OPTIMUM SEISMIC PROTECTION AND BUILDING DAMAGE STATISTICS

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METHODOLOGY AND INITIAL DAMAGE STATISTICS

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The methodology is presented for analyzing the costs and risks associated with designing tall buildings against earthquakes. The current status of studies concerning actual damage during the San Fernando earthquake and other earthquakes are discussed as well as some of the studies being made as part of the application of the methodology to tall buildings in Boston. The methodology is aimed at selecting seismic design requirements for a specific project or for use in a building code. However, the same general methodology can be used as a basis for insurance considerations or for federal disaster relief laws. The heart of the methodology is examination, in probabilistic terms, of the damage which one earthquake will cause to a particular building system built with a particular design strategy. This evaluation is repeated for different levels of earthquake, different design strategies, and different building systems. For each different design strategy, the initial cost required by that strategy is added to the present value of possible future losses.

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PREFACE

This report is based upon an oral presentation to the National Conference on Earthquake Engineering held in Los Angeles on the first anniversary (7-9 February 1972) of the San Fernando earthquake. The authors are all members of the faculty of the Department of Civil Engineering.

This is the first in a series of reports to be issued under the two NSF grants. Some of the subject matter of this report has been covered in earlier internal study reports.

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INTRODUCTION

It is generally agreed that a tall building must not collapse during the largest earthquake that is realistically imaginable. In addition, earthquakes which can be expected to occur during the lifetime of the building must not cause damage that is economically unacceptable to an owner or socially unacceptable to a community.

While both of these principles are widely accepted as the basis for seismic design, it is difficult to be precise in the implementation of these principles. The second principle clearly implies a balancing of risk of future loss against the initial cost of providing a stronger building. Even the first principal implies some balancing of risk, since the phrase "largest realistically imaginable earthquake" hardly provides a precise definition. The engineer by himself should not be expected to determine the balance point, for this choice involves many considerations affecting the owner and the community. Rather, the engineer's responsibility is to marshall all available facts into a form which makes the costs and risks clear to owners and public bodies.

For many years, engineers have juggled the available facts so as to recommend a reasonable balance between initial cost and risk of future damage, although seldom has the actual balance been stated in an explicit way. Today, it is beginning to be possible to face this balance openly and realisitically. In fact, the city of Long Beach, California, has recently adopted a new code that is explicitly based upon balanced risk (Wiggins and Moran, 1971).

In arriving at a reasonable balance between cost and risk, it is necessary to consider many diverse aspects of the overall problem and to analyze the interrelationships between these aspects. These interrelationships generally are quite complicated. Hence, it appears necessary to have an organized, systematic method for assembling the available facts and for carrying out the required analyses. Just such a methodology is now being developed at MIT under Grant GK-27955 from the National Science Foundation (NSF). To provide vital data concerning building damage during actual earthquakes, NSF has made a second grant (GI-29936) under which MIT is compiling statistics concerning the experience from the San Fernando earthquake of 9 February 1971.

Initial Focus for Study

The methodology itself is quite general and can be applied to many types of buildings and other engineered facilities. However, to provide a framework for the development of the methodology and also an initial trial of its usefulness, the study is focusing specifically upon design criteria for buildings having five or more stories to be constructed in Boston.

Tall buildings have been selected for this initial study because: (a) structural engineering considerations play a significant role in the design of such buildings, and (b) enough is known about the earthquake response of such buildings to permit a reasonably rational analysis of risk. Boston was selected as the locale to be studied partly for reasons of convenience but also because the need for earthquake design in Boston was thought to be a potentially controversial subject. These choices proved to be timely, because controversy has indeed arisen since the Boston City Council voted to require, starting 1 July 1971, design against earthquakes in accordance with the provisions of the Uniform Building

Code (UBC) for Zone 2. On the one hand, these new requirements appear to rule out certain systems building concepts now popular in Boston for high-rise buildings, and it is claimed that the new requirements will increase building costs greatly. On the other hand, the current version of the UBC indicates that the even more stringent provisions for Zone 3 should be applied to Boston, thus implying that the provisions now in effect in Boston are inadequate.

The MIT study is aimed at providing a basis for resolving just such controversy. However, it must be emphasized that the controversy will not automatically be laid to rest when the present study grant terminates in June 1973. First, it will be somewhat surprising if this new methodology works perfectly in its first trial. Second, the methodology is designed only to provide systematic and rational information concerning costs and risks; 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 judgment and experience, but rather provides for a systematic organization of such experience and judgment.

Scope of This Report

This report describes the general outline of the methodology, discusses the current status of studies concerning actual damage during the San Fernando earthquake and other earthquakes, and then indicates some of the studies being made as part of the application of this methodology to tall buildings in Boston.

GENERAL METHODOLOGY

Figure 1 outlines, by means of a flow chart, the methodology for analyzing the costs and risks associated with designing tall buildings against earthquakes. As outlined in Figure 1, the methodology is aimed at selecting seismic design requirements for a specific project or for use in a building code. However, the same general methodology can be used as a basis for insurance considerations or for federal disaster relief laws. A very similar methodology has already been applied to estimating possible future losses to residential dwellings in California (ESSA, 1969).

