PHASE I REPORT

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A RATIONAL APPROACH TO DAMAGE MITIGATION IN EXISTING STRUCTURES EXPOSED TO EARTHQUAKES

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Any opinions, findings, conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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TABLE OF CONTENTS

Page

1. Introduction

2. Description of Methodology

3. Discussion and Conclusions

APPENDICES

A. Damage to Type III Buildings in Past Earthquakes and Possible Modification Schemes

A.4 Improvement Schemes for Type III Buildings

B. Damage Statistics for Masonry Structures

Page

C. Computer Program "DAMSTAT"

D. Illustrative Example

1. INTRODUCTION

1.1 Statement of the Problem

Earthquakes have and will continue to occur around the world inflicting great losses on societies both in terms of lost human lives and property losses. The severe earthquake of 1964 in Alaska and the moderate earthquake of 1971 in San Fernando, California, accounted for nearly 200 deaths, thousands of injuries and a combined property loss of approximately 1 billion dollars. An earthquake in San Francisco of a magnitude similar to the 1906 earthquake could cause death and injury to thousands and property losses in the billions; such an event has a high probability of occurrence. Can these expected losses be minimized?

The degree of losses suffered from earthquakes is amplified due to lack of any premonitory signs or seasonal characteristics associated with other natural disasters such as tornados and floods. This random characteristic of earthquakes makes it necessary for the Disaster Preparedness Agencies and the society in general to estimate the degree of exposure they have to possible future earthquakes and take necessary actions well in advance to minimize the loss of life and property.

In recent years, considerable work has been done to determine or predict the exposure of regions to future earthquakes. Some of the work has been directed toward determining long-term seismic exposure based on historical seismicity of the region (ambient seismicity) and others have been directed towards short-term prediction of large earthquakes. The results of the former type of studies are already available for certain regions. Short-term earthquake prediction is expected to become possible within the next quarter century or even sooner.

The degree of usefulness of the ambient seismicity information or a short-term earthquake prediction depends on the society's ability to utilize this information to decrease the potential loss from the forecasted earthquakes. Responsible governmental agencies have already issued reports on how to guard against death or injury from future earthquakes (e.g., Disaster Preparedness and Meeting the Earthquake Challenge). Similarly, procedures to reduce the expected property losses from future earthquakes should also be developed. While some studies on possible modification schemes have been published, property owners are presently without a comprehensive guide to decisions on the protection of their property from earthquake damage.

1.2 Need for Methodology

In a region exposed to high ambient seismicity or for which a specific short-term earthquake prediction is made by credible sources, the owners or the administrators of structures in the exposed area face a decision as to what course of action to take to minimize the potential loss to their property and danger to occupants. In the case of a short-term earthquake prediction, possible socio-economic chaos following the prediction will make the problem very far reaching and complex. The decision-maker will require answers to the following questions as well as a methodology for reaching a rational decision based on these answers:

- What are the possible improvement schemes applicable to the buildings?
- How much will each of these schemes cost?
- How much will each of these schemes reduce losses if the predicted earthquake occurs?
- Which scheme, including doing nothing, will minimize expected losses?
- In case of a short-term earthquake prediction, is there time to implement the most beneficial scheme?
- Is financing available for improvements and if so, on what terms?
- Can earthquake insurance be obtained?
- Is the building's present insurance policy adequate?
- Could it be worthwhile to invest in improvements even though the predicted earthquake may not occur?

Presently, no methodology exists describing how to answer these questions and how to use the answers in deciding which course of action to take for minimizing losses. As the ability to successfully determine the ambient seismic hazard at a site or to predict specific earthquakes is realized, the need for such a methodology increases. Therefore, society has to develop the methodology to utilize the seismic hazard information in mitigating the earthquake losses so that the information can be used if and when it is available.

1.3 Objective

The objective of this study is to develop a methodology to aid owners of existing buildings in seismic regions in deciding what action to take to minimize their expected losses due to future earthquakes.

Development of such a methodology requires consideration of the following items:

> Probabilities: Seismic hazard at a site due to ambient seismicity or due to a predicted earthquake has to be defined in probabilistic terms. Significant parameters defining the earthquake effects at a site (e.g., peak ground acceleration or intensity) should be associated with appropriate return periods or probabilities of occurrence. Specific short-term earthquake predictions should include a confidence factor as well as appropriate probability distributions of the significant parameters.
>
> Type and extent of expected earthquake damage: In the development of a method to rationally decide which, if any, modification scheme should be used, it is important to classify the type and extent of damage (structural or non-structural) expected from a given earthquake to the specific building. The information from earthquake damage histories for similar buildings provides

some of the necessary input for identifying areas most in need of modification. Fortunately, some efforts have been made in recording the nature of the damage resulting from past earthquakes (5, 6, 14, 36, 40, 47).* The data from these must be organized into a format useful in the decision analysis procedure. Further damage information can, of course, be obtained by an engineering analysis of the specific structure under study.

Evaluation of possible modification schemes: The major prerequisite for success in diminishing loss will be the development of feasible modification schemes for various structural types. There are many factors which will have to be considered in determining the feasibility of modification schemes, whether temporary or permanent:

- There are schemes that may or may not affect the structural integrity of the building, but which could prevent injury or loss of life.
- Modification schemes must consider damage to nonstructural as well as structural elements.
- Manpower, materials and equipment must be available in the necessary quantities.
- For obvious reasons, time available from prediction warning to implementation of the modification procedure is a critical factor.
- Economics will undoubtedly play a significant role in the

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*Numbers in parentheses refer to references listed in Section 4.

comparison of possible avenues of action to diminish the expected loss due to a future earthquake. Any modification scheme will require cooperation in terms of financing, insuring and constructing the modifications. Whether sufficient cooperation will exist after an earthquake prediction must be examined. Inflation and interest rates must be considered in the evaluation of the losses due to future earthquakes.

The process considering the factors described above can be summarized schematically as shown in Figure 1. This study attempts to describe the steps involved in this process and, in doing so, evaluates the feasibility of developing such a decision analysis methodology.

1.4 Scope

The work presented in this report is Phase I of a two-phase study. The purpose of Phase I is to study the feasibility of developing a Rational Decision Analysis Methodology to evaluate possible modification schemes for existing buildings exposed to a predicted earthquake. In this phase, the parameters involved in such a methodology are identified. Available procedures to determine the expected earthquake hazard at a given site are studied, and a methodology to apply the results of these procedures to the decision-making process is presented. A procedure to calculate the damages to various components of a building due to different levels of ground shaking is developed. To provide flexibility for future development, the indirect damages related to events like

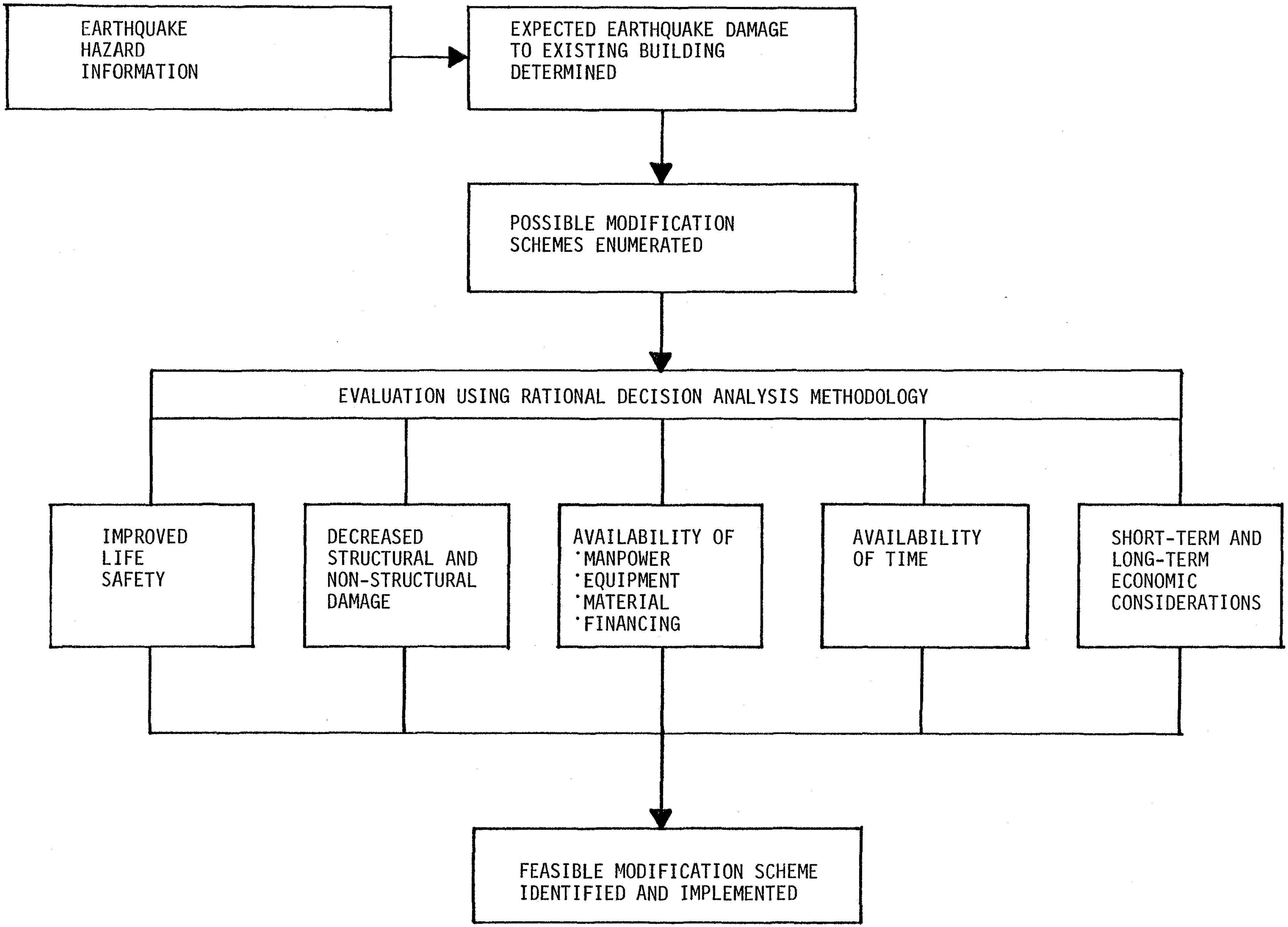


Figure 1: DECISION PROCESS

fire and substructure failure and their respective probabilities are also included in the methodology.

A computer program (DAMSTAT) is developed to automate the calculation steps for the proposed methodology. A description and listing of this computer program are presented in Appendix C. Appendix D describes an application of DAMSTAT to a hypothetical example.

The usefulness of the methodology greatly depends on the ability to estimate the damages to the building due to a given earthquake intensity. In order to successfully estimate the expected damage, a study of the performance of similar buildings in past earthquakes is necessary. In Appendix B, a method to generate damage matrices from historical damage data is developed. The method is applied to masonry buildings, and a number of damage statistics curves are generated for four classes of masonry buildings.

One of the building types of great interest is the older masonry Type III low-rise building. This building type is prevalent throughout the United States and has been found to be highly susceptible to earthquake damage and occupant injury. An extensive literature search was performed to gather information on the performance of these buildings during previous seismic events. Results of this literature search are reported, and the major weaknesses of this type of construction are identified in Appendix A, together with various possible improvement schemes.

Phase II of this study, if undertaken, will involve a further refined development of the proposed methodology and will apply it to the study of various common building types.

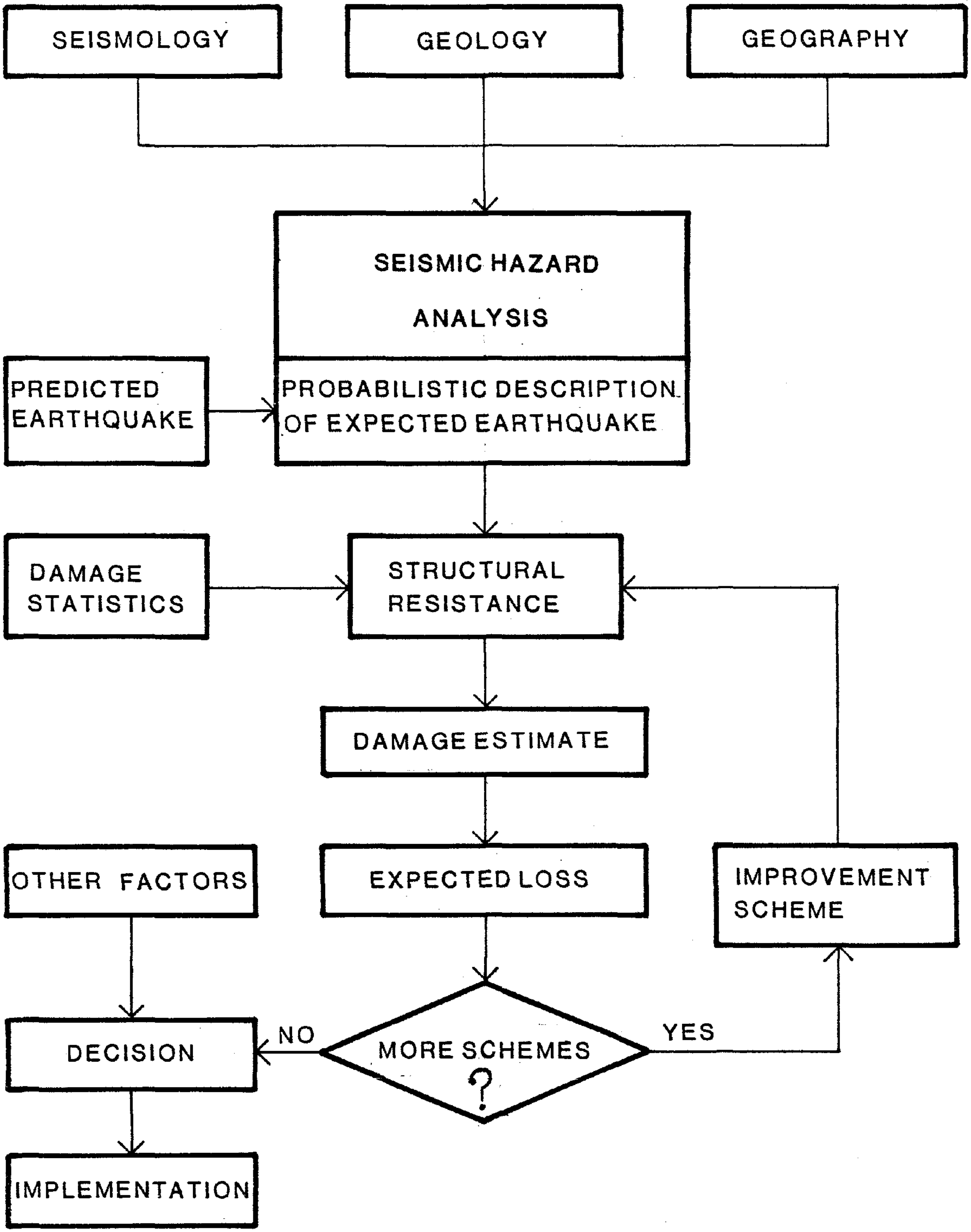
2. DESCRIPTION OF METHODOLOGY

2.1 Outline of the Proposed Methodology

The methodology to evaluate and reduce the available information to a meaningful form to the decision-maker for selection of the most feasible structural improvement scheme is presented schematically in Figure 2.

