, it is very difficult to develop reliable useful benefit/risk models. For example, cost/benefit studies as applied to water resource and flood problems have been under development for many years. Yet, despite all the effort in this area, many people still regard such models to be a poor basis for decision making.

Second, such analyses inevitably involve evaluation of loss of life and other human suffering and social losses. Many people simply are unwilling to accept a design which implies any well-defined risk of loss of life.

Third, risk/benefit studies typically give losses averaged over relatively long periods of time, and provide no guarantee that a large, rare earthquake will not occur within a few years. Many people find it difficult to think in such long range terms, and are more impressed by a description of what might happen during a single large earthquake.

Fourth, many people really are not interested in rational answers to questions concerning priorities on the allocation of funds to mitigate hazards. They frankly prefer the political approach of arguing for "all you can get," and see benefit/risk analyses as an obstacle to their efforts to secure funds to support their particular approach to hazard reduction.

This listing of obstacles does indicate the complexity of the problem and the need for effort at a scale large enough to overcome the obstacles. However, these are merely obstacles and not arguments against pushing ahead to achieve meaningful seismic design decision analyses. The aim of such analyses is not to provide hard and fast answers to questions of public policy, but rather to provide systematic and rational information concerning risks and benefits. Any proposed methodology for seismic design decision analysis can never (and should never) be a total substitute for judgement and experience, but rather provide for systematic organization of such experience and judgement. A major benefit of any benefit/risk analyses is to force a clear statement of objectives and a clear evaluation of the relative costs and benefits of adopting different policies. A large and growing segment of citizens is demanding just such clear thinking and clear information concerning national priorities and allocation of national resources.

GENERAL METHODOLOGY

Figure 1 outlines, by means of a flow diagram, the general methodology for seismic design decision analysis. There are three major types of effort: analysis of the earthquake hazard; quantification of the relationship between design requirements and (a) initial cost of a facility and (b) resistance to damage by earthquakes; and evaluation of all of the costs and losses. The evaluation provides input for decision-making.

Hazard Analysis

As previously mentioned, techniques have been developed during recent years for assembling geological and seismological information so as to estimate seismic risk (Cornell, 1970; Algermissen, 1972). Geological and tectonic information is used to define fault lines or provinces, and the historical record is used to evaluate the recurrence rates for earthquakes of different magnitude along the various faults or within the various provinces. The historical record also is used to evaluate the rate of attenuation of ground shaking away from an epicenter. All of this information, plus measures of the uncertainty in the attenuation law, are combined together to give the overall probability of equalling or exceeding various intensities of ground motion at some location.

Typically, these analyses use a single measure of the intensity of ground shaking, such as peak ground acceleration, peak ground velocity or modified Mercalli intensity (MMI). Generally it is more desireable to work with an objective measure of intensity, such as peak acceleration. However, for most of the country the historical records of earthquakes can only be expressed by a subjective measure of intensity, such as MMI. Moreover, much of the past experience concerning damage to engineered facilities can only be expressed in relation to MMI owing to the absence or scarcity of strong motion records during many important past earthquakes. Hence, in many problems, it is preferable to carry out the anlysis in terms of MMI rather than converting to peak acceleration using some very uncertain correlation between MMI and acceleration.

Design vs. Cost Vs. Damage

This portion of the total analysis evaluates the cost of providing additional seismic resistance and quantifies the beneficial effect of this additional resistance.

Earthquake engineers often say that additional seismic resistance can be achieved with little or no additional cost. It certainly is true that a significant improvement in seismic resistance can often be made by rearranging a structure early in the total design process. However, unless a building already has been designed with considerable conservatism, some penalty must be paid to provide additional resistance. (Even a rearrangement of a building may mean some penalty in esthetic or functional terms!) A 2% increase in the cost of a building becomes significant when it is added up over many buildings.

The beneficial effect of increased seismic resistance may conveniently be expressed by a damage probability matrix (DPM). Figure 2 shows a form of DPM suitable for buildings. The level of damage is described by a series of damage states. Each number in the matrix is the probability that a particular state of damage will occur, given that a certain level of earthquake intensity is experienced. There are several reasons why there is uncertainty in the damage caused by a particular intensity:

1. Individual buildings, from a group of buildings all designed to meet the same requirements, will have different resistances to earthquake damage depending upon the skill and inclination of the individual designer and contractor.
2. The details of ground motion, and hence the dynamic response of identical structures, will differ at different locations all experiencing the same general intensity of ground motion.

Hence damage to be expected in future earthquakes must be expressed in probabilistic terms. A separate DPM is required for each different set of design requirements, and the differences between these DPM quantify the effects of the design requirements.

Evaluation

By combining seismic risk with the information in the damage probability matrix, the probability that a facility will receive various levels of damage may be determined. These results might be expressed in terms of probability per year or probability during the lifetime of the facility. Then it is possible to evaluate the expected future costs and losses.

On one hand, there are the costs incurred to repair damage or to replace buildings that are destroyed. Such costs are readily expressable in monetary terms.

On the other hand, there are other losses that are difficult to express in monetary units. These include loss of function during repairs and, in extreme cases, injury and loss of life and impact on community. These are termed incident losses.