The heart of the methodology is examination, in probabilistic terms, of the damage which one earthquake will cause to a particular building system built with a particular design strategy. This evaluation is repeated for different levels of earthquake, different design strategies and, where appropriate, different building systems. For each different design strategy, the initial cost required by that strategy is added to the present value of possible future losses.

In simplest terms, a particular <u>building system</u> might be defined as: all buildings having 8 to 13 stories. In a more refined study, a building system might be: 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 soil conditions upon which the building is to be built also form part of the definition of the building system.

The simplest statement of <u>design strategy</u> is: design in accordance with the Uniform Building Code for Zone 2 (or 0, 1 or 3). More refined variations on the design requirements may also be considered, such as requirements concerning ductility. The initial cost is a function of the design strategy. This cost might be expressed 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 earthquake occurance probability. This is the probability that a ground motion of some given intensity will occur during, say, 1 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. Methods now exist for making reasonable estimates for the earthquake intensity probability for any location, by appropriate analysis of the historical record and of geological information (Cornell, 1971).

The effect of various levels of ground motion upon the building system is expressed by a family of damage probability matrices. Each matrix 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. Table 1 shows one possible categorization of levels of damage. These levels of damage are described both by words and by the ratio, to replacement cost, of physical damage to the building and its contents. Fig. 2 illustrates a damage probability matrix based on the categories of damage in Table 1. For example, the numbers in the column labeled intensity 8 (modified Mercalli) show the fraction of all buildings expected to experience each of the levels of damage, given that an earthquake of intensity 8 occurs.

With each damage state, there is an associated cost. These are different from the costs shown in Table 1, which are intended only to identify the level of damage. The total associated cost for each damage state includes, in addition to repair of structural and non-structural damage, loss of function or lost time during repairs and, in extreme cases, injury and loss of life and impact on community. Not all of the factors can be readily expressed in dollars, and many engineers and politicians find it very difficult to accept the notion of placing any sort of value on life. Yet today communities already make such judgment implicitly. For example, how do we know that it is better to make a building owner pay extra for added resistance to earthquakes instead of contributing the same sum toward a transit system which would reduce highway deaths?

If it were possible to express all losses in dollars, then the criterion for optimization would be minimum present total expected cost. Actually, future losses will be only partly expressible in dollars, and multi-attribute objectives must be considered. Nonetheless, the approach here outlined will serve to make clear the considerations which must be balanced to achieve an optimum design.

DAMAGE PROBABILITY MATRICES

A family of damage probability matrices is required: one for each different building system and each design strategy for that building system. The matrices are at the heart of the optimization study. The final results of applying the optimization methodology can be no better than the information incorporated into these matrices. Hence a major effort has been mounted to compile information concerning damage to buildings during earthquakes. Two approaches are being employed: (a) one which relates actual observed damage (or non-damage) directly to intensity of earthquake ground motion, and (b) a second method in which theoretical predictions of dynamic response are used to interpret and extrapolate the empirical information concerning damage and non-damage.

Damage vs. Intensity

The San Fernando earthquake offered a unique opportunity to gather the type of statistics required for the damage probability matrices. As a result of this earthquake, whose epicenter was on the northern fringe of metropolitan Los Angeles, tall buildings were subjected to ground motions ranging from very intense to negligible. Furthermore, newer buildings had been designed to resist earthquake effects while old buildings had not. Thus data were available for several different design strategies.

Data base: The first step in MIT's study of the San Fernando earthquake experience has been to compile a list of all buildings having 5 or more stories in metropolitan Los Angeles. This list is called the *data base*. Such a list is needed as a starting point for planning steps to obtain meaningful data concerning damage. Ideally the data base would include several items of pertinent information concerning each building: actual number of stories, date constructed (to indicate required level of earthquake resistance), type of construction (steel, etc.), gross square feet and type of subsoil and foundation.

No such list was actually available at the beginning of the study, and it proved quite difficult to compile the list--especially regarding the older buildings. Finally, a listing of all elevators was made available by the state agency responsible for inspecting elevators, and this source provided at least approximate information concerning number of stories and approximate date of construction.

The list compiled from this source contained 1645 buildings. Virtually all buildings had been constructed either prior to 1933 or after 1947; the depression and World War II together held down construction of tall buildings during the intervening years. Table 2 gives a breakdown according to date of construction and story height.

Figures 3 through 5 give the geographic distribution of the buildings, both for the entire listing and also for the two age group categories. The blocks in Figures 3 through 5 are each approximately 4 miles square. The major expressways and airports have been shown for help in identifying the various localities. Downtown Los Angeles occupies the square near the center of the map where many expressways intersect. Figure 3 shows that most of the pre-1933 buildings are located in or near downtown Los Angeles. The San Fernando Valley, which was the region of most intense shaking, lies in the upper left hand portion of the map.

This first attempt at a data base is, as yet, neither complete nor accurate, although it does give an adequate picture of the total number of buildings and then distribution with regard to age and geographic location. Steps are now being taken to check the list for accuracy and to add information to it.

First data concerning damage: Steinbrugge et al have presented damage cost data for some sixty multi-story buildings constructed since 1947, and for a few buildings which were constructed before earthquake resistance design was first required in 1933. These data were obtained from a quick survey immediately following the earthquake. From the standpoint of the present study, the two main conclusions were:

1. From a percentage loss standpoint, the damage to modern completed steel frame buildings designed to resist earthquakes never exceeded about 1% of value. A total of 5 modern reinforced concrete structures had losses over 1%, and two of these had losses over 5%.
2. Older non-earthquake resistive high-rise buildings performed quite badly when compared to modern high-rise construction. A limited selection of older structures in the downtown Los Angeles area all had losses over 5%.