The first step in this process is determining the seismic hazard at the specific site under study, i.e., determining the probabilities of occurrence of various levels of ground shaking at the site during a certain time period. In regions with known history of seismic activity, available techniques can be utilized to determine the "ambient seismic hazard" at the site based on the local seismological, geological and geographical data. The end result of this step is a probabilistic description of the expected earthquake activity at the site for a given period.

In the case of a short-term earthquake prediction, the authorized agencies should provide the probabilistic description of the expected earthquake, including the probability distributions for magnitude, location of the epicenter and the focal depth. From this information, seismic hazard at a specific site due to the predicted earthquake can be estimated in a fashion similar to the ambient case.



OUTLINE OF METHODOLOGY

FIG. 2

The next step involves the estimation of damages to the building due to each level of intensity of ground motion. These damages can be estimated by utilizing relevant statistical data from past earthquakes or by performing an analysis of the building. In either case, engineering judgement and experience must be exercised.

Finally, the seismic hazard information for the ambient and the predicted cases is combined with the damage estimates to determine the expected values of damages for each modification scheme. Monetary values of damages expected to occur in the future are converted to present values and then combined with the expected damages due to short-term predicted earthquake and the cost of the improvements. Resulting values are the present values of the total expected losses for each modification scheme.

The decision-maker, presented with the expected values of losses for each possible scheme, has to consider these values along with other factors such as availability of funds, time limitations, insurance coverage, liabilities, lawsuits, and other possible subjective considerations in order to finally select one scheme for implementation. The present study concentrates only on the monetary values of the expected losses. Treatment of other factors is left for Phase II studies.

2.2 Decision-Making Process

In the previous section the basic methodology to calculate the expected values of losses for each modification scheme was outlined. It should be emphasized that expected value is an artificial quantity which never occurs in the real world. It is found by multiplying the possible outcome of each scheme by its probability of occurrence and adding all the products. However, expected value is a convenient and consistent measure for comparing alternate schemes.

In the event of a short-term earthquake prediction, the decision-maker will have several options available, including doing nothing, selling the property, buying insurance or strengthening the building to various levels of resistance. However, for the purposes of this Phase I study, the following simple example can be used to demonstrate the decision analysis process.

In the simplest case the decision-maker is confronted, in the event of an earthquake prediction, with two main choices, a_1 and a_2: a_1 represents doing nothing, and a_2 represents modifying the structure. After choosing one of the possible courses of action one of two possible outcomes Θ_1 or Θ_2 can occur: Θ_1 representing no earthquake occurring, and Θ_2 representing the predicted earthquake occurring. These events have associated probabilities of $P(\Theta_1)$ and $P(\Theta_2)$ respectively. Also for each outcome there is an associated monetary consequence (or loss) $V(a_i, \Theta_j)$ which is a function of the severity of the expected earthquake and the ability of the structure to withstand damage.

For each course of action, the expected monetary value (or cost) emv (a_i) can be written as follows:

$$\text{emv}\ (a_1) = C_1 + P(\Theta_1)\ V\ (a_1,\Theta_1) + P(\Theta_2)\ V\ (a_1,\Theta_2)$$

$$\text{emv}\ (a_2) = C_2 + P(\Theta_2)\ V\ (a_2,\Theta_1) + P(\Theta_2)\ V\ (a_2,\Theta_2)$$

where,

C_1, C_2 = Cost of implementing the chosen course of action a_1 or a_2, respectively.

If the decision is made purely on the basis of expected monetary loss, as assumed above, then the course of action with the smallest emv will be chosen.

2.3 Determination of Seismic Hazard

Seismic hazard at a site is the likelihood of occurrence of various levels of ground shaking during a specified time period.

The ambient seismic hazard at a specific site can be determined by first evaluating the seismic hazard at the potential earthquake sources in the vicinity of the site (e.g., developing the recurrence relationships for the neighboring faults) and then determining the seismic hazard at the site through appropriate attenuation relationships.

Evaluation of the seismic hazard at a site due to a predicted earthquake requires a knowledge of the expected location of the epicenter, focal depth of the earthquake, probability distribution of the magnitude, and an appropriate attenuation relationship valid for the geologic conditions between the potential earthquake source and the site.

For a given structure, the damage expected from an earthquake is a function of:

1) the characteristics of the ground motion at the site;
2) the resistance or strength of the structure.

The characteristics of the ground motion at the site of interest can be described by a combination of the following parameters:

1) intensity, given in terms of any one of the several intensity scales.
2) peak values of the ground motion at the site (displacement, velocity or acceleration).
3) spectral values of displacement, velocity or acceleration for the given building.

In this study, peak ground acceleration (pga) is used as the parameter describing the level of earthquake intensity at a site. This parameter is commonly used by engineers and can conveniently be related to the expected damage from an earthquake. For a given building and a value of peak ground acceleration, probable damage to the building can be estimated either through analysis or through an evaluation of the statistical data collected from past earthquakes.

Seismic hazard analysis procedures have been developed to determine the probability that a site will be subjected to certain levels of peak ground acceleration during a given time period (2, 15, 20, 24, 37). Probabilities associated with a certain number of peak ground acceleration levels (or ranges) can be calculated by these procedures to form a probability vector for the peak ground acceleration levels. This vector will be called P_{pga}.

Example:

pga level	pga range (g)	probability	
1	0.00-0.05	0.01	
2	0.05-0.15	0.05	
3	0.15-0.25	0.10	
4	0.25-0.35	0.20	
5	0.35-0.45	0.30	= P_{pga}
6	0.45-0.55	0.20	
7	0.55-0.65	0.10	
8	0.65-	0.04	

Each number in the P_{pga} vector is the probability of at least one earthquake, with corresponding peak ground acceleration level, occurring during the specified time period. The number of the peak ground acceleration levels to be used depends on:

1) the accuracy with which the probabilities can be calculated;
2) the accuracy with which the damage to the building at each level can be estimated;
3) the structural characteristics of the building; and
4) the relative importance of the physical damage to the building with respect to other factors such as loss of human lives, lawsuit costs, etc.

For an older unreinforced brick building without any ductility, three peak ground acceleration levels corresponding to small, medium and large earthquakes may be sufficient, whereas for a high-rise steel building, the selection of a higher number of peak ground acceleration levels similar to the one given in the example above might be justified.

P_{pga} vectors can be developed for any given time period. If a given building has an expected economic life of 30 years, this life span can be divided into, say, 6 periods of 5 years each. Then P_{pga} vector developed for five years represents the earthquake hazard during each of these periods. This P_{pga} vector will be called the "ambient P_{pga}" vector.

In the case of a short-term earthquake prediction, a separate P_{pga} vector can be generated using the prediction information. This information should include the expected location and depth of the earthquake, the probability distribution of the magnitude, and an appropriate attenuation relationship. The P_{pga} vector obtained for a predicted earthquake will be called "predicted P_{pga}".

2.4 Damage Statistics and Evaluation of Total Expected Loss

In the previous section, it was noted that peak ground acceleration levels could be related to the expected damages due to an earthquake. It is almost impossible to accurately determine the total damage expected to be induced on a building by an earthquake with a given peak ground acceleration level. However, with use of proper judgement and experience from past earthquakes, reasonable estimates can be made.

In order to simplify the process of damage estimation, the damages must be classified according to the type, cause and the "sub-system" of the building by which they are incurred.

In general, damages can be classified in two basic groups:

1) structure related damages: damages incurred by various parts of the building.
2) extra-structural damages: damages due to deaths, injuries, lawsuits, loss of income from the building, etc.

The latter type of damages is extremely difficult to quantify and, at times, controversial. In this part of the study only the structure related damages will be considered. Inclusion of the extra-structural damages in the methodology will be left for the Phase II studies.

2.4.1 Classification and Evaluation of Structure Related Damages

In the simplest form, the structure related damages can be expressed as a ratio of the monetary value of the damages to the total monetary value of the building (Damage Ratio). The monetary value of the damages and the total building value can be expressed in several different ways which may, under certain circumstances, vary greatly from each other. Damage value can be based on insurance losses, loss as defined by the cost to bring the structure back to its pre-earthquake condition (not new), or on loss as defined by actual repair costs. The building value can be based on replacement value, market value (before or after earthquake), or assessed value.

In this study, the monetary values of damages will be based on the actual repair costs. Building value will be expressed in terms of the actual replacement value. However, any combination of the definitions for the damages and the building value can be used to express the damage ratios.

To simplify the process of damage estimation, buildings can be divided into major parts, or "subsystems". For a high-rise building, the subsystems can be classified as:

1) Structural (beams, columns, shear walls, etc.);
2) Architectural;
3) Mechanical;
4) Electrical.

This classification is in agreement with the common practice in building industry.

For an old, low-rise brick building a classification according to structural elements may be more convenient for estimating damages, for example:

1) brick walls;
2) partitions;
3) roof and floor diaphragms;
4) columns.

In the classifications above, each subsystem can be assigned its own replacement value. The building value, then, can be represented with a replacement value vector R:

Subsystem No.	Description	Replacement Value ($)	
1	Structural	1,500,000	= R
2	Architectural	2,400,000	
3	Mechanical	1,200,000	
4	Electrical	900,000	

It should be noted that the sum of the components of the replacement value vector R must equal the total replacement value of the building.

For a given peak ground acceleration level I, a "damage ratio" vector D_I can be defined with each component representing the expected value of the damage ratio for a subsystem.

Determination of the damage ratio vectors D_I, for different peak ground acceleration levels, is the most important step in the procedure. As noted previously, these values can be obtained from the applicable data from the past earthquakes. In the absence of satisfactory data, the ratios can be estimated by means of an engineering analysis of the structure.

During an actual earthquake, two very similar buildings located next to each other are very likely to suffer different amounts of damage due to minor differences, local soil conditions and various other reasons. Therefore, statistical damage information for certain types of buildings is usually given as a distribution of different levels of damage. Expected values of the damage ratios can be calculated from this information as follows:

Subsystem No.	Percentage of Buildings with Indicated Damage Ratio				(D_I) Expected Value
	0.00	0.25	0.50	1.00	
1	0.60	0.25	0.10	0.05	0.1625
2	0.50	0.25	0.15	0.10	0.2375
3	0.70	0.20	0.05	0.05	0.1250
4	0.60	0.20	0.15	0.05	0.1750

The last column in the above example is the damage ratio vector D_I for the applicable peak ground acceleration level, I. The expected value of the damage ratio for subsystem 1 is obtained as a weighted average:

$$0.00 \times 0.60 + 0.25 \times 0.25 + 0.50 \times 0.10 + 1.00 \times 0.05 = 0.1625$$

After the damage ratio vectors D_I are determined for each peak ground acceleration level I, then the monetary values of the total expected damages at these peak ground acceleration levels designated as L_I, are found simply:

$$L_I = D_I^T \times R$$

Further, if a "damage matrix" D is formed by assuming D_I vectors as rows, a new vector L is calculated:

$$\begin{Bmatrix} L_1 \\ L_2 \\ L_3 \\ L_4 \end{Bmatrix} = \begin{Bmatrix} D_1^T \\ D_2^T \\ D_3^T \\ D_4^T \end{Bmatrix} \times \{R\}$$

or

$$L = D \times R$$

The vector L will be called "expected damage vector".

The final step is to calculate the "total expected damage" by simply multiplying the expected damage vector with the probability vector for the peak ground acceleration levels:

$$\text{Total Expected Damage} = P_{pga}^{T} \times L$$

The last two steps can be combined to give:

$$\text{Total Expected Damage} = P_{pga}^{T} \times D \times R$$

In the preceding, if m is the number of peak ground acceleration levels and n is the number of the subsystems, then P_{pga} is a (mx1) vector (or P_{pga}^{T} is (1xm)), D is (mxn) and R is a (nx1) vector. The final answer "Total Expected Damage" is in dollars.

2.4.2 Classification and Evaluation of Damages due to Earthquake Induced Events

In Section 2.4.1 a procedure has been described to evaluate the monetary value of the total expected damage for a given building due to possible earthquakes. In this procedure, the actual "causes" of the damage are not identified, or implicitly, the damages are assumed to be due to direct ground shaking.

However, most earthquakes are followed by earthquake induced fires, landslides or liquifactions, tsunamis and even floods (due to failure of dams or dikes). In some cases, the damage to the buildings due to these secondary events can exceed the damages suffered due to actual ground motion.

The exposure of a given site to any or a combination of these secondary hazards, under certain circumstances, can be estimated. For example, if a building is downstream from an old earth dam, the probability of total loss due to a flood is the conditional probability of the dam breaking in a given earthquake.

In the following, two earthquake induced events, fire and sub-structure failure, will be considered. The damage matrix D described in Section 2.4.1. will be modified to reflect the damaging effects of these two secondary events. The use of the following method is dependent on the ability to estimate the conditional probabilities of these events given an earthquake, as well as the ability to estimate the damage ratios for a combination of each event with the earthquake. The method is simple and flexible so that if satisfactory information does not exist or the user does not wish to consider the secondary effects, the following steps can be completely eliminated by assigning zero probabilities to these secondary events.

The damages suffered by the subsystems of a building can be due to direct earthquake effect only, or it can be due to earthquake combined with fire, substructure failure (liquifaction, landslide, etc.), tsunamis or other similar phenomena. If only fire and substructure failure are considered, then the damages can be due to four possible combinations of events (damage states) conditional on the earthquake happening:

1) damage due to earthquake only;

2) damage due to earthquake combined with fire;

3) damage due to earthquake combined with substructure failure;

4) damage due to earthquake combined with both fire and substructure failure.

If fire and substructure failure are assumed to be independent events and they are assigned conditional probabilities (i.e., probability of fire, given an earthquake occurring with a certain peak ground acceleration level), then the probabilities associated with each of the four "damage states" can be calculated.

Let:

F = Event that fire occurs
$\overline{F}$ = Event that no fire occurs
SS = Event that substructure failure occurs
$\overline{SS}$ = Event that no substructure failure occurs
$P(F)$ = Probability of fire occurring
$P(SS)$ = Probability of substructure failure occurring
P_1, P_2, P_3, P_4 = Probability of each damage state

Then,

$$P_1 = P\ (\overline{F} \cap \overline{SS}) = P\ (\overline{F}) \times P\ (\overline{SS})$$
$$P_2 = P\ (F \cap \overline{SS}) = P\ (F) \times P\ (\overline{SS})$$
$$P_3 = P\ (\overline{F} \cap SS) = P\ (\overline{F}) \times P\ (SS)$$
$$P_4 = P\ (F \cap SS) = P\ (F) \times P\ (SS)$$

For a given subsystem (e.g., architectural) and a certain peak ground acceleration level, if d_1, d_2, d_3 and d_4 describe the expected percentage damages for that subsystem due to states 1, 2, 3 and 4, respectively, and if each of these states has the probability of occurrence as described above, then the expected damage for this peak ground acceleration level can be expressed as:

$$\text{Expected Architectural Damage} = P_1d_1 + P_2d_2 + P_3d_3 + P_4d_4$$
$$= \sum_{i=1}^{4} P_id_i$$

This procedure can be repeated for each subsystem. Each of these values is a component of the damage ratio vector D_I corresponding to the peak ground acceleration level I, as described in Section 2.4.1.