The final step in evaluation is to combine together all of the cost and loss information, in a form useful for decision makers. Several approaches have been suggested:

1. In cost/benefit analysis, all costs and losses are expressed in monetary units. In addition, a discount rate is used to put future losses and initial capital expenditures on the same basis. The results of a cost/benefit analysis may be graphed as shown in Figure 3.
2. As an alternative to placing a monetary value on human life, the risk of death may be evaluated. Starr (1969) has evaluated the risk of death from various natural and man-made hazards. Using Starr's data, Wiggens and Moran (1970) suggested that 10^{-6} to 10^{-7}

fatalities/person-exposed/year might be used as a target for seismic design requirements.
3. Whereas the first two approaches involve 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-off between net discounted expected future repair costs (but without costs of human life or other social costs) and lives lost, as sketched in Figure 4. Techniques have been developed for assessing the preferences of individuals or groups with regard to such trade-offs, and thus assisting decision-makers in their choices.

Different approaches will appeal to different decision makers, and it is necessary to adapt the criteria and measures of effectiveness to the problem being examined.

Discussion

The overall methodology is quite general in its potential applicability, although many of the details must be tailored to the type of building or facility being studied. In particular, the methods of expressing seismic risk and damage probability are problem dependent and also dependent upon the type of evaluation criteria to be used. Hence there must be feedback among the three major areas, as shown by the dashed flow lines on Figure 1.

Good progress has been made in the area of seismic risk analysis, although there are severe limitations stemming from an inherent lack of understanding of the earthquake process. As will be discussed in the final section, it is necessary to make some important extensions to current seismic risk techniques to make them applicable to lifelines.

Much has been learned concerning the resistance of buildings to earthquakes, and there are clear evidences that significant improvements can be made in resistance of buildings to earthquakes. This knowledge must still be expressed in a form useful to seismic design decision analysis, and much work remains to be done in this way. In addition, the engineering behavior of many types of facilities is still poorly understood.

However, the biggest need lies in the area of evaluation. Criteria for acceptability must be developed, based upon experience in applying seismic design decision analysis.

PILOT APPLICATION TO APARTMENT BUILDINGS IN BOSTON

This pilot application considered multi-story apartment buildings, having heights in the range of 5 to 20 stories. The question to be answered was: for which seismic zone of the 1970 Uniform Building Code should these buildings be designed? Thus the lateral forces to be considered in design, and the reinforcement requirements, were varied and the costs and benefits were examined. In all other ways, the buildings were assumed to comply with the Boston Building Code and with common local practice. This application has been described by Whitman et al (1973). It is reviewed briefly here to illustrate the workings of the methodology and the types of conclusions that can be reached through its application.

The seismic risk analysis was carried out in terms of modified Mercalli intensity (MMI), since the seismic history of the region is available only through use of MMI. Figure 5 gives results from the analysis. Curve 1 indicates the best estimate of seismic risk to buildings in Boston founded on firm ground, while curve 2 is a crude, prelimnary first estimate for soft ground. Curves 3, 4 and 5, which extend at constant slope to larger intensities, result from introduction of conservative assumptions. While these curves, especially curve 5, are thought to be unrealistically conservative, they have been included to reflect the great uncertainty as to the true seismic risk in the region of Boston.

As a guide to development of information about design vs. cost vs. damage, a series of "designs" were made for a typical plan arrangement using different structural materials and assuming different story heights. These designs were carried to the point of determining member sizes and reinforcement requirements. Figure 6 presents the initial cost premiums for concrete frame buildings. The abscissa of the chart corresponds to the lateral force requirements for the four seismic zones of the Uniform Building Code. For a new super zone S, defined for purposes of this study, the design lateral forces are twice those for zone 3.

Damage probability matrices were developed using empirical data, theoretical analyses and subjective evaluations (Whitman, 1973). Damage statistics were collected from several different earthquakes, especially the 1971 San Fernando earthquake (Whitman et al, 1973a and 1973b). The "designs" described in the previous paragraph were modelled mathematically, and the dynamic response computed for different gound motions was translated into damage. Engineers from California were asked to review these "designs" and provide their judgement as to the damage probabilities.

Since the study dealt with a large family of buildings, the expected cost of repairing damage could be expressed by the mean damage ratio for each MMI. Figure 7 shows the curves of mean damage ratio that were developed from all of the information described in the previous paragraph. In a similar way, curves of mean life lost ratio as a function of MMI was developed by using the damage probabilities for the most severe damage states (states C, T and H in Figure 2) and the average number of deaths that would occur when typical apartment buildings experience these levels of damage; these results are given in Figure 8. (The curves in Figures 7 and 8 apply only to multi-story buildings in Boston built with conventional framing, and should not be used directly for other types of buildings constructed elsewhere with different types of details.)

All of these results were assembled together into cost/benefit graphs, as in Figure 3, using a discount rate of 5%. In all cases, even considering the most conservative estimate of seismic risk, the cost of providing increased seismic resistance was considerably greater than the expected reduction in repair cost. Thus the analysis clearly indicates that there is no benefit to requiring increased seismic resistance in conventional multi-story apartment buildings in Boston just for the purpose of reducing economic losses.

When the cost of human life was introduced (using $300,000 per life), and the most conservative seismic risk assumed (curve 5 of Figure 5), it was found that design for the requirements of zone 3 of the building code led to minimum net discounted cost. However, with all the other seismic risk curves of Figure 5, total discounted cost was least when no seismic design was required. Apparently, even considering the cost of lost lives, no seismic design requirements are justified for conventional multi-story buildings in Boston unless (a) one is extremely conservative concerning the seismic risk for Boston, or (b) one values a human life at more than a million dollars.