There was considerable scatter in the cost data for any class of buildings at a given epicentral distance.

If it is assumed that all post-1947 tall buildings not covered by Steinbrugge's survey were undamaged, then it is possible to compute damage probabilities. The probabilities appearing in Figure 2 were estimated on this basis. Thus Figure 2 represents a first guess at the probabilities applying to modern buildings having 8 or more stories, founded on firm ground and designed approximately in accordance with the requirements of the Uniform Building Code for Zone 3. However, the probabilities of damage almost certainly are too low, and the probabilities of no damage too high.

A first estimate of damage probabilities for pre-1933 buildings was obtained as part of the MIT study by examining damage repair permits on file at Los Angeles City Hall. In this way, most of the buildings with major damage were identified, although permits generally were not obtained for buildings which experienced only non-structural damage. Usually, the actual total cost of repairs was considerably in excess of the estimate shown on the permit, and for purposes of compiling statistics the permit costs were multiplied by 4. Figure 6 gives the resulting first guess at damage probabilities for pre-1933 buildings. Once again the probability of zero damage is undoubtedly much too large, while the probabilities for the various damage states are greatly underestimated (particularly the states with small damage). Comparison of Figures 2 and 6 does, however, confirm the expected result; that is, older buildings not designed for earthquakes experienced more severe damage than modern earthquake resistant buildings.

Further studies: As part of the MIT study, several steps are underway to compile more complete information regarding damage (or non-damage) and hence to improve the damage probability estimates.

First a very short questionnaire was sent to 250 selected buildings, and a personal followup was conducted to increase the rate of return of these questionnaires. The buildings were selected randomly from groupings of buildings according to location (intensity of ground shaking), age (design requirements) and story heights. The total return was about 120, or about 50%. Results from these questionnaires, which are still being analyzed, have confirmed the earlier suspicions that damage is underestimated by the probabilities in Figures 2 and 6.

More recently, arrangements have been made with the Building Owners and Managers Association to undertake a much more complete survey by questionnaires plus follow up.

Other earthquakes: Efforts also are underway to compile similar information from other earthquakes. Extensive and very useful information is available from the Caracas earthquake in July 1967. Other useful information can be obtained from the earthquakes in Alaska (1964), San Francisco (1957) Seattle (1965), and Kem County (1952). Steps have been initiated to obtain data from earthquakes in Japan and Mexico.

While data from these other earthquakes will not be as extensive as those from the San Fernando earthquake, all such data are useful for providing a more complete picture concerning damage probabilities.

Damage vs. Dynamic Response

The totally empirical approach just described will not possibly be able to provide all of the information needed to complete the required family of damage probability matrices. There simply is insufficient well documented data from actual earthquakes. Moreover, design strategies not yet tested by actual earthquakes must be considered. Hence theory must be used to fill the gaps among and to extend beyond, the empirical data.

A theoretical approach involves, first, prediction of the dynamic response of a building system to a specified ground motion. A computer program has been written to facilitate the non-linear analysis of buildings, making it possible to consider a variety of force-deflection relations including the effects of strength and stiffness degradation. Then one or more measures of the dynamic response--such as peak interstory displacement--are used to assess damage.

To provide a basis for the second of these steps, a study is being made of the correlation between dynamic response and damage for 6 tall buildings shaken by the San Fernando earthquake. As part of the EERI/NOAA study, mathematical models were developed for these buildings to match the observed roof accelerations. At the request of MIT, the engineers performing these studies--Conrad Associates and John A. Blume Associates--punched the complete computed time histories for all interstory displacements and floor accelerations. It has also arranged to obtain detailed statements as to the nature and cost of damage in these buildings, on a floor by floor basis where possible. These data for cost are now being correlated with various characteristics of the computed response to determine which give the most reliable correlations with various components of the economic damage (e.g., equipment, finishes, etc).

Future Steps

In the studies made to date, only one measure of the intensity of ground motion has been used: modified Mercalli intensity. In the long run, it will almost certainly be necessary to develop and use a more satisfactory measure. For example, a better measure may be: the spectral acceleration for the period applicable to a particular building system, and the duration of significant shaking.

As soon as processing of the ground motions records made during the San Fernando earthquake is complete and these records are available in corrected digitized form, MIT plans to correlate the damage data compiled for many of the buildings in the data base to the corresponding spectral accelerations.

STATUS OF STUDIES FOR BOSTON

The family of damage probability matrices, as a function of type of building system and design strategy applied to the system, should have universal applicability. However, certain additional studies are necessary in order to apply the overall methodology to a specific city such as Boston.

Choice of Building Systems

As shown in Table 3, three types of structural systems and three ranges of story heights have been selected. Thus a total of 3 x 3 = 9 building systems will be considered. These nine systems were selected on the basis of a listing of all existing tall buildings in Boston plus a judgement as to the types and sizes of buildings that are likely to be built in the future. Very tall buildings will not be considered in this initial study, since there are very few of them and since such buildings should be specifically checked for wind and earthquake loadings.

An actual 13-story steel frame building has been selected for a pilot study, to establish the procedures to be used for the other eight building systems.