It should be noted that the effects of fire and substructure failure can be completely eliminated, if so desired, by simply assigning zero probabilities to these events, i.e.,

$P(F) = 0$ $\qquad P(\overline{F}) = 1.0$

$P(SS) = 0$ $\qquad P(\overline{SS}) = 1.0$

and

$P_1 = 1.0$

$P_2 = P_3 = P_4 = 0$

The procedure described in this section can be summarized in matrix form:

$$D_I = D_{DS,I} \times P_{DS,I}$$

where:

$P_{DS,I}$ = (n x 1) vector, each component of which represents the probability of a damage state occurring for a peak ground acceleration level I.

$D_{DS,I}$ = (m x n) matrix. A component $d_{DS,I}(i,j)$ represents the percentage damage expected for subsystem i, in the event that damage state j occurs for a given peak ground acceleration level I.

D_I = Damage ratio vector (m x 1) as described in Section 2.4.1.

m = Total number of subsystems.

n = Total number of damage states. (For the case considered, n = 4)

2.4.3 Calculation of Total Expected Losses

For a given modification scheme the total expected loss due to seismic hazard can be divided into the following components:

1) Cost of modification.
2) Losses due to structure related damages for:
    a) Short-term earthquake prediction.
    b) Ambient seismic hazard during the useful life of the building.

3) Losses due to extra-structural damages.

Since the monetary value of the losses is a function of the time these losses occur, all components should be expressed in terms of a common monetary unit. The present value of the local monetary unit (Dollar) can conveniently be used for this purpose.

In this study it is assumed that the selected modification scheme will be implemented immediately following the decision. Therefore, the cost of such a scheme can be estimated in terms of "present value" directly, by using the present time material and labor costs.

In Sections 2.4.1 and 2.4.2 a methodology to calculate the expected value of the structure related damages is presented. This methodology is applicable to both a predicted earthquake and the ambient seismicity case provided that the probability vector for peak ground acceleration levels (P_{pga}) is given.

For the predicted earthquake case, the calculation is straightforward if the prediction period is assumed to be short compared to the useful life of the building. With this assumption, present values can be used in the replacement value vector (R), and the expected damages are calculated directly in terms of present values.

No earthquake prediction can be made with 100% confidence. Therefore, the expected loss due to a predicted earthquake should be reduced by a "confidence factor" before it is summed with the other components.

For the ambient case, the procedure can best be explained with an example:

Assume that a building with a certain modification scheme is given and the expected useful life is 30 years. This life span can be studied in 6 periods of 5 years each. For each of these 5 year periods, the vector P_{pga} (probability of peak ground acceleration levels) is identical. By using this P_{pga} vector and the present value of R (replacement value) vector the expected loss for a 5 year period can be calculated in terms of present values. This value of expected loss represents how much the losses would be if the seismic hazard expressed by the P_{pga} vector for a 5 year period had happened at present time. Next step is to answer the question: "How much would the same damage be worth in terms of today's money if it were to happen in the middle of each 5 year time period?"

If the inflation rate (or the rate of increase of the cost of repairs) is "i" per year, a certain amount of physical damage worth "D" dollars today will be worth "D_n" dollars in n years where D_n is given by:

$$D_n = De^{in}$$

In order to have D_n dollars available to do the repairs at the end of n years, "D_{pn}" dollars should be invested today with a return rate of "p" per year.

Then,

$$D_n = D_{pn}\ e^{pn}$$

From the two equations above:

$$D\ e^{in} = D_{pn}\ e^{pn}$$

$$D_{pn} = \frac{D\ e^{in}}{e^{pn}} = D\ e^{(i-p)n}$$

or,

$$D_{pn} = D\ e^{(i-p)n}$$

where D_{pn} is the present monetary value of expected damages occurring n years from today.

The last relationship can be applied to damage estimates for each time period and summed to obtain the present value of the expected loss for the useful life of the building.

The Total Expected Loss is the sum of the cost of modifications, expected losses due to predicted earthquake, and the present value of the expected losses due to ambient seismicity during the useful life of the building, i.e.,

$$TEL = C_m + D_p + \sum_{n=n_1,n_2\ldots} D_{pn}$$

where:

TEL = Total expected loss

C_m = Cost of modifications

D_p = Expected losses due to predicted earthquake

D_{pn} = Present value of expected damages if they occurred in n years from now

$n_1, n_2 \ldots$ = Time in years from today to the middle of each time interval

With the methodology described above, the total expected loss for various modification schemes can be calculated. These values then can be used to identify the economically most feasible modification scheme.

As noted in Section 2.4, losses due to extra-structural damages are not considered in this study and will be considered in Phase II studies.

3. DISCUSSION AND CONCLUSIONS

3.1 Discussion

The objective of this two-phase study is to develop a methodology to be used by building owners or managers as a decision-making tool in the selection of the economically most feasible course of action to minimize their financial losses from future earthquakes. Phase I work described in this report was undertaken to study the feasibility of developing such a methodology.

In Section 2 of this report, a rational decision analysis methodology to evaluate possible seismic improvement schemes for existing buildings is described. Based on this methodology, a computer program (DAMSTAT) was developed. The flow chart and the computer listing of this program are presented in Appendix C.

To check the practicality of the program "DAMSTAT", several hypothetical example problems were studied. One such example is presented in Appendix D. In this example, a hypothetical building with a present value of $5.9 million and a useful lifetime of 20 years is considered. Seismic hazard due to a predicted earthquake as well as the ambient hazard is taken into account. It is assumed that there are three possible schemes (including doing nothing) to be considered and compared for final selection. The results of the computer analysis for this problem are summarized in Table 1. Four different cases representing different combinations of earthquake hazard with fire and substructure failures are tabulated. These results are also plotted as shown in Figure 3.

Table 1 and Figure 3 are the typical analysis results to be presented to the decision-maker. From Figure 3, it can be seen clearly that Scheme No. 2 minimizes the total expected losses due to the predicted and the ambient earthquake hazard. Therefore, if the decision-maker is going to make a decision purely on the basis of this economic comparison, Scheme No. 2 will be selected for implementation. However, for the specific example shown in Figure 3, the decision-maker may wish to analyze an intermediate scheme between Scheme Nos. 2 and 3, which may reduce the total expected loss even further with a nominal initial cost increase over Scheme No. 2.

As part of this study, a panel of consultants in the economic, financial and real estate fields was formed. The objectives of the study and the outline of the proposed methodology were described to the panel, and the opinions of the panel members were solicited on the following basic questions:

- Is there a need for the methodology being developed by this study?
- If the methodology is further developed, will the building owners be willing to use it as a tool in their decision-making process?

TABLE 1

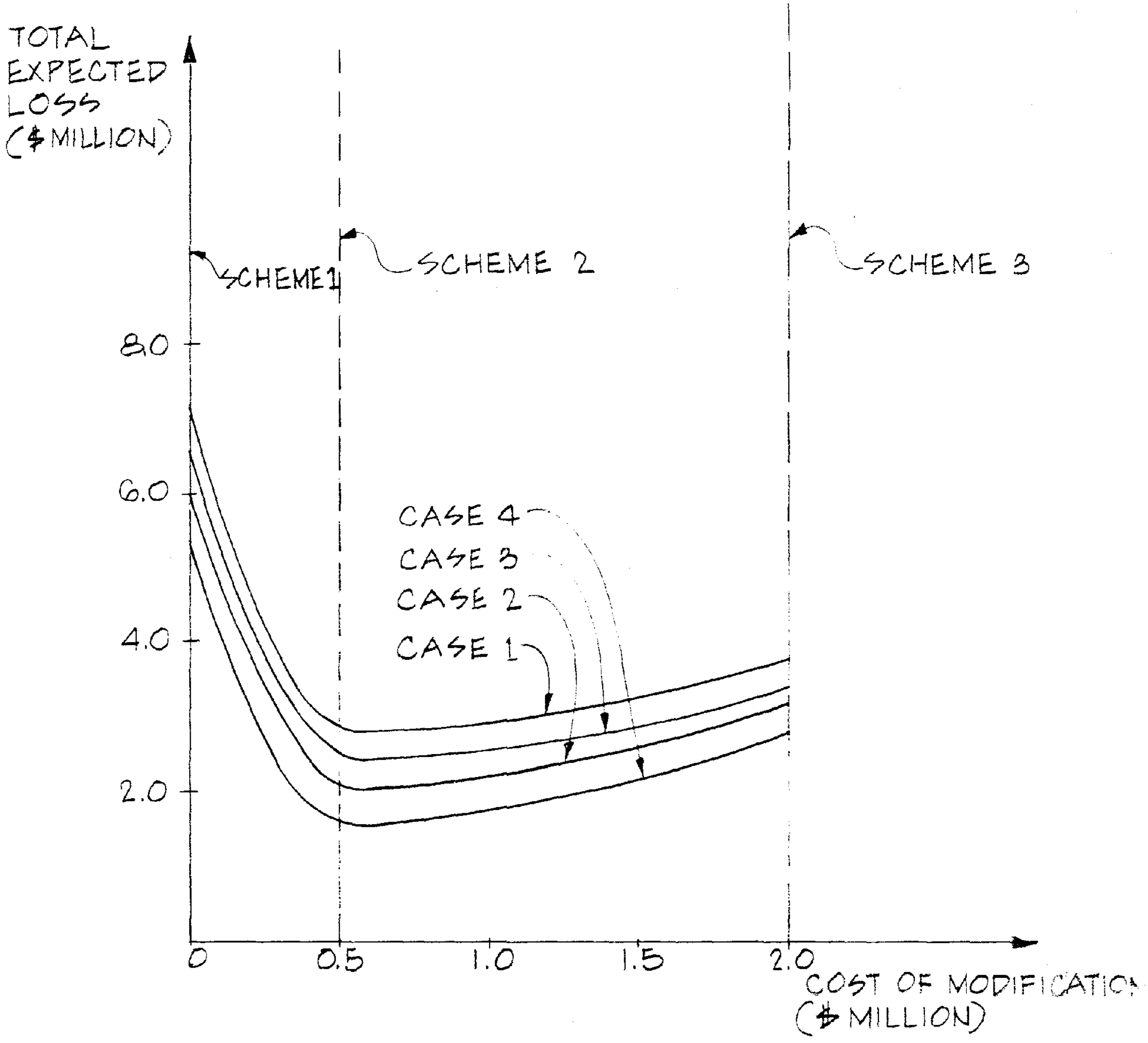
SUMMARY OF EXAMPLE ANALYSIS

CASE NO.	COST/BENEFIT	SCHEME NO.		
		1	2	3
1	COM	0.0	0.5	2.0
	TEL	7.2	2.9	3.8
2	COM	0.0	0.5	2.0
	TEL	6.0	2.1	3.2
3	COM	0.0	0.5	2.0
	TEL	6.6	2.5	3.4
4	COM	0.0	0.5	2.0
	TEL	5.4	1.6	2.8

NOTES:

1. COM = Cost of Modification ($ Millions)
   TEL = Total Expected Loss ($ Millions)

2. Case numbers correspond to the following:
   1 = Probabilities of fire and substructure failure are considered.
   2 = Probability of fire is disregarded.
   3 = Probability of substructure failure is disregarded.
   4 = Probabilities of both fire and substructure failure are disregarded.



SUMMARY OF EXAMPLE ANALYSIS
FIGURE 3

- What other segments of the building and financing industries may have use for this or a similar methodology?

The responses to the first two questions were affirmative. It was agreed that building owners presently did not have any rational tool to analyze the economic cost-benefit relations for various alternate schemes. It was suggested that the use of such a methodology by building owners should be strictly on a voluntary basis and any regulation attached to the studies (similar to OSHA regulations) would discourage the use of the methodology. It was also suggested that the methodology could be applied to new construction at the design stage, in order to determine the most cost-effective performance levels above and beyond the levels provided by building codes. The potential use of the methodology by insurance and financing companies was thought to be a good possibility.

3.2 Conclusions

The work described in this report intended to study the feasibility of developing a rational decision-making methodology to be used by building owners (or managers) in seismically active regions. The methodology would be a tool in the selection of the economically most feasible course of action to protect their investments from earthquake hazards.

The approach adopted to study the feasibility of developing such a methodology was to attempt developing a preliminary methodology that could be applied to realistic problems. Opinions of the potential users of the methodology were also an important factor in the conclusions of the study.

In this report, a preliminary methodology has been developed and described. The process has been fully computerized and successfully applied to several realistic problems. Opinions of the panel of consultants from economic, financial and real estate fields have indicated that there was a need for a rational decision-making methodology, and it would be used by building owners and managers as well as the financing and insurance industries.

Therefore, it is concluded that there is a national need for the methodology this work has attempted to develop, and futhermore, such a methodology can be developed and applied to practical problems. Hence, it is recommended that Phase II studies be conducted for further development of the ideas and procedures described in this report.

Phase II studies should refine and further develop the ideas and procedures described in this report. The following subjects are recommended for further study as part of Phase II work:

1. Incorporate seismic hazard determination procedures into the methodology.
2. Develop actual damage matrices for a number of building types from past earthquake data. Efforts should be made to include the effects of earthquake triggered events on the damages (e.g., fire, flood, soil liquifaction, etc.).

3. Attempt to develop analytical models for predicting earthquake damage on structures. Describe the methodology for developing damage matrices in the absence of statistical data.
4. Incorporate "extra-structural" or non-physical damages, such as loss of life, injuries, lawsuits, lost wages and rent, and insurance into the methodology.
5. Further study the improvement schemes for various building types.
6. Apply the methodology to an actual building.

A proposal for the Phase II work is being prepared by Earthquake Engineering Systems, Inc., and will be submitted shortly following this report.

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Appendix A

DAMAGE TO TYPE III BUILDINGS IN PAST EARTHQUAKES AND POSSIBLE MODIFICATION SCHEMES

A.1 Description of Type III Buildings

The particular group of buildings designated as Class C in many of the older building codes and as Type III in the Uniform Building Code (39) is defined by R. R. Martel (36):

> Class C or Type III buildings - ordinary masonry construction; i.e., exterior masonry bearing walls with interior load-bearing construction of wood, steel or masonry. Partitions, roof, and floor framing may be wood. Type III is not confined to brick; yet, at the time of earthquake (Long Beach, 1933), practically all Type III buildings in Long Beach were brick construction.

Type III buildings constructed prior to 1933 are of special interest, since these buildings were designed for gravity loads only, without any necessary consideration for earthquake resistance. Due to its construction simplicity this type of structure was very popular for buildings of one to four stories in height. As a result, thousands were built during the pre-1933 period, and most of these buildings are still in use.

A typical pre-1933 Type III building has exterior walls (12 to 13 inches in thickness) made up of three wythes of brick (1). The outer wythes are fully bedded in mortar while the inner wythe is usually made up of rubble or pieces of broken bricks. The mortar has been sloshed into this interior space without any special effort to fill the voids. The sand and lime mortar employed for the wall construction is exceedingly variable in strength and quality. In some cases, it has varying amounts of cement.

The floors and roof framing may consist of either wood joists or nailed wood trusses. These members bear on pockets provided in the walls. In most roofs,the interior wythe stops at the ceiling line in order to provide a sill for support of the roof framing. In some cases, cripple studs are used to raise the roof framing above ceiling joists to provide an attic space. The floor and roof framing members are usually tied to the walls with T-bar anchors spaced at six to eight feet.