The death risk was also computed. For the seismic risks represented by curves 1 and 2 in Figure 5, this risk was less than 10^{-6} deaths/person-exposed/year. For the other seismic risk curves 3, 4 and 5, this death risk ranged from 10^{-6} to 10^{-4} deaths/person-exposed per year. These latter death risks are high, and reflect both the conservatism of the conventionally accepted risk limit of 10^{-6} deaths/person-exposed/year and the extreme conservatism of the risks curves 3, 4 and 5.

The analysis also indicates that a repeat of Boston's 1755 earthquake might cause some deaths from partial or total collapse of conventionally-framed multi-story apartment buildings constructed over poor ground. This risk was estimated at 10^{-4} deaths/person-exposed/year.

These results must be interpreted in the light of one's own personal reaction to risk. To illustrate the type of conclusion that may be reached from seismic design decision analysis, the writer's personal, tentative interpretations are:

1. For multi-story buildings in Boston with conventional framing, and hence with at least nominal ductility, the type of seismic design requirements specified by the Uniform Building Code (other than anchoring parapets, etc.) apparently are not justified.
2. Special design attention should be given to buildings of unusual shape or with unusual construction, especially if built over poor soil conditions, to ensure that they will develop at least nominal ductility.

These conclusions imply that the writer is willing to risk some earthquake-induced loss of life, preferring to see funds that would be required to provide special resistance in conventionally-framed buildings spent in reducing other risk to life. Such conclusions, which may be modified after further study, are in effect a reinterpretation to Boston's situation of the general design guidelines listed in the introduction.

APPLICATION TO LIFELINES

Lifeline earthquake engineering deals with the design of utility, transportation and communication systems to withstand the effects of earthquakes. Precisely because earthquake engineering of lifelines is still in its infancy, it is especially important to use seismic design decision analysis to guide the effective development of this new discipline. Lifeline systems are large and expansive, and it is essential that money spent to increase the seismic resistance of lifelines be used efficiently. A balanced approach to design criteria is particularly important for regions where the seismic risk is not as great as in California.

This section will discuss some of the potential uses of seismic design decision analysis for lifelines, and some of the developments that are essential before this potential can be realized. Efforts along these lines are underway, but at a very preliminary level.

Design Alternatives and Overall Objectives

The potential design alternatives are much broader in scope for lifeline systems than for buildings. Not only is it possible to make individual components (bridges, dams, pipelines, etc.) more resistant, but it is possible to introduce redundancy into a system so that failures of one link in a system does not necessarily mean failure of the entire system. For gas lines where escaping gas is a potential hazard, shut-down valves might be used to limit the extent and duration of the hazard. Finally, organizing to provide temporary and permanent restoration of service is an important part of the overall design of any lifeline.

As was noted in the introduction, general risk-oriented design guidelines have evolved in the case of buildings; e.g. the largest earthquake may cause damage but should not cause a failure that might lead to death. As yet, similar clearly stated guidelines have not yet emerged with regard to lifelines. It is essential that such guidelines be developed as soon as possible, even though they will inevitably be changed and refined as time passes.

One general concept adapted from design of buildings will also apply to lifelines: during the largest earthquake there may be damage but there should be no failure that will endanger lives. This principle applies to

water storage structures in developed areas, to large bridges and perhaps to gas pipelines. There still is the problem of what is meant by the "largest earthquake," especially in the less seismic portions of the country. As with buildings, use of this principal will imply some small risk of death, and it will be important to recognize and gain general acceptance for this level of risk.

However, it is easy to envision many failures of lifelines that will cause great human suffering and economic loss even though the direct risk of death is very small. Perhaps the best example is loss of water for fighting fires and the attendant possiblity that a rapidly spreading fire might develop. Other examples are: interruption of local traffic networks required for rescue and relief; blockage of major transportation facilities required for bringing in supplies; loss of drinking water and attendant sanitation problems, etc. It probably is not feasible to design lifeline systems to as to prevent all such failures anywhere in a system, and guidelines are needed to indicate acceptable levels of failure.

Table 1 is an attempt by the writer to suggest, mainly for the sake of argument, a possible set of guidelines. Several words of explanation are necessary.

* It is difficult to provide a simple definition of "major" and "moderate" earthquakes, precisely because a lifeline system extends over a large area. At this stage it is not clear which type of earthquake might be more damaging to lifelines; a very large earthquake at moderate distance which might have a moderate effect on a large part of the system, or a moderate earthquake with a very intense effect upon a a small part of the system.

* It seems impractical to prevent all loss of service during a major earthquake, and even during a moderate earthquake. This leads to concept of acceptable loss of service. The service lost during a major earthquake might be restored in several stages, with minimal necessary service restored quickly and full service over several months. As an easterner, the writer might liken the acceptable loss of service during a moderate earthquake to that which occurs during a bad ice storm.

Undoubtedly all or part of these criteria are unobtainable, and the types of criteria may represent wrong thinking. The writer hopes that the ensueing panel discussion will lead to an acceptable version.

Evaluation: Measures of Effectiveness

In the pilot application of seismic design decision analysis to buildings, only death risk and net discounted cost were used as measures of the effectiveness of seismic resistance. Clearly additional measures of effectiveness will be needed in the case of lifelines, so that the analysis will truly involve multiple-attributes. Possible additional measures might be:

1. For utility systems, the product of the number of families without service and the days without service.
2. For transportation systems, some measure of transit time between points. (The same sort of analysis used to study the value of a new link in a highway system should be useful for studying the effect of losing a link.)

Since different levels of service are needed immediately following an earthquake and in the longer range recovery period, different measures of effectiveness may be needed for different time periods.