Design Strategies

For the initial study, 5 design strategies are being considered. Four of these correspond to the four zones of the UBC. The fifth is designed for a new Zone 4, requiring base shear coefficients twice those for Zone 3. In the initial study, no attempt will be made to vary the ductility requirements for the several zones from those stipulated by the UBC.

Initial Cost Study

At present, the effect of applying the different design strategies to the pilot building (which had not been designed for earthquakes) is under study. Changes in the structural system and in mechanical and electrical systems, necessary to meet the requirements for Zones 1 through 4, are being identified and costed.

Earthquake Occurence Probability

A detailed study has been made of the seismic history of Boston and of zones which are potential sources of earthquakes affecting Boston. The resulting site intensity occurrence probability curve is shown in Figure 7 for a site in the vicinity of downtown Boston. This curve implies that earthquake ground motions of intensity 6 or greater have a probability of about 10^{-3} of occurring in any one year (i.e., a probability of about 5% in any 50 year period) or alternatively that such motions occur, on the average, once every 1000 years. The maximum expected intensity is 7 plus; that is, roughly the intensity felt in downtown Los Angeles during the San Fernando earthquake.

It must be emphasized that Figure 7 applies to motions felt on firm ground; more intense motions will occur over the soft ground which is frequently encountered in the Boston area.

Effect of Soil Conditions

Experience during actual earthquakes in various parts of the world has shown very clearly that Boston blue clay and near surface fill or organic soils all greatly amplify earthquake ground motions. Such soil conditions may increase the modified Mercalli intensity by at least one unit as compared to firm ground; moreover, the increase in structure response may be 4 to 8 times in the case of very tall buildings founded over very deep Boston blue clay.

Theoretical methods for analyzing soil amplification will be used to study this effect. The key parameter in these methods is the shear wave velocity of the Boston clay; this velocity is being measured both *in situ* and in the laboratory using undisturbed samples. Plans have been made to measure microtremors to provide a check against the computed characteristic frequencies of the soil.

FINAL COMMENTS

As indicated in the introduction, the goals for the current study are:

1. To develop an organized, systematic method for carrying out the analyses required to select a rational balance between initial cost for seismic resistance and risk of future loss during possible earthquakes.
2. To assemble and analyze data concerning building damage--a vital ingredient for such an analysis.
3. To apply the method, as an initial trial, to tall buildings in Boston.

It must be emphasized that the methodology aims to supply meaningful information to decision makers; the methodology by itself cannot choose the proper balance between initial cost and risk.

The schedule for the initial trial study for Boston is roughly as follows:

*Complete analysis of pilot building system: May 1972

*Complete analysis for nine building systems on firm ground: January to March 1973

*Complete analysis for effects of soil conditions: May 1973

The study will by no means be complete when the first grant from NSF expires in mid-1973. For example, it now appears that the implications of ductility requirements will not have been explained by that date. However, it is hoped and expected that the validity and usefulness of the general approach will be amply demonstrated by that time.

ACKNOWLEDGEMENTS

Several engineering firms are participating in this study. The data base for Los Angeles was compiled for MIT by the J.H. Wiggins Company of Palos Verdes Estates, California. The firm of Ayres, Cohen and Hayakawa of Los Angeles has assisted with the collection of data for damage during the San Fernando earthquake, and in determining initial costs for different design strategies as applied to mechanical and electrical equipment. LeMessurier and Associates of Cambridge, Massachusetts is providing engineering services in connection with study of actual buildings in the Boston area. Two organizations have contributed their services in connection with the measurement of shear wave velocity of Boston clay: C.L. Guild Co. of Providence, R.I. and Weston Geophysical Engineers of Weston, Massachusetts.

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Table 1

Damage States

	Description of Level of Damage	Ratio to Replacement Cost
0	No Damage	0
1	Minor non-structural damage--a few walls and partitions cracked, incidental mechanical and electrical damage	.001
2	Localized non-structural damage--more extensive cracking (but still not widespread); possibly damage to elevators and/or other mechanical/electrical components	.005
3	Widespread non-structural damage--possibly a few beams and columns cracked, although not noticeable	.02
4	Minor structural damage--obvious cracking or yielding in a few structural members; substantial non-structural damage with widespread cracking	.05
5	Substantial structural damage requiring repair or replacement of some structural members; associated extensive non-structural damage	.10
6	Major structural damage requiring repair or replacement of many structural members; associated non-structural damage requiring repairs to major portion of interior; building vacated during repairs	.30
7	Building condemned	1.0
8	Collapse	1.0

Table 2

Number of Buildings in LA Data Base

Height Groups (Stories)		Age Groups		
		1900-1933	1934-1948	1949-Present
	5 - 7	375	54	468
	8 - 13	245	29	332
	14 and above	20	1	121

Table 3

Building Systems for Initial Trial Study

Type of Structural Frame	No. of Stories
Steel Moment Resisting Frame	5 to 7
Concrete Moment Resisting Frame	8 to 13
Concrete, Shear Wall Braced	14 to 20