When steel or wood girders are used, these are also set into pockets provided in the walls. At these locations, the walls are thickened to form pilasters.

In order to carry the brick masonry over large wall openings, steel beam headers are provided. However, these beams are merely seated on the brick and are not anchored to the wall by any positive means such as straps or bolts. Typical detail drawings for these Type III buildings can be found in Figure 1 of Reference 1.

A.2 Background

As noted in Section A.1, prior to 1933 Type III masonry buildings were designed without any consideration of seismic resistance. After the destructive Long Beach earthquake of 1933, the Riley Act was adopted so as to establish minimum standards for earthquake resistance. However, the provisions of this act were not made retroactive, and they applied only to new construction. During the same year, the State of California adopted the Field Act, setting standards for earthquake-resistant design of public schools.

Also, with the lessons learned from past earthquakes and a recognition of the hazard in old masonry buildings, various cities have passed "parapet laws" requiring that hazardous parapets and cornices be either strengthened or removed. Thousands of such buildings in the City and County of Los Angeles have had such corrections made. The results of the program undoubtedly saved many persons from injury or death during the San Fernando earthquake of 1971 (35).

Some cities in recent years have passed regulations requiring demolition of hazardous buildings or the rehabilitation and repair to meet existing standards for earthquake resistance. The program undertaken by the City of Long Beach, California, in 1959 is an example.

Presently, over 20,000 pre-1933 buildings exist in the Los Angeles area (35). Approximately 60% of these are residential buildings; 35% are commercial and industrial buildings, and warehousing and storage facilities; and the remaining 5% are hospitals and meeting or assembly-hall facilities. The continued use of these buildings without any strengthening involves very large risks in terms of loss of property and human lives.

Within the next section, the findings of an extensive literature search on performance of these buildings in past earthquakes are presented. This provides an identification of major structural problem areas and causes of failure.

A.3 Description of Damages to Type III Buildings

As a part of this study, a literature search was performed to obtain as much information as possible on the performance of Type III brick buildings in past earthquakes. The objective of this effort was to understand the behavior of these buildings during earthquakes, and to identify the major weaknesses of this type of construction. The findings of this study were used to develop a list of possible fixes and modification schemes to improve the performance in future earthquakes.

The general patterns of failure of unreinforced masonry buildings reported for different earthquakes are quite similar. The various authors describing the damages due to the Santa Barbara earthquake of 1925 (6), Long Beach earthquake of 1933 (36) and San Fernando earthquake of 1971 (1) gave similar descriptions of damages and agree on the major weaknesses of this type of building.

One of the most commonly described type of damage is the failure of the parapets, cornices and ornamentations and their lethal shower of debris onto the sidewalks. This hazard was recognized after the Long Beach earthquake, and improvement programs have been undertaken by some cities as noted in Section A.1. Exterior walls have suffered various types of damages. Most of the walls which survived the reported earthquake without total collapse had permanent displacements in both the longitudinal and the perpendicular directions. The former were caused by shear failure in the form of diagonal cracking, and the latter was caused by failure of the ties to the roof or floor diaphragms and/or by lack of flexural strength of the wall in perpendicular directions. In some cases the outer wythes of bricks fell off due to lack of ties or bond between the brick layers. The failure of walls was almost invariably associated with the poor quality or deterioration of lime mortar, the lack of ties and headers between bricks, and/or the low quality of bricks and workmanship. It is interesting to note that front walls with large glass window openings suffered minimal damage even when other walls of the same building failed. The reasons for this behavior have not been clearly explained, but flexibility of these walls and the support provided by adjacent buildings have been suggested. In general, buildings adjacent to other buildings suffered less damage than buildings that were not attached to any adjacent buildings.

Floor and roof framing separated from the walls and therefore failed to provide the diaphragm action which is vitally necessary for wall support. Some roof collapses were reported due to the loss of support when the walls separated. In some cases, failures at floors were reported where the stairs were rigidly connected to the floor framings. In these instances, stairs acted as diagonal bracing inducing large concentrated loads on the floors.

One report (1) noted that the extent of damage was not proportional to the maximum ground acceleration experienced at the site. Damages suffered by buildings in areas recording 9% of gravitational acceleration were similar to that suffered by buildings in areas recording more than twice that acceleration. This points out the brittle nature or the lack of ductility in the brick walls, i.e., when the shear or flexural capacity of the masonry is exceeded, the walls crack and parapets fall, regardless of the intensity of the actual accelerations beyond the low failure level.

Reports and conclusions about the effect of soil properties on the extent of damage vary and sometimes are contradictory. Reference 36 concludes that in the Long Beach earthquake of 1933, the damage to buildings on soft, waterlogged soil was somewhat less than to those on more firmly consolidated soil. Alternatively, in Reference 48, it is noted that the most destructive damage occurred to buildings on soft ground in the San Francisco earthquake of 1906.

From the observations described above, the major weaknesses of this type of building can be summarized:

1. Brick masonry walls do not have any vertical or horizontal reinforcement. Therefore, they do not have any significant flexural capacity in perpendicular direction and have low shear capacity in their own plane.
2. The deterioration of the commonly used lime mortar causes loss of strength and bond between bricks, resulting both in the spalling of brick layers and a complete loss of shear strength.
3. There is no mechanical tie between bricks, or orthogonal brick walls.
4. There is no bond or anchorage between the headers above wall openings and the wall.

5. Reinforced concrete bond beams at floor levels are inadequate.
6. Floor and roof construction lacks the strength and detailing to act as a diaphragm. No diaphragm chords or collector members are provided.
7. Roof and floor framing members are not tied to the walls adequately.
8. In some instances, low quality bricks have been used.
9. Quality of workmanship greatly affects the performance of the buildings, and in many cases this quality has been poor.

A.4 Improvement Schemes for Type III Buildings

A.4.1 General

In Section A.3, the typical damages to Type III buildings in past earthquakes are studied, and major structural deficiencies of this building type are identified. Most of these deficiencies can be fixed, and the building can be upgraded to various levels of earthquake resistance. The extent of repairs and improvements depends on the following factors, among others:

1. Occupancy: The repairs and improvements required for a public assembly building (e.g., a theater) can be very extensive whereas a smaller degree of improvements may be acceptable for a storage building.
2. Time limitations: In case of a short-term earthquake prediction, the lead time may not be sufficient to complete extensive improvements and repairs, therefore

requiring temporary fixes.

3. Economic considerations: In many cases, especially where danger to human lives is minimal, a smaller degree of reinforcement may be justified on the basis of cost-benefit relationships. The methodology to evaluate these cost-benefit relationships is given in the main text of this report.

The modifications can in general be classified as (1) temporary, or (2) permanent.

A.4.2 Temporary Modifications

These modifications can be done quickly at a reasonable cost. The main objectives are to prevent a total collapse of the building or its various parts (walls, parapets, etc.) and to minimize the danger to human lives as well as the financial losses. The following are possible temporary modifications:

1. shoring interior and exterior spaces where danger of falling debris exists;
2. shoring or bracing window and door openings;
3. external or internal bracing of brick walls perpendicular to their plane;
4. providing temporary timber posts at outer walls to support the floor or roof diaphragm;
5. providing temporary in-plane bracing for the exterior walls;

6. shimming or wedging the gaps between interior frames and the exterior walls and the gaps between adjacent buildings to prevent "hammering;"
7. tying down, anchoring or removing the building contents which can create a falling hazard;
8. using cables to brace walls and/or diaphragm.

A.4.3 Permanent Modifications

These modifications require a reasonable time for design and construction. The modified structure may be required to conform with the latest earthquake resistance requirements for new buildings. Some of the possible permanent modifications are:

1. creating new floor or roof diaphragms by plywood overlay over the existing diaphragms or by cross bracing in the horizontal plane and providing new chord and collector members (ties);
2. anchoring exterior and interior masonry walls to the diaphragms;
3. removal or strengthening of masonry walls which lack adequate strength to resist earthquake loads perpendicular to their planes;
4. in-plane bracing of masonry walls or installation of new shear walls;
5. installation of tie-downs for overturning on walls or frames;
6. removal or anchorage of interior or exterior parts of building which are falling hazards.

Appendix B

DAMAGE STATISTICS FOR MASONRY STRUCTURES

B.1 General

In the following, a procedure to develop damage matrices for a class of buildings using statistical data from past earthquakes is presented. This study was conducted for EES, Inc., at Stanford University, Stanford, California, under the supervision of Professor Haresh C. Shah.

B.2 Procedure

The study is based on actual data reported in the literature for a number of earthquakes. Subjective terms used by reporters to describe the quantity and the extent of damage are treated as follows:

Quantity:

Single, Few	5%
Some	25%
Many	50%
Most	75%

Damage:

Slight	5%
Moderate	10%
Heavy	40%
Destruction	90%
Total Damage (Collapse)	100%

Masonry buildings are classified into four groups:

Masonry A: Engineered reinforced masonry with good materials and good workmanship. Designed to resist earthquakes.

Masonry B: Reinforced masonry with good workmanship and materials. Not designed to resist earthquakes.

Masonry C: Unreinforced masonry with ordinary workmanship and materials. Not designed to resist earthquakes (Type III buildings).

Masonry D: Poor materials, such as adobe, and poor workmanship. Little or no earthquake resistance.

Data from the following earthquakes are considered in the study:

1) Owens Valley, March 26, 1872
2) San Francisco, April 18, 1906
3) Hawke's Bay (New Zealand), February 3, 1931
4) Long Beach, March 10, 1933
5) Imperial Valley, May 18, 1940
6) Kern County, California, July 21, 1952
7) Skopje, Yugoslavia, 1963
8) Lima, Peru, October, 1974
9) Caldiran, Turkey, November 24, 1976
10) Guatemala, 1976
11) Chile, 1913 through 1966.

For each of the above earthquakes mean damage ratios (MDR) applicable to each of the four building classes are determined for various intensity levels, and plotted on logarithmic paper as shown in Figures B-1 through B-4. The curves shown in the figures are obtained by regression analysis.

On Figure B.1, curves corresponding to mean damage ratios for structural, architectural, mechanical and electrical damages are shown in addition to the total mean damage ratio curve. These curves were obtained by assuming the following distribution of the damage:

Structural damage = 40%
Architectural damage = 50%
Mechanical damage = 7%
Electrical damage = 3%

B.3 Illustrative Example

With the curves relating mean damage ratios to intensities determined, damage vectors with any number of peak ground acceleration levels can be generated. Table B-1 shows a representative damage vector for Type A masonry buildings. The peak ground accelerations (A) are related to the Modified Mercalli Intensities (I) using the following formula by Trifunac:

$$\text{Log } A = 0.014 + 0.3I$$

B.4 List of References Used for Appendix B Study

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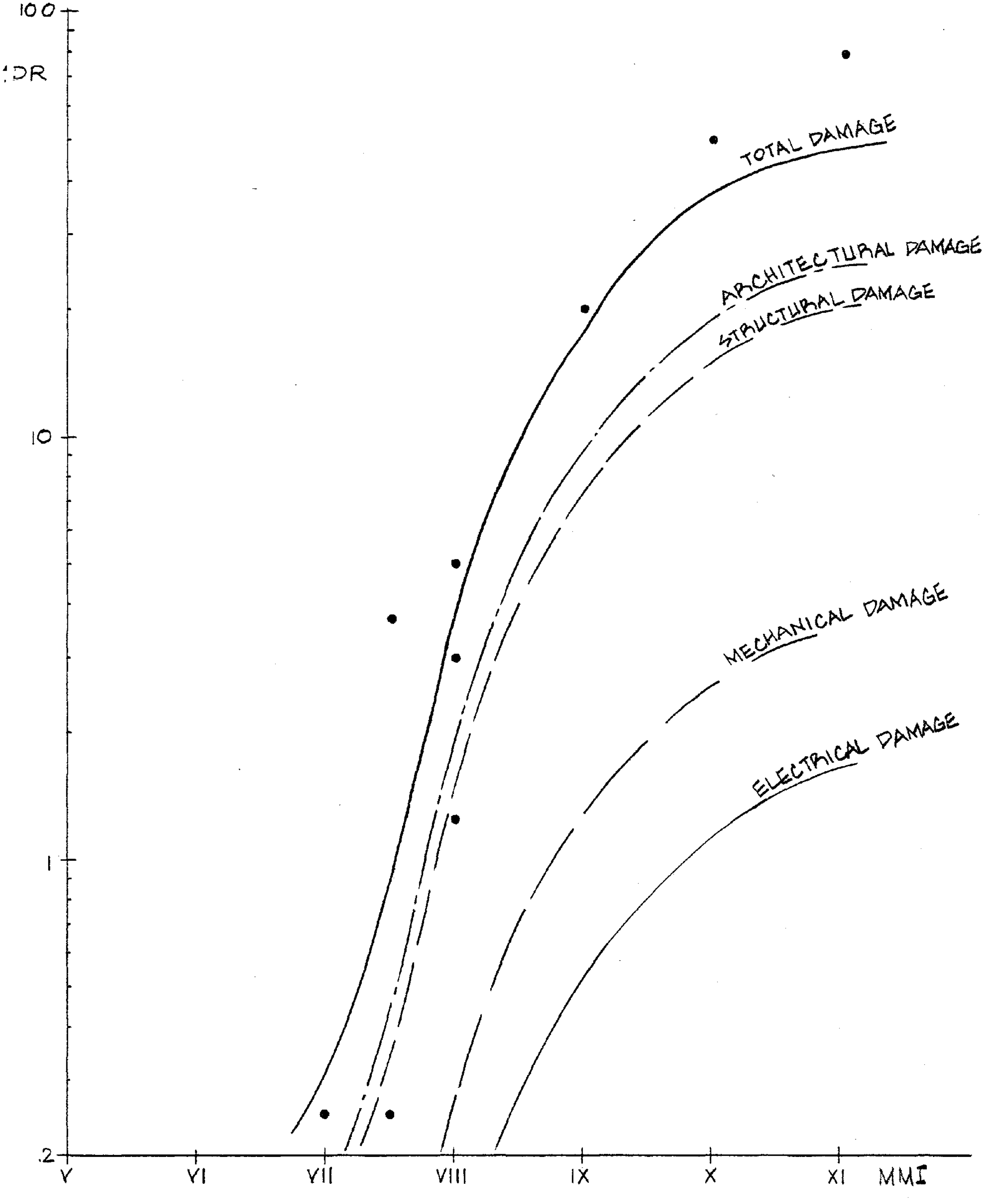