The ensueing panel discussion might profitably address itself to recommendations concerning appropriate measures for evaluating the effectiveness of design alternatives.

Seismic Risk

For the pilot application of seismic design decision analysis to buildings in Boston, seismic risk could be expressed in terms of the level of ground motion which might occur at a single point. Given the apparent nature of the earthquake threat to Boston, the same seismic risk applies to all points within the city having similar soil conditions, and hence to the entire family of buildings built over such soils. On the other hand, a lifeline system is spread over a considerable geographical area and different seismic risk generally apply to different parts of the area. Moreover, the overall risk to the entire system will depend upon the nature of the system.

To illustrate these ideas, consider the several types of lifeline systems shown in Figure 9. With the series system, a failure in any part of the system prevents all through-flow, although access is still possible from each end. If two different links fail, then a part of the system is completely isolated. With a parallel system, it is possible for only a single link to fail and thus for through-flow to continue although with reduced efficiency. With a network system, the overall impact on the system will depend very much upon how many and which links fail. Work is underway at M.I.T. to extend Cornell's seismic risk model to these various types of situations. For some lifeline systems, it will be necessary to include the possibility of damage by fault displacement as well as damage by ground shaking (Jacobsen et al, 1973).

Damage States

New forms of damage states must be developed for lifeline systems.

For buildings, the damage states were selected to reflect the cost of repair and the likelihood of death or injury. For lifelines, damage states must be chosen with an eye toward the effect of damage to the overall performance of the system.

Once damage states are defined, then the effect of design strategies upon expected performance must be quantified by estimating damage probability matrices or other suitable expressions of expected response to earthquakes. Although there has been considerable study of the damage to dams, bridges, electrical equipment, etc., considerable effort will be needed to convert the available information into damage probability matrices and there will be significant gaps to be filled by further research.

CONCLUSIONS

As a major effort is launched in the area of lifeline earthquake engineering, a high priority must be given to the establishment of general design guidelines. To achieve an equitable balancing of expenditures to mitigate the effects of various natural and man-made hazards, these guidelines must be based upon careful consideration of the risks involved and benefits to be expected. It is not enough to examine only the risk of earthquake occurence, it is also essential to use realistic quantitative appraisals of the change in expected performance as a result of changed designed requirements and of the initial cost of meeting such requirements. Many diverse facts and criteria must be considered, and there is need for a systematic organization and processing of such information. Such a systematic approach has herein been referred to as seismic design decision analysis. Analyses of this type will not give hard and fast answers, but will provide a systematic basis for making judgements and decisions, and use of such analyses clearly is in the spirit of "20/20 Planning for the Year 2020".

ACKNOWLEDGEMENTS

This study has been supported by the National Science Foundation through Grants GK-27955 and GI-29936. Co-principal investigators for the study are Profs. J. M. Biggs, C.A. Cornell and the writer. Numerous faculty, staff and students, and several engineering firms in Massachusetts and California, have made contributions to the study, and their efforts are gratefully acknowledged.

REFERENCES

1. Algermissen, S. T., 1972: "The Problem of Seismic Zoning", Building Practices for Disaster Mitigation, U.S. Dept. Commerce, National Bureau of Standards, Building Science Series 46, pp. 112-125.
2. Cornell, C. A., 1968: "Engineering Seismic Risk Analysis", Bull. Seismological Soc. America, Vol. 54, No. 5, pp. 1583-1606.
3. deNeufville, R. and D.H. Marks, (eds.), 1974: Systems Planning and Design: Case Studies in Modelling, Optimization and Evaluation, Prentice-Hall, Inc.
4. Grandori, G. and D. Benedetti, 1973: "On the Choice of the Acceptable Seismic Risk", Int. J. Earthquake Engineering and Structural Dynamics, John Wiley & Sons, Vol. 2, No. 1, pp. 3-10.
5. Jacobsen, S. E., M. Torabi and P.P. Bansal, 1973: "On the Consideration or Risk in Water Resource Systems", in Optimization of Water Resource Systems Incorporating Earthquake Risk: 1973 Contributions, Universtiy of California Water Resources Center Contribution No. 141.
6. Liu, S. C. and F. Neghabat, 1972: "A Cost Optimization Model for Seismic Design of Structures", The Bell System Technical Journal, Vol 51, No. 10, pp. 2209-2225.
7. NBS, 1972: Building Practices for Disaster Mitigation, U.S. Dept. Commerce, National Bureau of Standards, Building Science Series 46.
8. OST, 1970: Earthquake Hazard Reduction, Report of the Task Force on Earthquake Hazard Reduction, Executive Office of the President, Office of Science and Technology.
9. Shah, H. C. and V. N. Vagliente, 1972: "Forecasting the Risk Inherent in Earthquake Resistant Design", Proc. Int. Conf. on Microzonation, University Washington, Seattle, Vol. 11, pp. 693-718.
10. Scholl, R. E. and I. Farhoomand, 1973: "Statistical Correlation of Observed Ground Motion with Low-Rise Building Damage", Bull. Seismological Society America, Vol. 63, No. 5, pp. 1515-1537.

11. Starr, C., 1969: "Social Benefit vs. Technical Risk", Science, Am. Assoc. Advancement Science, Vol. 165, September, pp. 1232-1238.

12. Steinbrugge, K. V., F. E. McClure and A. J. Snow, 1969: Appendix A to Studies in Seismicity and Earthquake Damage Statistics, 1969, U. S. Dept. Commerce, Coast and Geodetic Survey.