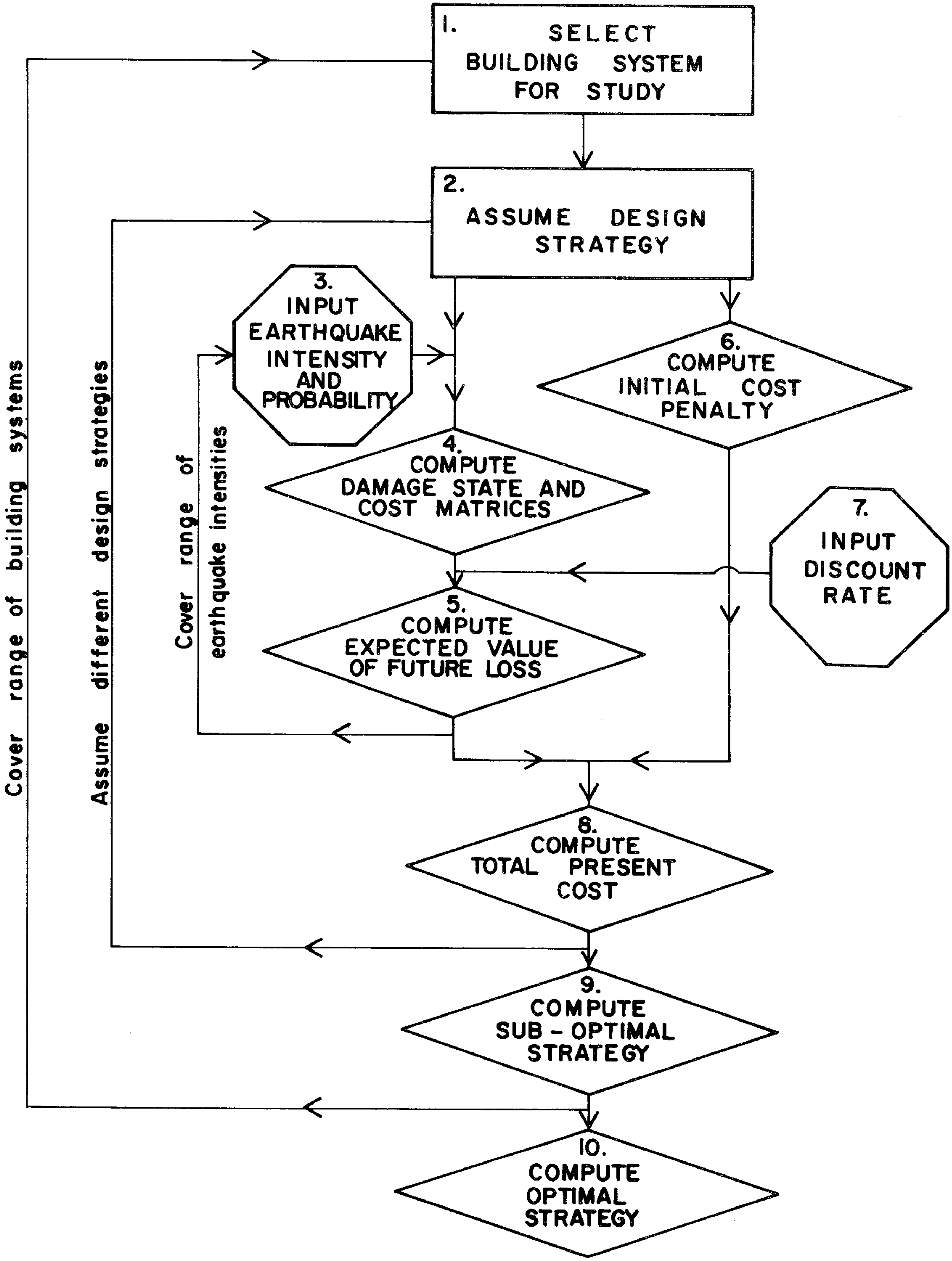


FIGURE 1: FLOW DIAGRAM FOR GENERAL METHODOLOGY

EARTHQUAKE INTENSITY							
LEVEL (MMI)		4	5	6	6.5	7	8
DAMAGE STATE	0	1.00	0.99	0.90	0.85	0.80	0.25
	1	0	0.01	0.09	0.10	0.12	0.25
	2	0	0	0.01	0.04	0.05	0.20
	3	0	0	0	0.01	0.02	0.15
	4	0	0	0	0	0.01	0.10
	5	0	0	0	0	0	0.04
	6	0	0	0	0	0	0.01
	7	0	0	0	0	0	0
	8	0	0	0	0	0	0

FIGURE 2 Example of Damage Probability Matrix for a Particular Building System Built to a Particular Design Strategy