FIG. B-1. MASONRY TYPE "A" BUILDINGS

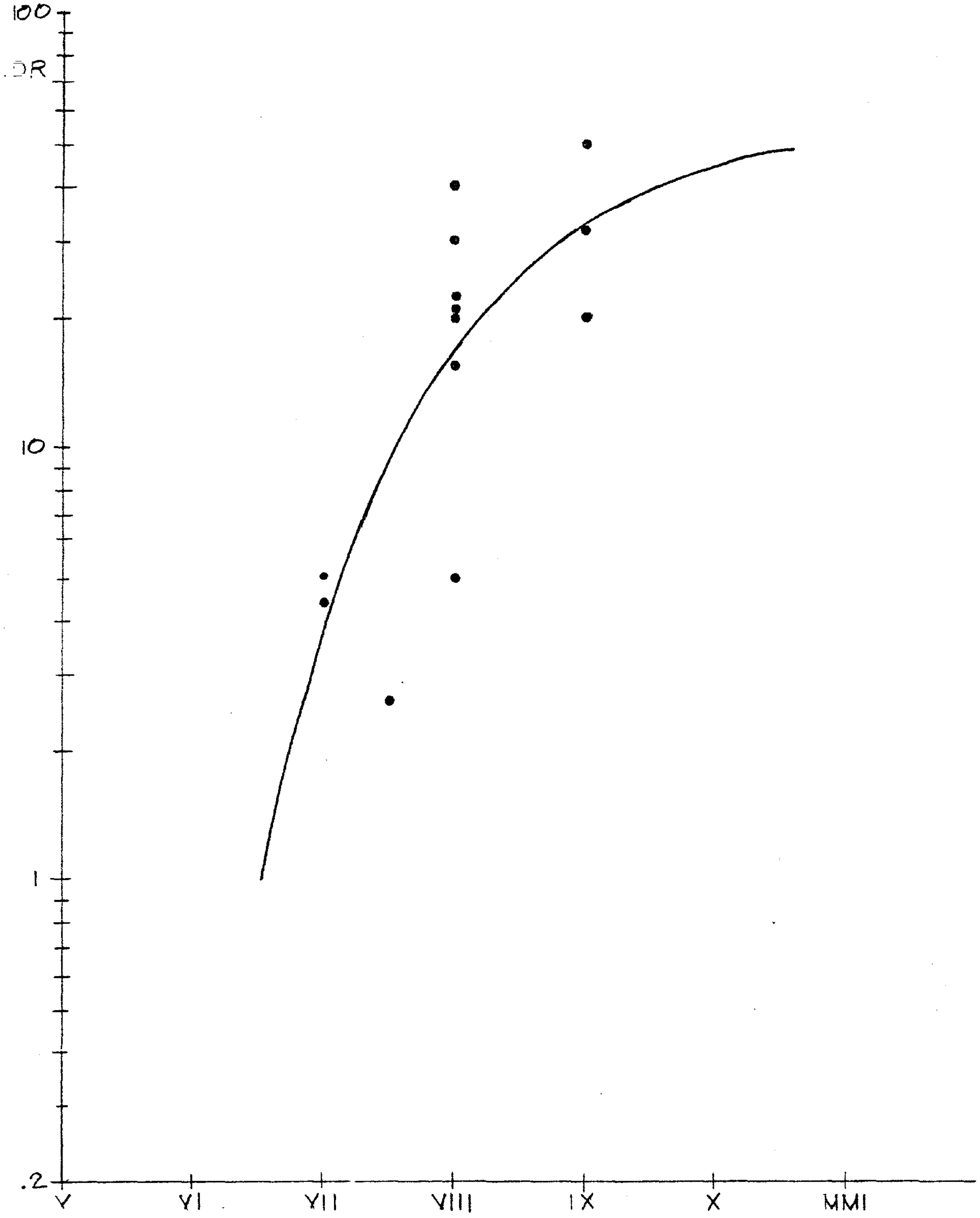

FIG. B-2 MASONRY TYPE "B" BUILDINGS

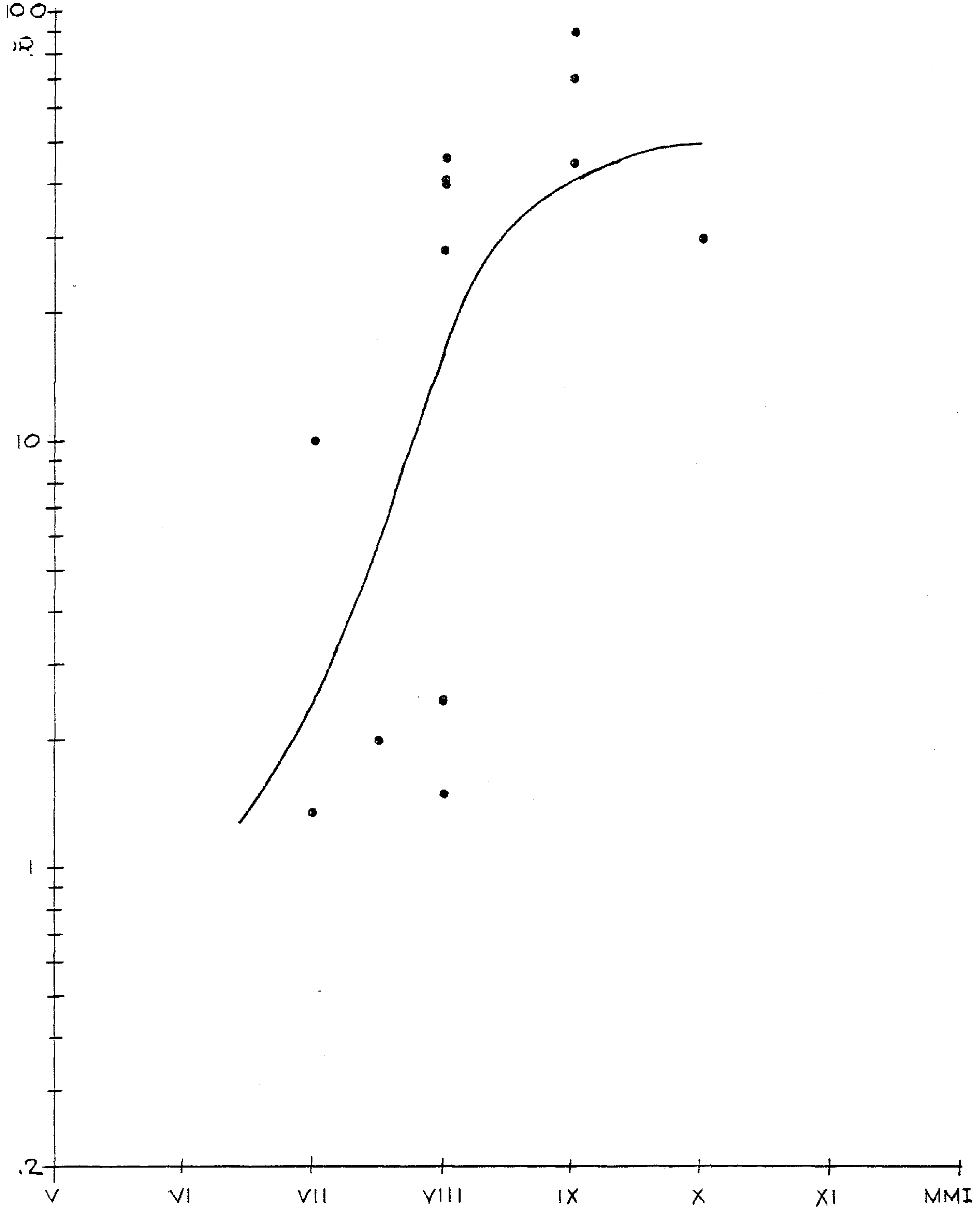

FIG B-3. MASONRY TYPE "C" BUILDINGS

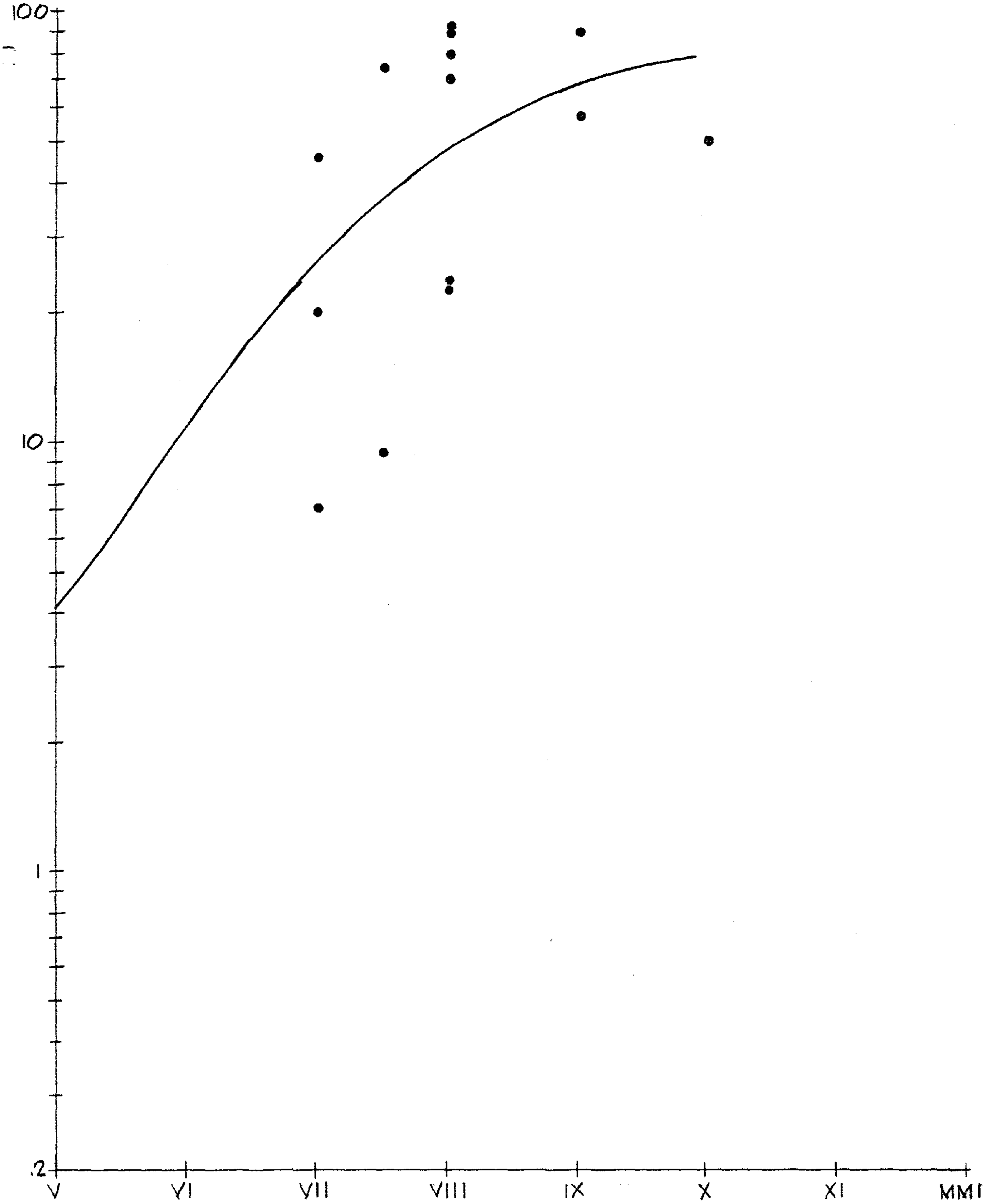

FIG. B-4. MASONRY TYPE "D" BUILDINGS

Table B.1

EXAMPLE DAMAGE MATRIX FOR MASONRY TYPE A BUILDINGS

MMI	pga (g)	MEAN DAMAGE RATIO			
		Structural	Architectural	Mechanical	Electrical
4.6	0.025	0.	0.	0.	0.
6.6	0.10	0.	0.	0.	0.
7.6	0.20	0.005	0.006	0.001	0.001
8.2	0.30	0.023	0.030	0.004	0.002
8.6	0.40	0.047	0.060	0.008	0.003
8.9	0.50	0.066	0.085	0.011	0.005
9.2	0.60	0.090	0.110	0.015	0.007
9.3	0.65	0.098	0.120	0.017	0.007

Appendix C

COMPUTER PROGRAM "DAMSTAT"

C.1 Description of the Program "DAMSTAT"

The methodology described in the main text of this report was fully automated through the development of a computer program (DAMSTAT) coded in FORTRAN language. An effort was made to present input and output information in a simple, tabular form so that results could be understood and evaluated by persons without any knowledge of computers or computer programming.

Table C.1 shows the "flow chart" for the program "DAMSTAT". Section C.2 presents the complete listing for the program and the associated subroutines. Output from the program for a hypothetical example problem are presented in Appendix D.

C.2 Listing of the Program "DAMSTAT"

(See the following pages.)