13. Whitham, K., W. G. Milne and E.E.T. Smith, 1970: "The New Seismic Zoning Map for Canada, 1970 Edition", The Canadian Underwriter, June 15.

14. Whitman, R. V., 1973: "Damage Probability Matrices for Prototype Building", Seismic Design Decision Analysis Report No. 8, M.I.T. Dept. of Civil Engineering.

15. Whitman, R. V., S.-T. Hong and J. W. Reed, 1973a: "Damage Statistics for High-Rise Buildings in the Vicinity of the San Fernando Earthquake", Seismic Design Decision Analysis Report No. 7, M.I.T. Dept. of Civil Engineering Research Report R73-24.

16. Whitman, R. V., J. W. Reed and S. -T. Hong, 1973b: "Earthquake Damage Probability Matrices", Proc. 5th World Conf. Earthquake Engineering, Paper No. 321.

17. Whitman, R. V., J. M. Biggs, J.A. Brennan II, C. A. Cornell, R. L. de Neufville and E. H. Varmarcke, 1973: "Summary of Methodology and Pilot Application", Seismic Design Decision Analysis Report No. 9, paper presented to Am. Soc. Civil Engineers Annual Meeting, New York City, M.I.T. Dept. Civil Eng. Research Report R73-58.

18. Wiggins, J. H., Jr. and D. F. Moran, 1970: "Earthquake Safety in the City of Long Beach Based on the Concept of Balanced Risk", report by J. H. Wiggins, Co., Redondo Beach, Calif.

Table 1

POSSIBLE GENERAL DESIGN GUIDELINES FOR LIFELINES

(for sake of discussion)

CATEGORY OF LIFELINE		MAJOR EARTHQUAKE	MODERATE EARTHQUAKE
		Intense ground motion or faulting in some part of system.	Moderate ground motion in some part of system.
WATER SUPPLY	Water storage reservoir	No failure that will endanger lives	No damage
	Local sources of water for fire-fighting	Adequate supplies remain available	Damage Level B
	Distribution systems	Damage Level A^1	
HIGHWAY SYSTEM	Bridges, overpasses	No collapses	No structural damage
	Roadways	Damage Level A	Damage Level B
ELECTRICAL SYSTEM		Damage Level A	Damage Level B
GAS SYSTEM		Damage Level A, but no contribution to fires	Damage Level B

Damage level A: No more than 20% of area without service; service fully restored within one month (within one week for damage level A^1).

Damage level B: No more than 1% of area without service; service fully restored within hours.

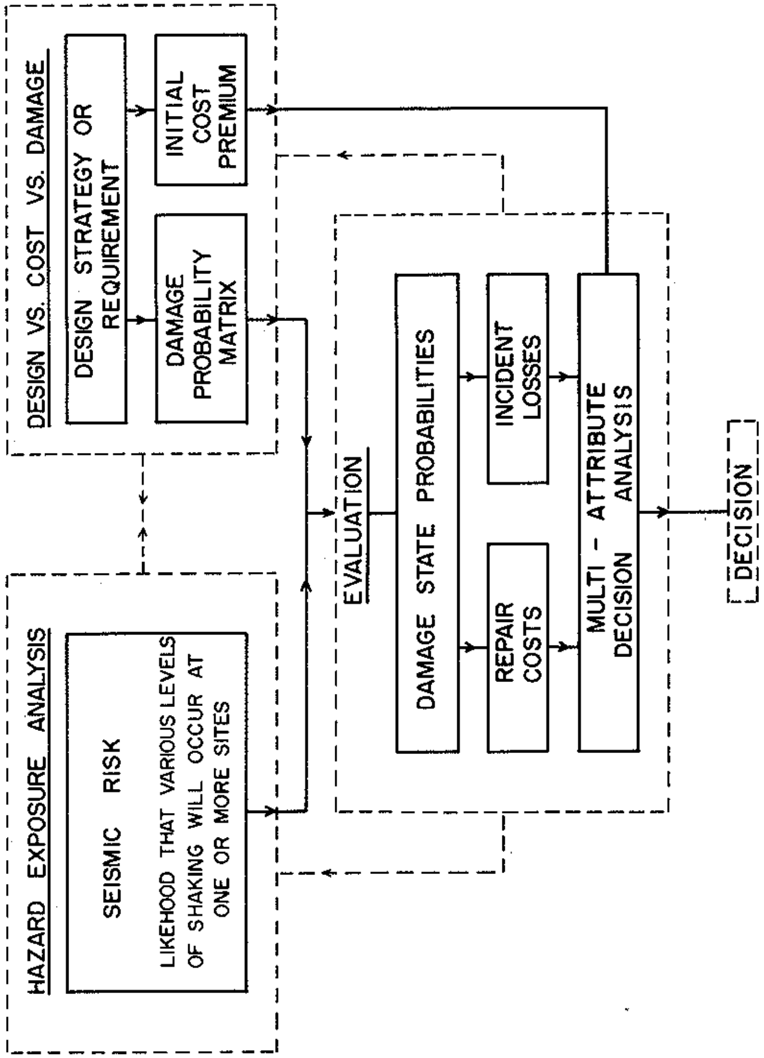


FIGURE I FLOW DIAGRAM FOR GENERAL METHODOLOGY

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 2 FORM OF DAMAGE PROBABILITY MATRIX