FIGURE 3

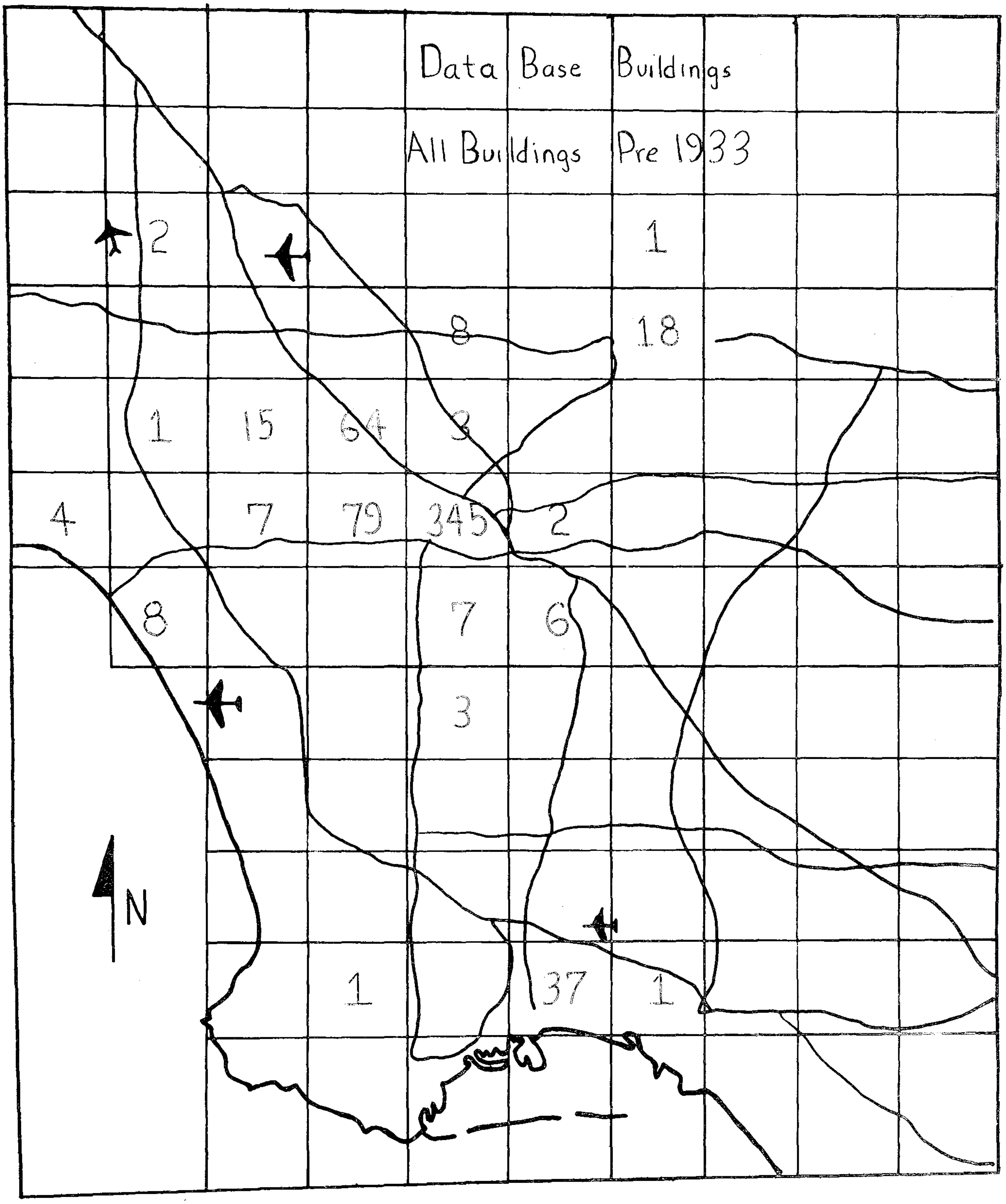

Data Base Buildings
All Buildings Pre 1933
2
1
8
18
1
15
64
3
4
7
79
345
2
8
7
6
3
N
1
37
1