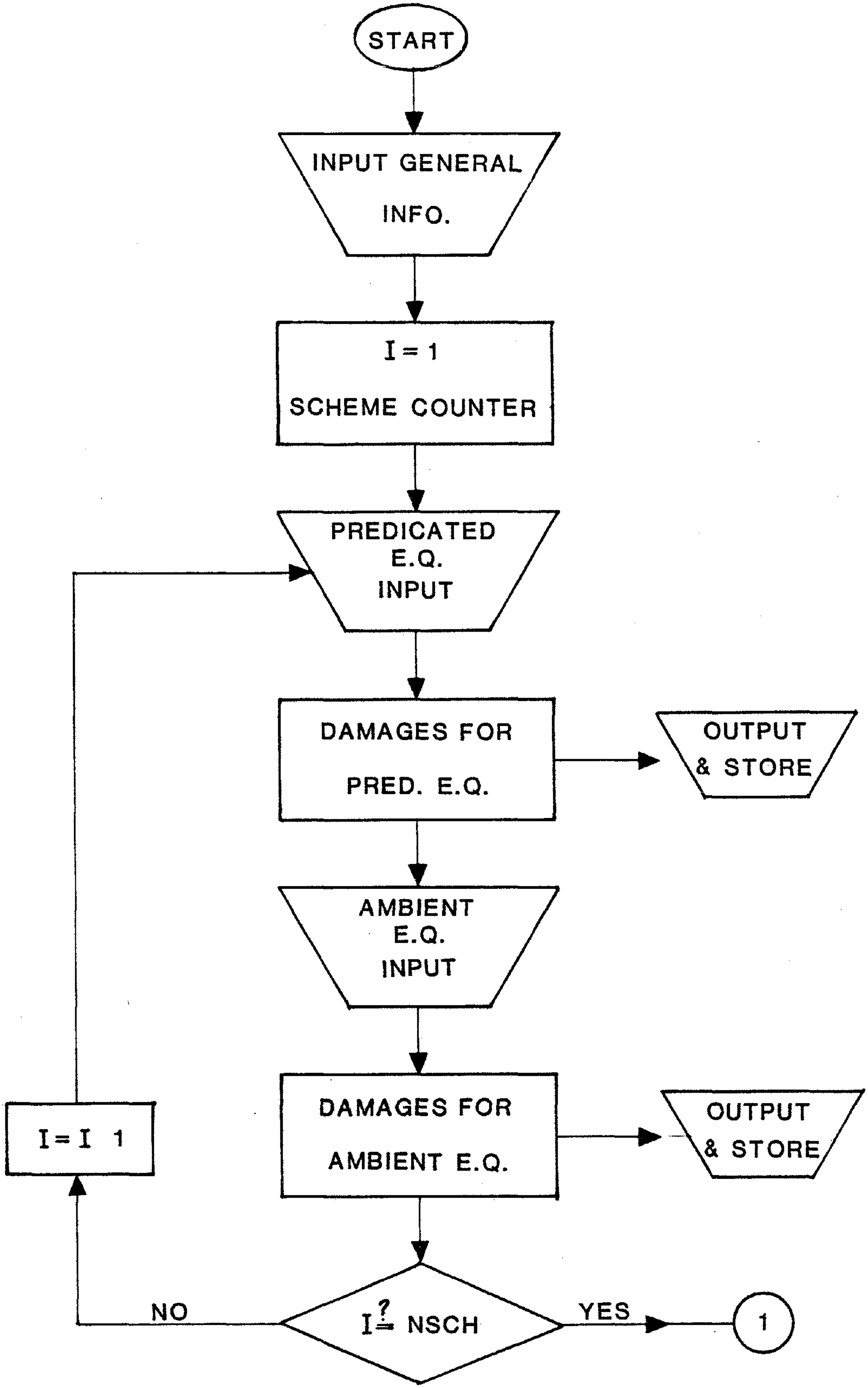

TABLE C-1 FLOW CHART FOR PROGRAM DAMSTAT

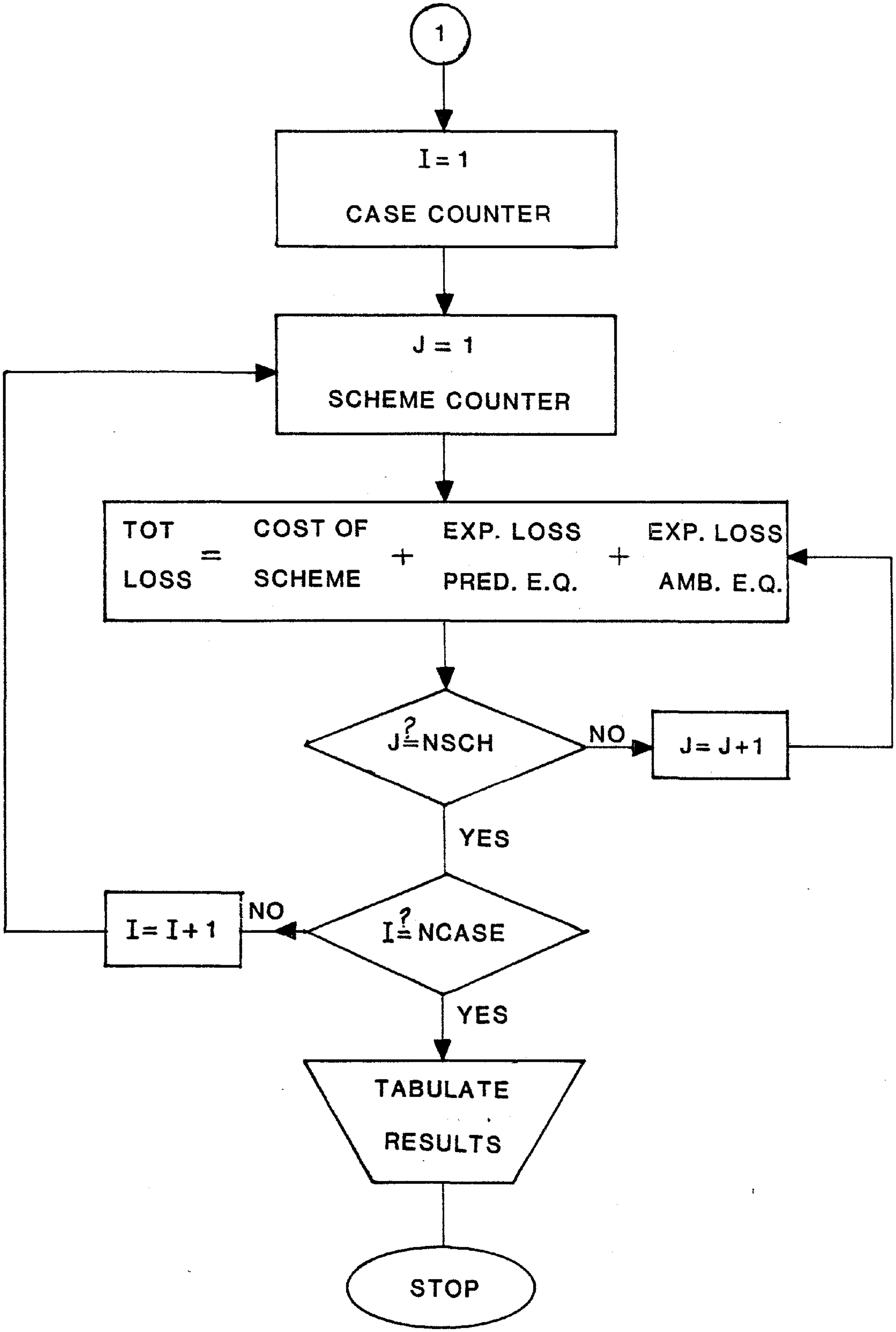

TABLE C-1 (CONTINUED)

```
      PROGRAM DAMSTAT ( INPUT. OUTPUT )
C
      COMMON/ BLDG / RV(4), NLIFE. NPER. NSCH. CSCH(6)
C
      CALL DATA1
C
      DO 100 I= 1. NSCH
      PRINT 1
      CALL PREDICT ( I )
      CALL AMBIENT ( I )
C
  100 CONTINUE
      CALL SUMMARY
C
    1 FORMAT ( 1H1 )
C
      STOP
      END
      SUBROUTINE DATA1
C
      COMMON/ ACCEL / NPP. PPGAP(10), NPA, PPGAA(10)
      COMMON/ BLDG / RV(4), NLIFE, NPER, NSCH, CSCH(6)
      COMMON/ PRED / PPRED
      COMMON/ MONEY / DTOT( 6,2,4 ), RD
      DIMENSION TITLE(8)
C
      READ 1. TITLE
      PRINT 2, TITLE
C
      READ 3, ( RV(I), I= 1. 4 )
      PRINT 4
      PRINT 5, ( RV(I), I= 1, 4 )
C
      READ 6. NLIFE. NPER
      PRINT 7, NLIFE
      PRINT 8, NPER
C
      READ 3, RINF, RINT
      PRINT 20, RINF
      PRINT 21. RINT
      RD = RINF - RINT
C
      READ 6, NSCH
      PRINT 9, NSCH
C
      READ 3. ( CSCH(I), I= 1. NSCH )
      PRINT 10
      DO 100 I= 1, NSCH
  100 PRINT 11. I, CSCH(I)
C
      READ 3, PPRED
      READ 6. NPP
      PRINT 12, PPRED
      PRINT 13
      DO 110 IP= 1, NPP
      READ 3, LOW, HIGH, PPGAP(IP)
      PRINT 14, IP, LOW, HIGH, PPGAP(IP)
  110 CONTINUE
C
      READ 6. NPA
      PRINT 15
      PRINT 13
      DO 120 IP= 1, NPA
      READ 3. LOW, HIGH, PPGAA(IP)
      PRINT 14. IP. LOW, HIGH. PPGAA(IP)
  120 CONTINUE
```

```
C
      PRINT 16
C
    1 FORMAT ( 8A10 )
    2 FORMAT ( 1H1, 8A10 )
    3 FORMAT ( 6F10.0 )
    4 FORMAT (// * REPLACEMENT VALUES ARE AS FOLLOWS :*)
    5 FORMAT ( * STRUCTURAL     =*,F14.2.* DOLLARS*/.
     1         * ARCHITECTURAL =*,F14.2.* DOLLARS*/.
     2         * MECHANICAL    =*,F14.2,* DOLLARS*/,
     3         * ELECTRICAL    =*,F14.2,* DOLLARS* / )
    6 FORMAT ( 6I5 )
    7 FORMAT ( /* ECONOMIC LIFE OF BUILDING =*, I3, * YEARS * )
    8 FORMAT ( * NO. OF TIME INTERVALS      =*, I3 )
    9 FORMAT ( /* NO. OF MODIFICATION SCHEMES =*. I3 )
   10 FORMAT ( /* SCHEME NO.*. 4X, * COST (DOLLARS) * )
   11 FORMAT ( 5X, I2, 10X, F12.2 )
   12 FORMAT ( 1H1,//* PREDICTION PERIOD*/* CONFIDENCE OF PREDICTION =*.
     1         F6.3 )
   13 FORMAT (//3X,*PGA LEVEL*,4X,*FROM (G)*,4X,*TO (G)*,4X,*PROBABILITY
     1*/ )
   14 FORMAT ( 6X. I2,7X, F6.3, 5X. F6.3, 7X, F6.3 )
   15 FORMAT ( //* AMBIENT PERIOD :* )
   16 FORMAT (/* DAMAGE STATE CLASSIFICATION :*/,
     1         * DAMAGE STATE = 1 : EARTHQUAKE DAMAGE ONLY*/,
     2         * DAMAGE STATE = 2 : EARTHQUAKE + FIRE DAMAGE*/,
     3         * DAMAGE STATE = 3 : EARTHQUAKE + SUBSTRUCTURE FAILURE*/.
     4         * DAMAGE STATE = 4 : EARTHQUAKE + FIRE + SUBSTRUCTURE*,
     5         * FAILURE*/ )
   20 FORMAT ( /* ANNUAL INFLATION RATE      =*, F6.3 )
   21 FORMAT ( * ANNUAL INTEREST RATE       =*, F6.3 )
C
      RETURN
      END
      SUBROUTINE DATA2 ( NP )
C
      COMMON/DAM/DS(4,4,10)
      COMMON/HAZARD/ PF(10), PSS(10), PS(4,10)
C
      DO 200 IP= 1, NP
C
      READ 6, PF(IP), PSS(IP)
      PRINT 7, IP
      PRINT 61, PF(IP). PSS(IP)
      CALL STATES (IP)
      PRINT 8
      PRINT 9, ( PS(I,IP), I= 1, 4 )
C
      DO 190 II= 1, 4
      READ 10,( DS(II,J,IP), J= 1. 4 )
      IF(II.EQ.1) PRINT 11, ( DS(II,J,IP), J= 1. 4 )
      IF(II.EQ.2) PRINT 12, ( DS(II,J,IP), J= 1, 4 )
      IF(II.EQ.3) PRINT 13, ( DS(II.J,IP), J= 1, 4 )
      IF(II.EQ.4) PRINT 14, ( DS(II,J,IP). J= 1, 4 )
C
  190 CONTINUE
  200 CONTINUE
C
C
    6 FORMAT ( 2F10.0 )
    7 FORMAT (/* PGA LEVEL = * , I2 )
    8 FORMAT (* DAMAGE STATE NO=*,10X,1H1, 9X,1H2,9X,1H3,9X,1H4)
    9 FORMAT (* PROBABILITY=*,10X,F6.3,3(4X,F6.3))
   10 FORMAT ( 4F10.0 )
   11 FORMAT (* STRL. DAM. RATIO  *, 4(4X,F6.3))
   12 FORMAT (* ARCH  DAM. RATIO  *, 4(4X,F6.3))
```

```
   13 FORMAT (* MECH  DAM. RATIO  *, 4(4X,F6.3))
   14 FORMAT (* ELEC. DAM. RATIO  *, 4(4X,F6.3))
   61 FORMAT ( /* PROBABILITY OF FIRE =*, F6.3/,
     1            * PROBABILITY OF S. S. FAILURE =*, F6.3/ )
C
      RETURN
      END
      SUBROUTINE DAMAGE (IP, DT)
      COMMON/DAM/DS(4,4,10)
      COMMON/ BLDG / RV(4), NLIFE, NPER, NSCH, CSCH(6)
      COMMON/HAZARD/ PF(10), PSS(10), PS(4,10)
      DIMENSION DTP(4)
C
C
C
      DO 100 K= 1, 4
      DTP(K)= 0
  100 CONTINUE
C
      DO 200 I= 1, 4
C
      DO 190 K= 1, 4
      DTP(I) = DTP(I) + DS(I,K,IP) * PS(K,IP)
  190 CONTINUE
  200 CONTINUE
C
      DT = 0
      DO 300 I= 1, 4
      DT = DT + DTP(I) * RV(I)
  300 CONTINUE
C
      RETURN
      END
      SUBROUTINE STATES (IP)
C
      COMMON/HAZARD/ PF(10), PSS(10), PS(4,10)
C
      PFN = 1. - PF(IP)
      PSSN = 1. - PSS(IP)
      PS(1,IP) = PFN * PSSN
      PS(2,IP) = PF(IP) * PSSN
      PS(3,IP) = PFN * PSS(IP)
      PS(4,IP) = PF(IP) * PSS(IP)
C
      RETURN
      END
      SUBROUTINE PREDICT ( NSCH )
C
      COMMON/ ACCEL / NPP, PPGAP(10), NPA, PPGAA(10)
      COMMON/ MONEY / DTOT( 6,2,4 ), RD
      DIMENSION DTOTL( 4 )
C
      PRINT 1, NSCH
      CALL WORKER ( NPP, PPGAP, DTOTL )
C
      DO 100 I= 1, 4
C
      DTOT( NSCH, 1, I ) = DTOTL( I )
  100 CONTINUE
C
    1 FORMAT ( 1H1,* SCHEME NO.= *, I2, /* PREDICTION PERIOD...* / )
      RETURN
      END
      SUBROUTINE AMBIENT ( NSCH )
C
      COMMON/ ACCEL / NPP, PPGAP(10), NPA, PPGAA(10)
```

```
      COMMON/ MONEY / DTOT( 6.2.4 ), RD
      DIMENSION DTOTL( 4 )
C
      PRINT 1, NSCH
      CALL WORKER ( NPA. PPGAA, DTOTL )
C
      DO 100 I= 1. 4
C
      DTOT( NSCH, 2. I ) = DTOTL( I )
  100 CONTINUE
C
    1 FORMAT ( 1H1. * SCHEME NO. = *, I2, /* AMBIENT PERIOD...* / )
C
      RETURN
      END
      SUBROUTINE SUMMARY
C
      COMMON/ BLDG / RV(4), NLIFE, NPER, NSCH, CSCH(6)
      COMMON/ PRED / PPRED
      COMMON/ MONEY / DTOT( 6,2,4 ), RD
      DIMENSION TLOSS(6), CDTOT(6)
C
C
      PRINT 1
      DO 100 I= 1. NSCH
      DO 100 J= 1. 4
C
      DTOT( I,1,J ) = PPRED * DTOT( I.1.J )
  100 CONTINUE
C
      DO 200 K= 1, 4
C
      GO TO ( 111. 112, 113. 114 ) . K
  111 PRINT 11
      GO TO 120
  112 PRINT 12
      GO TO 120
  113 PRINT 13
      GO TO 120
  114 PRINT 14
C
  120 CONTINUE
      PRINT 20. ( I, I= 1. NSCH )
      PRINT 21. ( CSCH(I), I= 1. NSCH )
      PRINT 22, ( DTOT( I,1,K ), I= 1. NSCH )
C
      DO 130 I= 1, NSCH
  130 TLOSS(I) = CSCH(I) + DTOT( I,1,K )
C
      ANLIFE = NLIFE
      DELTAT = ANLIFE / NPER
C
      DO 140 II= 1, NPER
      TIME = II * DELTAT - DELTAT / 2.
C
      DO 145 I= 1, NSCH
      CALL CONVERT ( TIME. DTOT( I.2.K ), CDTOT( I ). RD )
  145 CONTINUE
C
      PRINT 23. ( II. ( CDTOT(I), I= 1. NSCH ) )
C
      DO 150 I= 1, NSCH
      TLOSS(I) = TLOSS(I) + CDTOT(I)
  150 CONTINUE
C
```