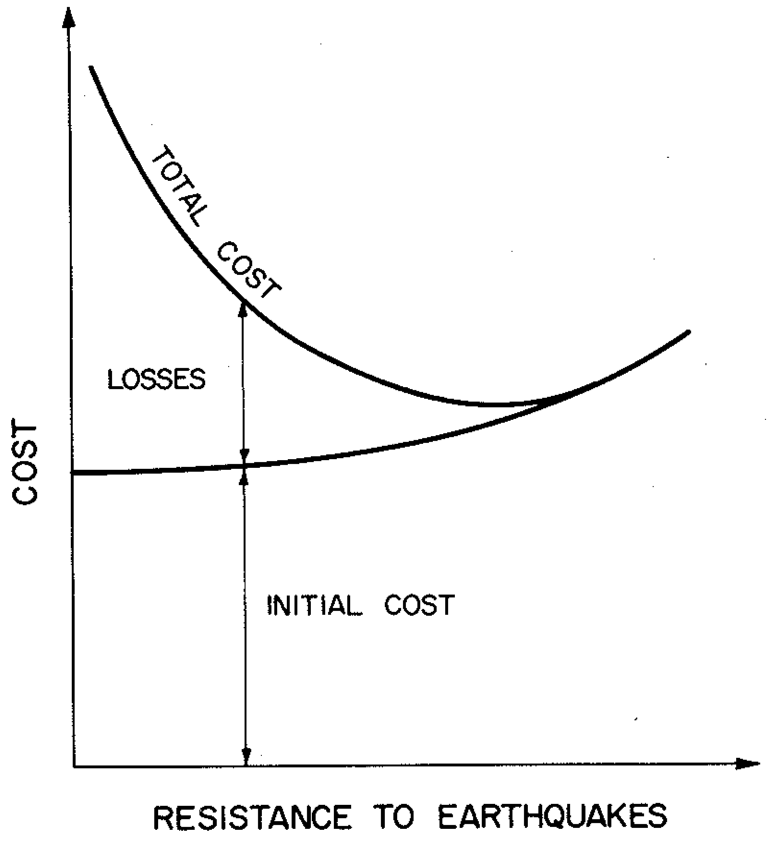


FIGURE 3 COST / BENEFIT ANALYSIS

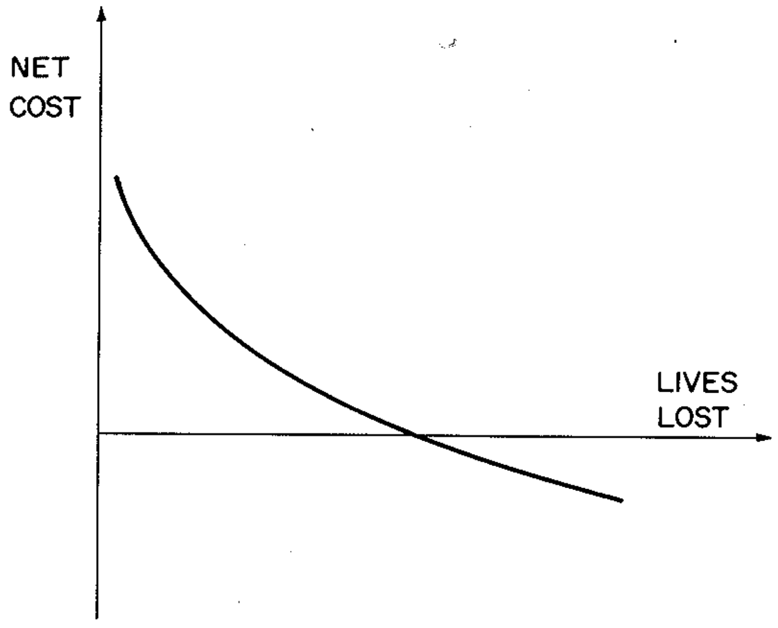


FIGURE 4 TRADE - OFF BETWEEN MULTIPLE OBJECTIVES

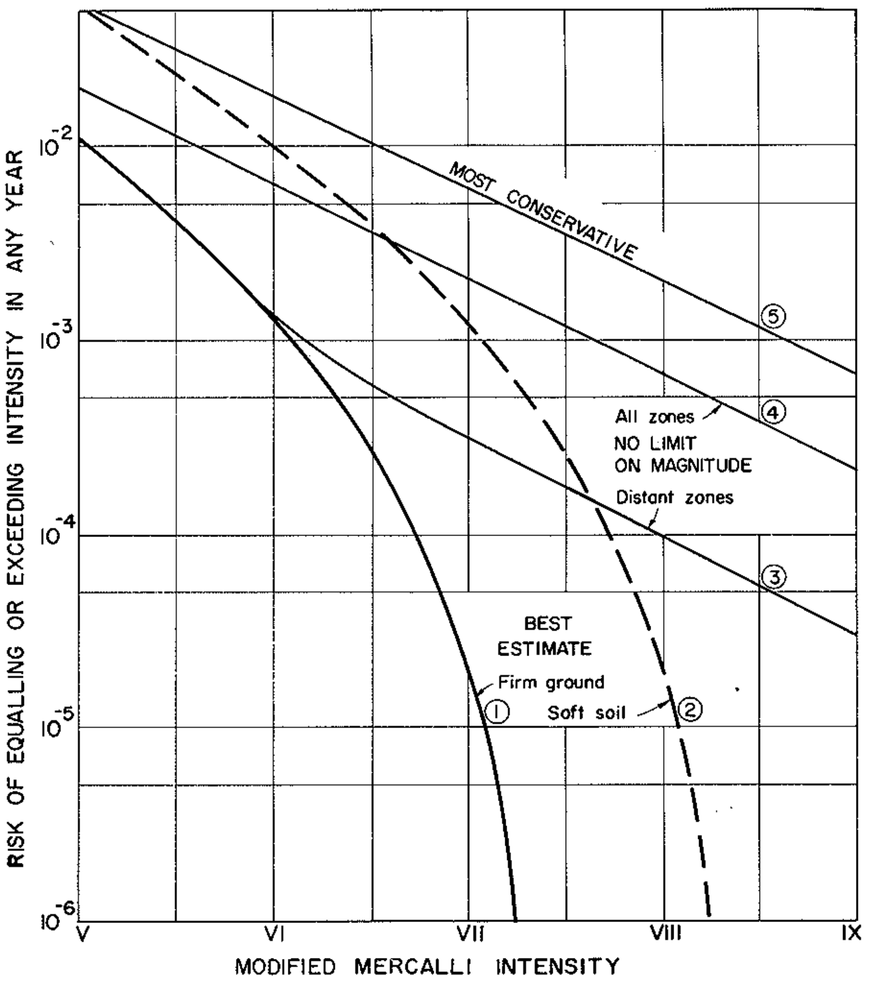


FIGURE 5 VARIOUS ESTIMATES OF SEISMIC RISK IN BOSTON