FIGURE 4

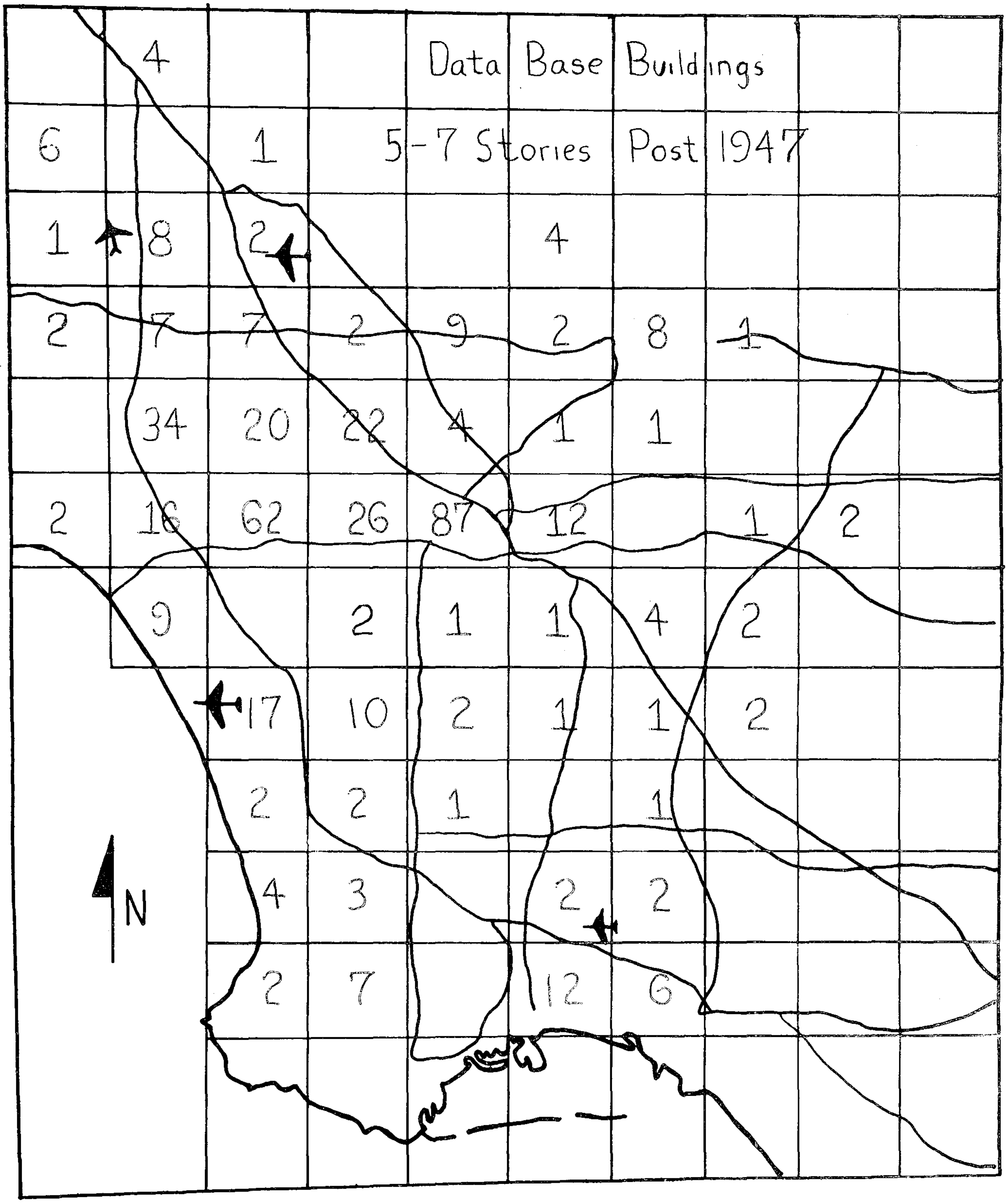
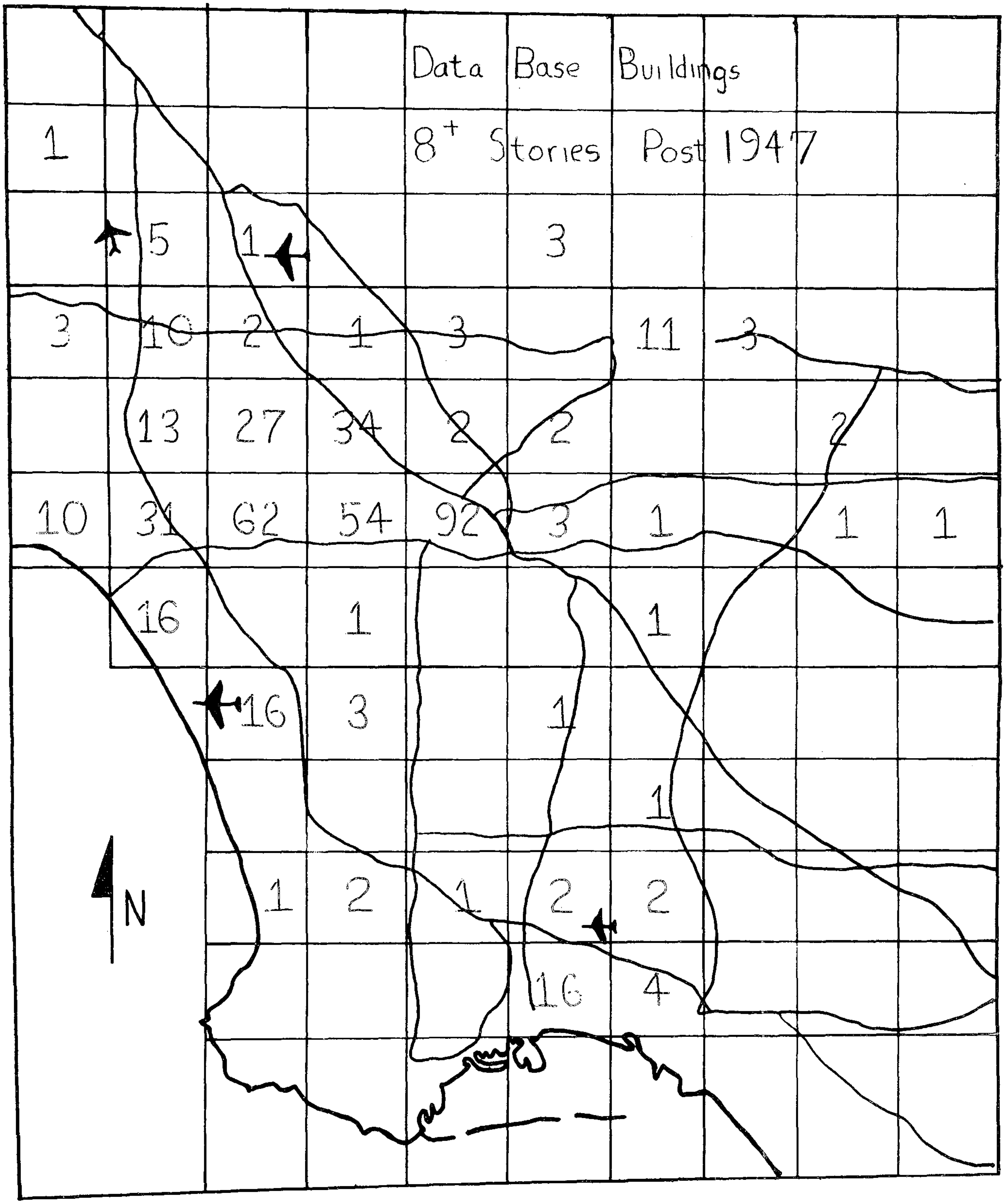