c2

```
C
      PRINT 24, ( TLOSS(I), I= 1, NSCH )
C
  200 CONTINUE
    1 FORMAT ( 1H1, *SUMMARY OF ANALYSIS FOLLOWS* )
   11 FORMAT ( //* CASE = 1*/* FIRE AND SUBSTRUCTURE FAILURE *,
     1          *CONSIDERED*/)
   12 FORMAT ( //* CASE = 2*/* PROBABILITY OF FIRE DISREGARDED*/ )
   13 FORMAT ( //* CASE = 3*/* PROBABILITY OF SUBSTRUCTURE*,
     1         * FAILURE DISREGARDED* /)
   14 FORMAT ( //* CASE = 4*/* PROBABILITY OF BOTH FIRE AND *,
     1         *SUBSTRUCTURE FAILURE DISREGARDED*/ )
   20 FORMAT ( * SCHEME NO. =*, 18X,4( I8,7X ) )
   21 FORMAT ( /* COST OF MODIFICATION*, 9X,4( 2X,F13.2 ) )
   22 FORMAT ( /* DAMAGE FROM PRED. E. Q.*, 6X,4( 2X, F13.2 ) )
   23 FORMAT ( * DAMAGE FROM AMB. PER. =*,I2, 4X,4( 2X, F13.2 ) )
   24 FORMAT ( /* TOTAL EXPECTED LOSS*, 10X,4( 2X, F13.2 ) )
C
      RETURN
      END
      SUBROUTINE WORKER ( NP, PPGA, DTOTL )
C
      COMMON/HAZARD/ PF(10), PSS(10), PS(4,10)
      DIMENSION PF1(10), PSS1(10), PPGA(10), DTOTL(4)
C
      NCASE = 1
      CALL DATA2 ( NP )
C
      DO 300 I= 1, 10
      PF1(I) = PF(I)
      PSS1(I) = PSS(I)
  300 CONTINUE
C
   90 DTOT = 0.
      IP = 1
C
  100 CALL DAMAGE ( IP, DT )
      DT = DT* PPGA( IP )
      DTOT = DTOT + DT
C
      IF ( IP.EQ.NP ) GO TO 200
C
      IP = IP + 1
      GO TO 100
C
  200 CONTINUE
C
      DTOTL ( NCASE ) = DTOT
      GO TO  ( 210,410,510,610 ) NCASE
  210 PRINT 1, NCASE
      PRINT 2, DTOT
C
      NCASE = 2
      DO 400 IP = 1, 10
      PF(IP) = 0.
      CALL STATES (IP)
  400 CONTINUE
      GO TO 90
C
  410 PRINT 3, NCASE
      PRINT 4, DTOT
      NCASE = 3
      DO 500 IP = 1, 10
      PF(IP) = PF1(IP)
      PSS(IP) = 0.
      CALL STATES (IP)
```

```
  500 CONTINUE
      GO TO 90
C
  510 PRINT 3, NCASE
      PRINT 5, DTOT
C
      NCASE = 4
      DO 600 IP = 1, 10
      PF(IP) = 0.
      PSS(IP) = 0.
      CALL STATES (IP)
  600 CONTINUE
      GO TO 90
C
  610 PRINT 3, NCASE
      PRINT 6, DTOT
C
    1 FORMAT ( //* CASE =*, I3 )
    2 FORMAT (1H ,*TOTAL EXPECTED DAMAGE WITH */,
     1         * FIRE AND SUBSTRUCTURE */,
     2         * FAILURE PROBABILITIES AS SHOWN  =*,F14.2,* DOLLARS.*)
    3 FORMAT (//1H ,*CASE =*, I3 )
    4 FORMAT (1H ,*TOTAL EXPECTED DAMAGE WITH */,
     1         * PROBABILITY OF FIRE DISREGARDED =*,F14.2,* DOLLARS.*)
    5 FORMAT (1H ,*TOTAL EXPECTED DAMAGE WITH */,
     1         * PROBABILITY OF SUBSTRUCTURE */,
     2         * FAILURE DISREGARDED             =*,F14.2,* DOLLARS.*)
    6 FORMAT (1H ,*TOTAL EXPECTED DAMAGE WITH */,
     1         * PROBABILITY OF BOTH FIRE AND */,
     2         * SUBSTRUCTURE FAILURE DISREGARDED=*,F14.2,* DOLLARS.*)
C
      RETURN
      END
      SUBROUTINE CONVERT ( T, XP, XT, RD )
C
C
      XT = XP * EXP ( RD*T )
C
      RETURN
      END
```

Appendix D

ILLUSTRATIVE EXAMPLE

D.1 Example Problem

In order to demonstrate the practicality of the computer program "DAMSTAT", a hypothetical problem was considered for evaluation. Even though the input data were hypothetical, an effort was made to make the data as "realistic" as possible.

In Section D.2 a computer print-out of the example problem is presented. The print-out is self-explanatory and expected to be understood without any specific knowledge of computers or computer programming.

In the first page of the print-out, the general data are listed. For this example,four subsystems (structural, architectural, mechanical, and electrical) were selected. The replacement values for these subsystems are assumed to be \$3 million, \$2 million, \$0.5 million and \$0.4 million, respectively, resulting in a replacement value of \$5.9 million for the whole building. The building is assumed to have a useful life of 20 years and this time span is studied in 5 time periods of 4 years each (ambient period). The annual rate of inflation is assumed to be 7%. Interest rate (or rate of return on investment) is taken 10%. These two values are used to estimate the present dollar value of damages from future earthquakes.

Three possible courses of action are considered. The first one is a "do nothing" scheme with an initial cost of zero. The second scheme is a minor modification or temporary bracing scheme which costs $0.5 million to the owner. The last scheme represents a major upgrading at a much higher original cost of $2 million. The second page of this print-out lists the available seismic hazard information. This information is presented in two parts. The first part defines a predicted earthquake. The confidence of the prediction is assumed to be 0.85. Probability distribution of the predicted earthquake over several levels of peak ground acceleration is shown under the column titled "probability."

The second part of the seismicity data represents the probability vector for the ambient period. This vector corresponds to a time period of four years. It should be noted that probability vectors can be defined for any number of peak ground acceleration levels. On the same page, classification of four "Damage States" are given. These states are referred to in the following pages with numbers 1, 2, 3 and 4.

Starting on the third page of the print-out, probabilities of fire and substructure failure and the damage matrices are listed for each scheme and for predicted and ambient seismicity.

At the end of each damage matrix, expected values of damages for the specific schemes and the seismicity vectors are listed for four different cases. These four cases provide flexibility in evaluating the results and allow for subjective considerations, e.g., if one owner does not wish to consider probabilities of fire or substructure failure he will base his decisions on the Case 4 results.

Once the expected values of damages due to two seismicity vectors (predicted and ambient) and three different schemes are calculated, these results are summarized in a tabular form. In this table, expected loss components are listed for each scheme and the four cases. These expected cost components are in terms of today's money and they have already been modified for the confidence of prediction and the interest and inflation rates. Final results are the "Total Expected Losses" for schemes 1, 2 and 3 for each case. If the owner chooses to ignore probability of fire and substructure failure he will consider the following values from case 4 for his final decision:

	Scheme No.		
	1	2	3
Initial Cost (million dollars)	0.0	0.5	2.0
Total Expected Loss (million dollars)	5.355	1.571	2.822

Assuming that the owner will choose the course of action on the basis of the Total Expected Loss, Scheme No. 2 will be chosen for implementation.

D.2 Computer Print-out for the Example Problem

(See the following pages.)

```
EXAMPLE NO. 6 ******************************

REPLACEMENT VALUES ARE AS FOLLOWS :
STRUCTURAL     =    3000000.00 DOLLARS
ARCHITECTURAL =    2000000.00 DOLLARS
MECHANICAL     =     500000.00 DOLLARS
ELECTRICAL     =     400000.00 DOLLARS


ECONOMIC LIFE OF BUILDING = 20 YEARS
NO. OF TIME INTERVALS      =  5

ANNUAL INFLATION RATE      =  .070
ANNUAL INTEREST RATE       =  .100

NO. OF MODIFICATION SCHEMES =  3

SCHEME NO.      COST (DOLLARS)
     1                  0.00
     2             500000.00
     3            2000000.00
```

```
PREDICTION PERIOD
CONFIDENCE OF PREDICTION =  .850


  PGA LEVEL     FROM (G)      TO (G)      PROBABILITY

      1          0.000         .050         0.000
      2           .050         .150         0.000
      3           .150         .250          .100
      4           .250         .350          .200
      5           .350         .450          .400
      6           .450         .550          .200
      7           .550         .650          .100
      8           .650        0.000         0.000


AMBIENT PERIOD :


  PGA LEVEL     FROM (G)      TO (G)      PROBABILITY

      1          0.000         .050          .200
      2           .050         .150          .300
      3           .150         .250          .200
      4           .250         .350          .150
      5           .350         .450          .100
      6           .450         .550          .050
      7           .550         .650         0.000
      8           .650        0.000         0.000

DAMAGE STATE CLASSIFICATION :
DAMAGE STATE = 1 : EARTHQUAKE DAMAGE ONLY
DAMAGE STATE = 2 : EARTHQUAKE + FIRE DAMAGE
DAMAGE STATE = 3 : EARTHQUAKE + SUBSTRUCTURE FAILURE
DAMAGE STATE = 4 : EARTHQUAKE + FIRE + SUBSTRUCTURE FAILURE
```

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```
 SCHEME NO.=  1
PREDICTION PERIOD...


PGA LEVEL =  1

PROBABILITY OF FIRE =  .010
PROBABILITY OF S. S. FAILURE =  .010

DAMAGE STATE NO=            1         2         3         4
PROBABILITY=             .980      .010      .010      .000
STRL. DAM. RATIO         .050      .500      .500      .700
ARCH  DAM. RATIO         .050      .600      .600      .650
MECH  DAM. RATIO         .050      .200      .300      .400
ELEC. DAM. RATIO         .050      .400      .200      .500

PGA LEVEL =  2

PROBABILITY OF FIRE =  .050
PROBABILITY OF S. S. FAILURE =  .020

DAMAGE STATE NO=            1         2         3         4
PROBABILITY=             .931      .049      .019      .001
STRL. DAM. RATIO         .100      .550      .550      .700
ARCH  DAM. RATIO         .150      .650      .650      .700
MECH  DAM. RATIO         .100      .250      .350      .400
ELEC. DAM. RATIO         .100      .450      .250      .500

PGA LEVEL =  3

PROBABILITY OF FIRE =  .100
PROBABILITY OF S. S. FAILURE =  .050

DAMAGE STATE NO=            1         2         3         4
PROBABILITY=             .855      .095      .045      .005
STRL. DAM. RATIO         .150      .600      .600      .800
ARCH  DAM. RATIO         .200      .700      .700      .750
MECH  DAM. RATIO         .150      .300      .400      .500
ELEC. DAM. RATIO         .150      .500      .300      .550

PGA LEVEL =  4

PROBABILITY OF FIRE =  .150
PROBABILITY OF S. S. FAILURE =  .100

DAMAGE STATE NO=            1         2         3         4
PROBABILITY=             .765      .135      .085      .015
STRL. DAM. RATIO         .200      .650      .650      .900
ARCH  DAM. RATIO         .300      .700      .700      .750
MECH  DAM. RATIO         .200      .400      .400      .550
ELEC. DAM. RATIO         .200      .500      .300      .600

PGA LEVEL =  5

PROBABILITY OF FIRE =  .250
PROBABILITY OF S. S. FAILURE =  .150

DAMAGE STATE NO=            1         2         3         4
PROBABILITY=             .638      .213      .113      .038
STRL. DAM. RATIO         .300      .700      .700      .850
ARCH  DAM. RATIO         .400      .700      .700      .750
MECH  DAM. RATIO         .250      .500      .400      .600
ELEC. DAM. RATIO         .250      .500      .300      .600

PGA LEVEL =  6
```

```
PROBABILITY OF FIRE =  .300
PROBABILITY OF S. S. FAILURE =  .200

DAMAGE STATE NO=            1          2          3          4
PROBABILITY=              .560       .240       .140       .060
STRL. DAM. RATIO          .400       .800       .700       .850
ARCH  DAM. RATIO          .500       .750       .700       .800
MECH  DAM. RATIO          .300       .550       .450       .650
ELEC. DAM. RATIO          .300       .600       .400       .700

PGA LEVEL =  7

PROBABILITY OF FIRE =  .400
PROBABILITY OF S. S. FAILURE =  .250

DAMAGE STATE NO=            1          2          3          4
PROBABILITY=              .450       .300       .150       .100
STRL. DAM. RATIO          .500       .850       .700       .900
ARCH  DAM. RATIO          .600       .750       .700       .900
MECH  DAM. RATIO          .350       .600       .450       .700
ELEC. DAM. RATIO          .400       .600       .450       .700

PGA LEVEL =  8

PROBABILITY OF FIRE =  .600
PROBABILITY OF S. S. FAILURE =  .300

DAMAGE STATE NO=            1          2          3          4
PROBABILITY=              .280       .420       .120       .180
STRL. DAM. RATIO          .600       .900       .700       .950
ARCH  DAM. RATIO          .700       .800       .750       .950
MECH  DAM. RATIO          .400       .700       .500       .750
ELEC. DAM. RATIO          .500       .700       .550       .800


CASE =  1
TOTAL EXPECTED DAMAGE WITH
FIRE AND SUBSTRUCTURE
FAILURE PROBABILITIES AS SHOWN  =    2629917.50 DOLLARS.


CASE =  2
TOTAL EXPECTED DAMAGE WITH
PROBABILITY OF FIRE DISREGARDED =    2192525.00 DOLLARS.


CASE =  3
TOTAL EXPECTED DAMAGE WITH
PROBABILITY OF SUBSTRUCTURE
FAILURE DISREGARDED             =    2420150.00 DOLLARS.


CASE =  4
TOTAL EXPECTED DAMAGE WITH
PROBABILITY OF BOTH FIRE AND
SUBSTRUCTURE FAILURE DISREGARDED=    1942000.00 DOLLARS.
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```
 SCHEME NO. =  1
AMBIENT PERIOD...