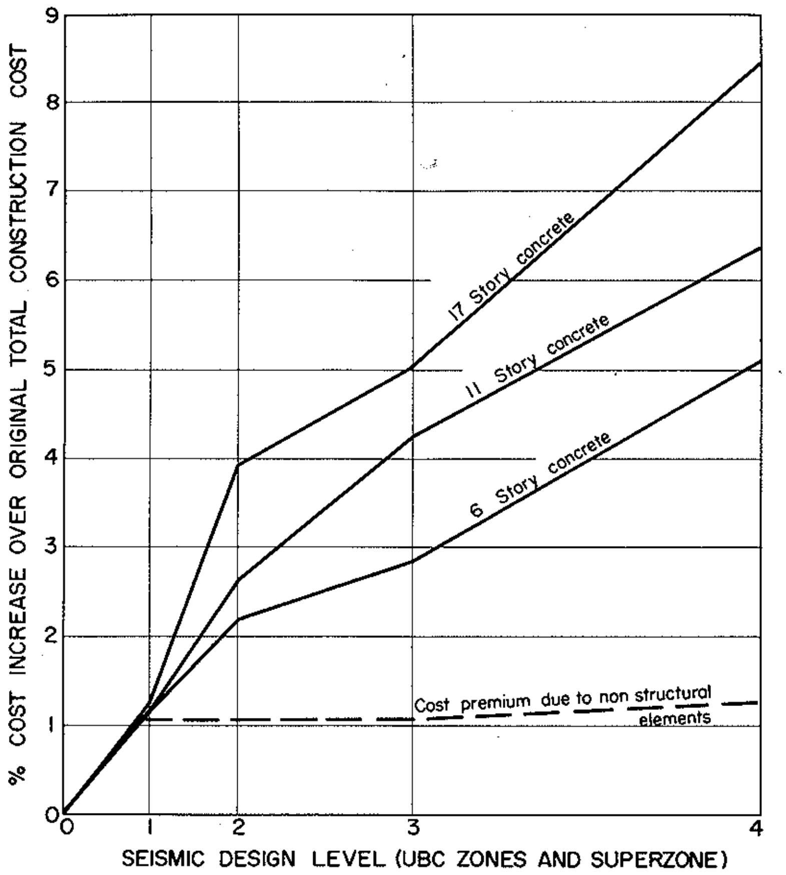


FIGURE 6 INITIAL COST PREMIUMS FOR TYPICAL CONCRETE APARTMENT BUILDINGS IN BOSTON

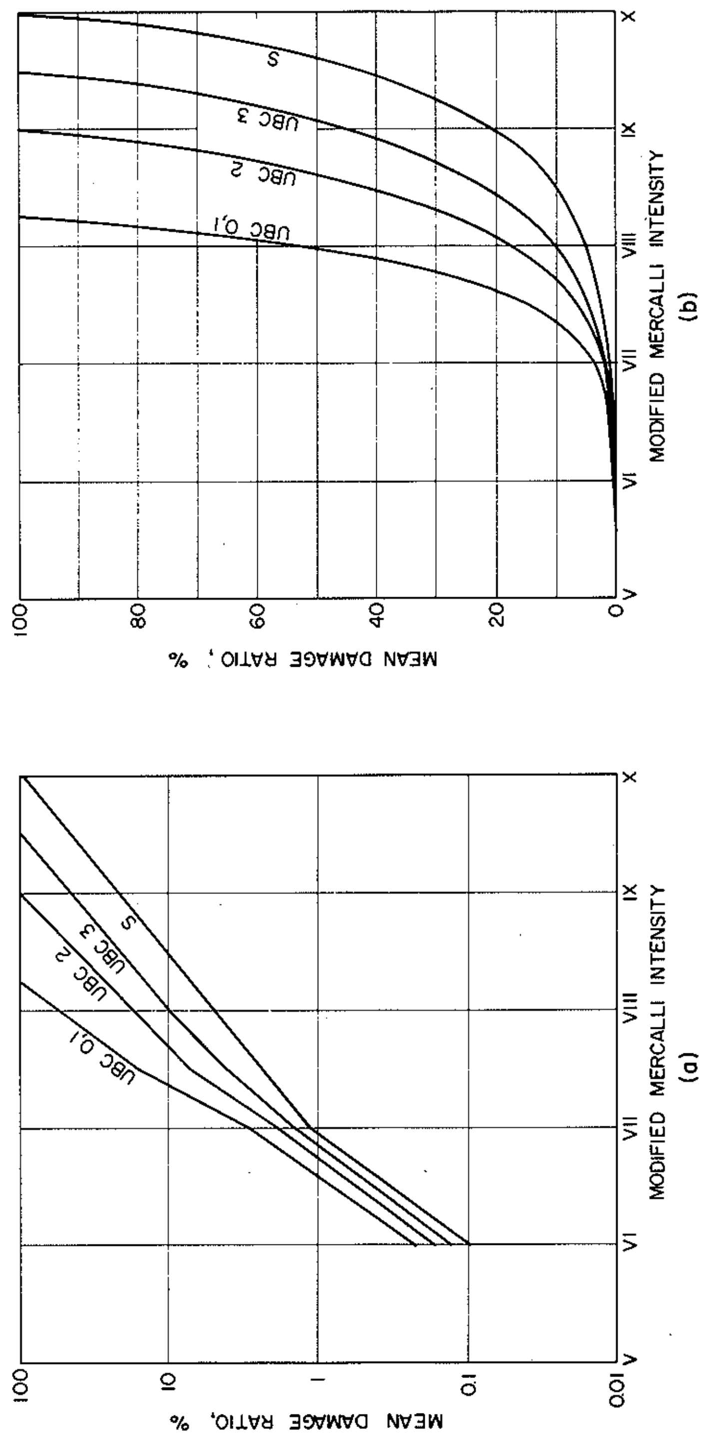


FIGURE 7 MEAN DAMAGE RATIOS FOR PILOT APPLICATION OF SEISMIC DESIGN DECISION ANALYSIS