Data Base Buildings
5-7 Stories Post 1947
N
4
6
1
1
8
2
4
2
7
7
2
9
2
8
1
34
20
22
4
1
1
2
16
62
26
87
12
1
2
9
2
1
1
4
2
17
10
2
1
1
2
2
2
1
1
4
3
2
2
2
7
12
6

FIGURE 5


Data Base Buildings
8+ Stories Post 1947
1
5
1
3
3
10
2
1
3
11
3
13
27
34
2
2
2
10
31
62
54
92
3
1
1
1
16
1
1
16
3
1
1
1
2
1
2
2
16
4
N

	EARTHQUAKE INTENSITY					
LEVEL (MMI)	4	5	6	7	8	9
0				.87		
1				.02		
2				.02		
3				.02		
4	(Values not estimated)			.02	(Values not estimated)	
5				.02		
6				.02		
7				.01		
8				0		

FIGURE 6 Damage Probability Matrix for Pre-1933 Buildings (First Estimate)

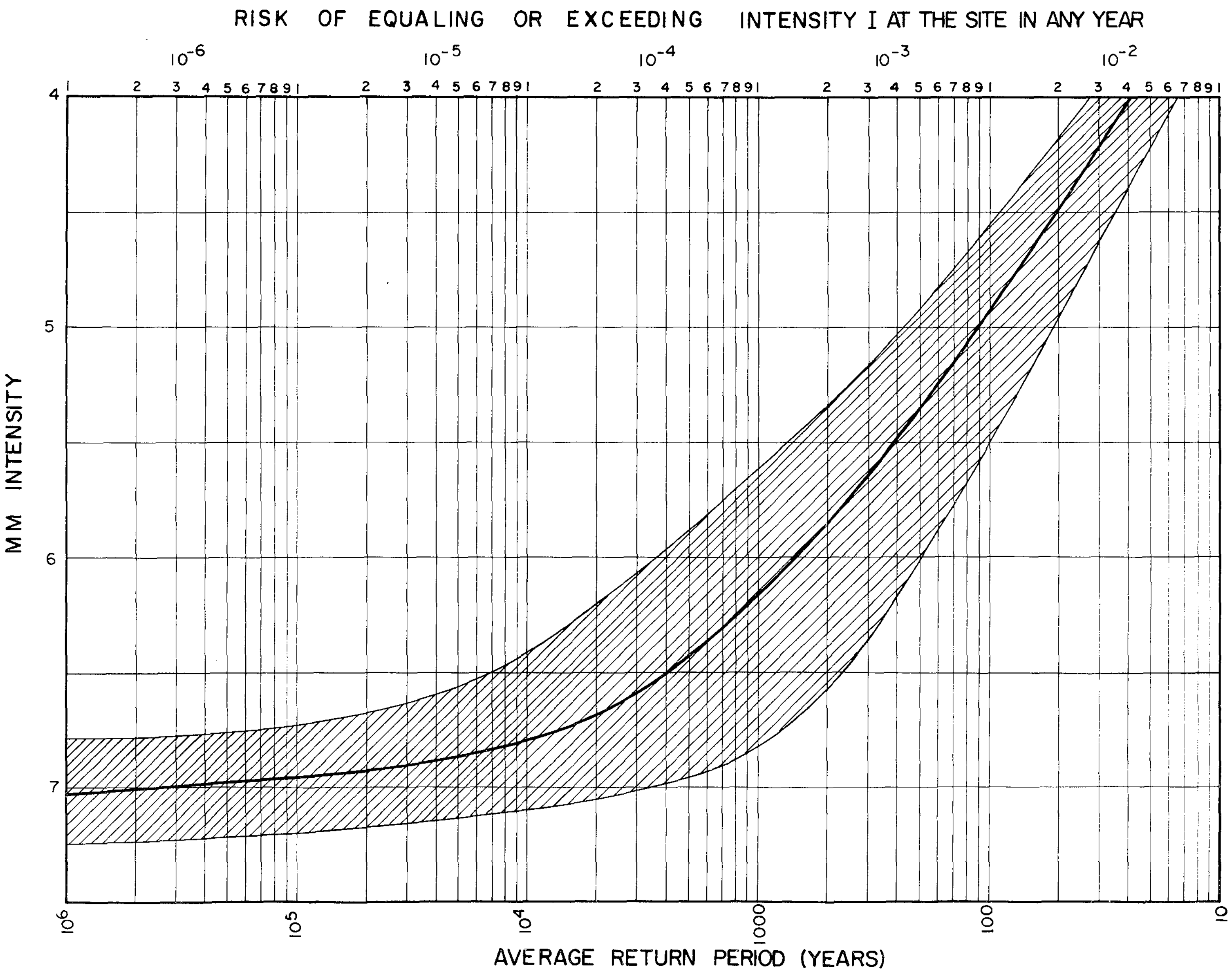


FIG. 7 ESTIMATED RISK AT BOSTON