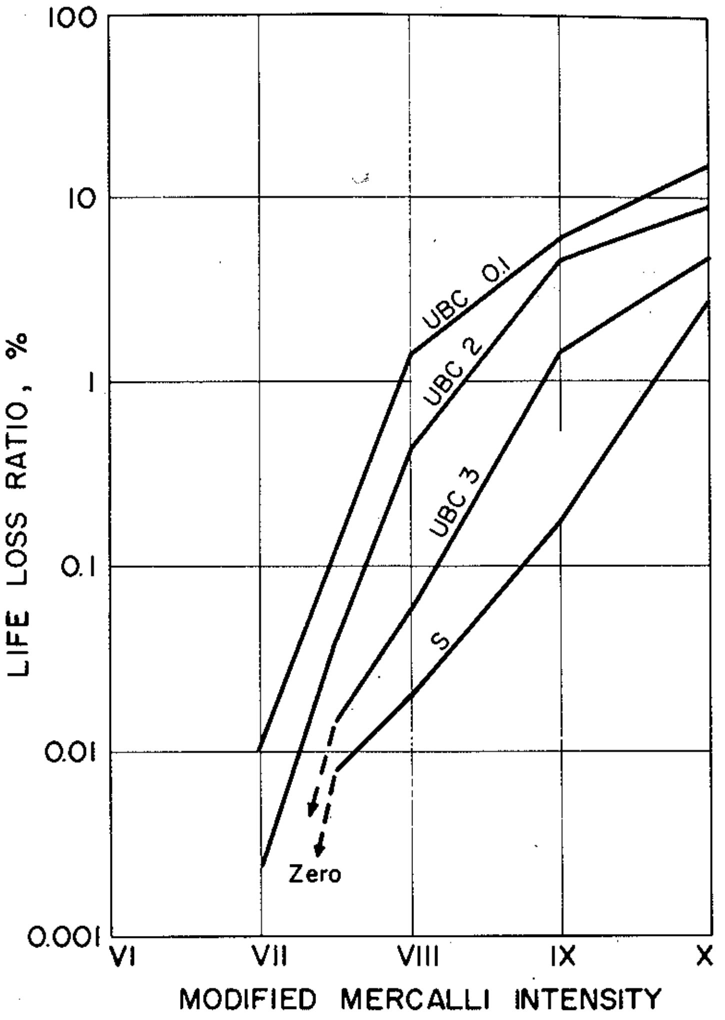
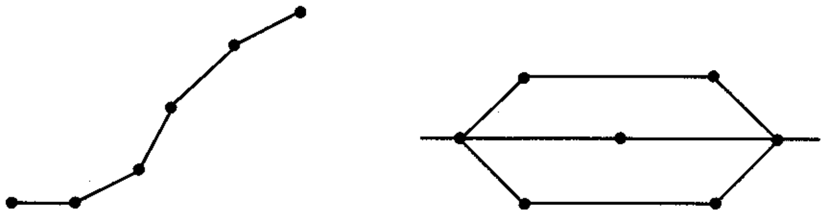
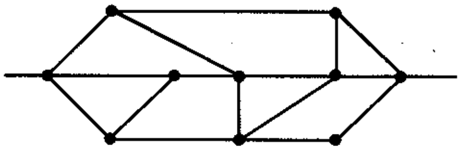


FIGURE 8 LIFE LOSS RATIO FOR UBC 0 DESIGN STRATEGY



(a) SERIES SYSTEM

(b) PARALLEL SYSTEM



(c) NETWORK

FIGURE 9 TYPES OF LIFELINE SYSTEMS