PGA LEVEL =  1

PROBABILITY OF FIRE =  .010
PROBABILITY OF S. S. FAILURE =  .010

DAMAGE STATE NO=             1          2          3          4
PROBABILITY=               .980       .010       .010       .000
STRL. DAM. RATIO           .050       .500       .500       .700
ARCH  DAM. RATIO           .050       .600       .600       .650
MECH  DAM. RATIO           .050       .200       .300       .400
ELEC. DAM. RATIO           .050       .400       .200       .500

PGA LEVEL =  2

PROBABILITY OF FIRE =  .050
PROBABILITY OF S. S. FAILURE =  .020

DAMAGE STATE NO=             1          2          3          4
PROBABILITY=               .931       .049       .019       .001
STRL. DAM. RATIO           .100       .550       .550       .700
ARCH  DAM. RATIO           .150       .650       .650       .700
MECH  DAM. RATIO           .100       .250       .350       .400
ELEC. DAM. RATIO           .100       .450       .250       .500

PGA LEVEL =  3

PROBABILITY OF FIRE =  .100
PROBABILITY OF S. S. FAILURE =  .050

DAMAGE STATE NO=             1          2          3          4
PROBABILITY=               .855       .095       .045       .005
STRL. DAM. RATIO           .150       .600       .600       .800
ARCH  DAM. RATIO           .200       .700       .700       .750
MECH  DAM. RATIO           .150       .300       .400       .500
ELEC. DAM. RATIO           .150       .500       .300       .550

PGA LEVEL =  4

PROBABILITY OF FIRE =  .150
PROBABILITY OF S. S. FAILURE =  .100

DAMAGE STATE NO=             1          2          3          4
PROBABILITY=               .765       .135       .085       .015
STRL. DAM. RATIO           .200       .650       .650       .800
ARCH  DAM. RATIO           .300       .700       .700       .750
MECH  DAM. RATIO           .200       .400       .400       .550
ELEC. DAM. RATIO           .200       .500       .300       .600

PGA LEVEL =  5

PROBABILITY OF FIRE =  .250
PROBABILITY OF S. S. FAILURE =  .150

DAMAGE STATE NO=             1          2          3          4
PROBABILITY=               .638       .213       .113       .038
STRL. DAM. RATIO           .300       .700       .700       .850
ARCH  DAM. RATIO           .400       .700       .700       .750
MECH  DAM. RATIO           .250       .500       .400       .600
ELEC. DAM. RATIO           .250       .500       .300       .600

PGA LEVEL =  6
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```
PROBABILITY OF FIRE =  .300
PROBABILITY OF S. S. FAILURE =  .200

DAMAGE STATE NO=              1          2          3          4
PROBABILITY=               .560       .240       .140       .060
STRL. DAM. RATIO           .400       .800       .700       .850
ARCH  DAM. RATIO           .500       .750       .700       .800
MECH  DAM. RATIO           .300       .550       .450       .650
ELEC. DAM. RATIO           .300       .600       .400       .700

PGA LEVEL =  7

PROBABILITY OF FIRE =  .400
PROBABILITY OF S. S. FAILURE =  .250

DAMAGE STATE NO=              1          2          3          4
PROBABILITY=               .450       .300       .150       .100
STRL. DAM. RATIO           .500       .850       .700       .900
ARCH  DAM. RATIO           .600       .750       .700       .900
MECH  DAM. RATIO           .350       .600       .450       .700
ELEC. DAM. RATIO           .400       .600       .450       .700

PGA LEVEL =  8

PROBABILITY OF FIRE =  .600
PROBABILITY OF S. S. FAILURE =  .300

DAMAGE STATE NO=              1          2          3          4
PROBABILITY=               .280       .420       .120       .180
STRL. DAM. RATIO           .600       .900       .700       .950
ARCH  DAM. RATIO           .700       .800       .750       .950
MECH  DAM. RATIO           .400       .700       .500       .750
ELEC. DAM. RATIO           .500       .700       .550       .800


CASE =  1
TOTAL EXPECTED DAMAGE WITH
FIRE AND SUBSTRUCTURE
FAILURE PROBABILITIES AS SHOWN  =    1323079.60 DOLLARS.


CASE =  2
TOTAL EXPECTED DAMAGE WITH
PROBABILITY OF FIRE DISREGARDED =    1108755.00 DOLLARS.


CASE =  3
TOTAL EXPECTED DAMAGE WITH
PROBABILITY OF SUBSTRUCTURE
FAILURE DISREGARDED             =    1214230.00 DOLLARS.


CASE =  4
TOTAL EXPECTED DAMAGE WITH
PROBABILITY OF BOTH FIRE AND
SUBSTRUCTURE FAILURE DISREGARDED=     986000.00 DOLLARS.
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 SCHEME NO.=  2
PREDICTION PERIOD...


PGA LEVEL =  1

PROBABILITY OF FIRE =  .010
PROBABILITY OF S. S. FAILURE =  .010

DAMAGE STATE NO=            1         2         3         4
PROBABILITY=             .980      .010      .010      .000
STRL. DAM. RATIO         .010      .250      .250      .350
ARCH  DAM. RATIO         .010      .300      .300      .330
MECH  DAM. RATIO         .010      .100      .150      .200
ELEC. DAM. RATIO         .010      .200      .100      .250

PGA LEVEL =  2

PROBABILITY OF FIRE =  .050
PROBABILITY OF S. S. FAILURE =  .020

DAMAGE STATE NO=            1         2         3         4
PROBABILITY=             .931      .049      .019      .001
STRL. DAM. RATIO         .020      .280      .280      .350
ARCH  DAM. RATIO         .030      .330      .330      .350
MECH  DAM. RATIO         .020      .130      .180      .200
ELEC. DAM. RATIO         .020      .230      .130      .250

PGA LEVEL =  3

PROBABILITY OF FIRE =  .100
PROBABILITY OF S. S. FAILURE =  .050

DAMAGE STATE NO=            1         2         3         4
PROBABILITY=             .855      .095      .045      .005
STRL. DAM. RATIO         .030      .300      .300      .400
ARCH  DAM. RATIO         .040      .350      .350      .380
MECH  DAM. RATIO         .030      .150      .200      .250
ELEC. DAM. RATIO         .030      .250      .150      .280

PGA LEVEL =  4

PROBABILITY OF FIRE =  .150
PROBABILITY OF S. S. FAILURE =  .100

DAMAGE STATE NO=            1         2         3         4
PROBABILITY=             .765      .135      .085      .015
STRL. DAM. RATIO         .040      .330      .330      .400
ARCH  DAM. RATIO         .060      .350      .350      .380
MECH  DAM. RATIO         .040      .200      .200      .280
ELEC. DAM. RATIO         .040      .250      .150      .300

PGA LEVEL =  5

PROBABILITY OF FIRE =  .250
PROBABILITY OF S. S. FAILURE =  .150

DAMAGE STATE NO=            1         2         3         4
PROBABILITY=             .638      .213      .113      .038
STRL. DAM. RATIO         .060      .350      .350      .430
ARCH  DAM. RATIO         .080      .350      .350      .380
MECH  DAM. RATIO         .050      .250      .200      .300
ELEC. DAM. RATIO         .050      .250      .150      .300

PGA LEVEL =  6
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```
PROBABILITY OF FIRE =  .300
PROBABILITY OF S. S. FAILURE =  .200

DAMAGE STATE NO=            1          2          3          4
PROBABILITY=             .560       .240       .140       .060
STRL. DAM. RATIO         .080       .400       .350       .430
ARCH  DAM. RATIO         .100       .380       .350       .400
MECH  DAM. RATIO         .060       .280       .230       .330
ELEC. DAM. RATIO         .060       .300       .200       .350

PGA LEVEL =  7

PROBABILITY OF FIRE =  .400
PROBABILITY OF S. S. FAILURE =  .250

DAMAGE STATE NO=            1          2          3          4
PROBABILITY=             .450       .300       .150       .100
STRL. DAM. RATIO         .100       .430       .350       .450
ARCH  DAM. RATIO         .120       .380       .350       .450
MECH  DAM. RATIO         .070       .300       .230       .350
ELEC. DAM. RATIO         .080       .300       .230       .350

PGA LEVEL =  8

PROBABILITY OF FIRE =  .600
PROBABILITY OF S. S. FAILURE =  .300

DAMAGE STATE NO=            1          2          3          4
PROBABILITY=             .280       .420       .120       .180
STRL. DAM. RATIO         .120       .450       .350       .480
ARCH  DAM. RATIO         .140       .400       .380       .480
MECH  DAM. RATIO         .080       .350       .250       .380
ELEC. DAM. RATIO         .100       .350       .280       .400


CASE =  1
TOTAL EXPECTED DAMAGE WITH
FIRE AND SUBSTRUCTURE
FAILURE PROBABILITIES AS SHOWN  =     957900.50 DOLLARS.


CASE =  2
TOTAL EXPECTED DAMAGE WITH
PROBABILITY OF FIRE DISREGARDED =     610985.00 DOLLARS.


CASE =  3
TOTAL EXPECTED DAMAGE WITH
PROBABILITY OF SUBSTRUCTURE
FAILURE DISREGARDED             =     783680.00 DOLLARS.


CASE =  4
TOTAL EXPECTED DAMAGE WITH
PROBABILITY OF BOTH FIRE AND
SUBSTRUCTURE FAILURE DISREGARDED=     388400.00 DOLLARS.
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 SCHEME NO. =  2
AMBIENT PERIOD...


PGA LEVEL =  1

PROBABILITY OF FIRE =  .010
PROBABILITY OF S. S. FAILURE =  .010

DAMAGE STATE NO=           1         2         3         4
PROBABILITY=             .980      .010      .010      .000
STRL. DAM. RATIO         .010      .250      .250      .350
ARCH  DAM. RATIO         .010      .300      .300      .330
MECH  DAM. RATIO         .010      .100      .150      .200
ELEC. DAM. RATIO         .010      .200      .100      .250

PGA LEVEL =  2

PROBABILITY OF FIRE =  .050
PROBABILITY OF S. S. FAILURE =  .020

DAMAGE STATE NO=           1         2         3         4
PROBABILITY=             .931      .049      .019      .001
STRL. DAM. RATIO         .020      .280      .280      .350
ARCH  DAM. RATIO         .030      .330      .330      .350
MECH  DAM. RATIO         .020      .130      .180      .200
ELEC. DAM. RATIO         .020      .230      .130      .250

PGA LEVEL =  3

PROBABILITY OF FIRE =  .100
PROBABILITY OF S. S. FAILURE =  .050

DAMAGE STATE NO=           1         2         3         4
PROBABILITY=             .855      .095      .045      .005
STRL. DAM. RATIO         .030      .300      .300      .400
ARCH  DAM. RATIO         .040      .350      .350      .380
MECH  DAM. RATIO         .030      .150      .200      .250
ELEC. DAM. RATIO         .030      .250      .150      .280

PGA LEVEL =  4

PROBABILITY OF FIRE =  .150
PROBABILITY OF S. S. FAILURE =  .100

DAMAGE STATE NO=           1         2         3         4
PROBABILITY=             .765      .135      .085      .015
STRL. DAM. RATIO         .040      .330      .330      .400
ARCH  DAM. RATIO         .060      .350      .350      .380
MECH  DAM. RATIO         .040      .200      .200      .280
ELEC. DAM. RATIO         .040      .250      .150      .300

PGA LEVEL =  5

PROBABILITY OF FIRE =  .250
PROBABILITY OF S. S. FAILURE =  .150

DAMAGE STATE NO=           1         2         3         4
PROBABILITY=             .638      .213      .113      .038
STRL. DAM. RATIO         .060      .350      .350      .430
ARCH  DAM. RATIO         .080      .350      .350      .360
MECH  DAM. RATIO         .050      .250      .200      .300
ELEC. DAM. RATIO         .050      .250      .150      .300

PGA LEVEL =  6
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```
PROBABILITY OF FIRE =  .300
PROBABILITY OF S. S. FAILURE =  .200

DAMAGE STATE NO=              1          2          3          4
PROBABILITY=               .560       .240       .140       .060
STRL. DAM. RATIO           .080       .400       .350       .430
ARCH  DAM. RATIO           .100       .380       .350       .400
MECH  DAM. RATIO           .060       .280       .230       .330
ELEC. DAM. RATIO           .060       .300       .200       .350

PGA LEVEL =  7

PROBABILITY OF FIRE =  .400
PROBABILITY OF S. S. FAILURE =  .250

DAMAGE STATE NO=              1          2          3          4
PROBABILITY=               .450       .300       .150       .100
STRL. DAM. RATIO           .100       .430       .350       .450
ARCH  DAM. RATIO           .120       .380       .350       .450
MECH  DAM. RATIO           .070       .300       .230       .350
ELEC. DAM. RATIO           .080       .300       .230       .350

PGA LEVEL =  8

PROBABILITY OF FIRE =  .600
PROBABILITY OF S. S. FAILURE =  .300

DAMAGE STATE NO=              1          2          3          4
PROBABILITY=               .280       .420       .120       .180
STRL. DAM. RATIO           .120       .450       .350       .480
ARCH  DAM. RATIO           .140       .400       .380       .480
MECH  DAM. RATIO           .080       .350       .250       .380
ELEC. DAM. RATIO           .100       .350       .280       .400


CASE =  1
TOTAL EXPECTED DAMAGE WITH
FIRE AND SUBSTRUCTURE
FAILURE PROBABILITIES AS SHOWN  =     432227.18 DOLLARS.


CASE =  2
TOTAL EXPECTED DAMAGE WITH
PROBABILITY OF FIRE DISREGARDED =     285661.00 DOLLARS.


CASE =  3
TOTAL EXPECTED DAMAGE WITH
PROBABILITY OF SUBSTRUCTURE
FAILURE DISREGARDED             =     356342.00 DOLLARS.


CASE =  4
TOTAL EXPECTED DAMAGE WITH
PROBABILITY OF BOTH FIRE AND
SUBSTRUCTURE FAILURE DISREGARDED=     197200.00 DOLLARS.
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 SCHEME NO.=  3
PREDICTION PERIOD...


PGA LEVEL =  1

PROBABILITY OF FIRE =  .010
PROBABILITY OF S. S. FAILURE =  .010

DAMAGE STATE NO=              1          2          3          4
PROBABILITY=               .980       .010       .010       .000
STRL. DAM. RATIO           .008       .200       .200       .280
ARCH  DAM. RATIO           .008       .240       .240       .260
MECH  DAM. RATIO           .008       .080       .120       .160
ELEC. DAM. RATIO           .008       .160       .080       .200

PGA LEVEL =  2

PROBABILITY OF FIRE =  .050
PROBABILITY OF S. S. FAILURE =  .020

DAMAGE STATE NO=              1          2          3          4
PROBABILITY=               .931       .049       .019       .001
STRL. DAM. RATIO           .016       .220       .220       .280
ARCH  DAM. RATIO           .024       .260       .260       .280
MECH  DAM. RATIO           .016       .100       .140       .160
ELEC. DAM. RATIO           .016       .180       .100       .200

PGA LEVEL =  3

PROBABILITY OF FIRE =  .080
PROBABILITY OF S. S. FAILURE =  .050

DAMAGE STATE NO=              1          2          3          4
PROBABILITY=               .874       .076       .046       .004
STRL. DAM. RATIO           .024       .240       .240       .320
ARCH  DAM. RATIO           .032       .280       .280       .300
MECH  DAM. RATIO           .024       .120       .160       .200
ELEC. DAM. RATIO           .024       .200       .120       .220

PGA LEVEL =  4

PROBABILITY OF FIRE =  .120
PROBABILITY OF S. S. FAILURE =  .100

DAMAGE STATE NO=              1          2          3          4
PROBABILITY=               .792       .108       .088       .012
STRL. DAM. RATIO           .032       .260       .260       .320
ARCH  DAM. RATIO           .024       .280       .280       .300
MECH  DAM. RATIO           .032       .160       .160       .220
ELEC. DAM. RATIO           .032       .200       .120       .240

PGA LEVEL =  5

PROBABILITY OF FIRE =  .200
PROBABILITY OF S. S. FAILURE =  .150

DAMAGE STATE NO=              1          2          3          4
PROBABILITY=               .680       .170       .120       .030
STRL. DAM. RATIO           .048       .280       .280       .340
ARCH  DAM. RATIO           .064       .280       .280       .300
MECH  DAM. RATIO           .040       .200       .160       .240
ELEC. DAM. RATIO           .040       .200       .120       .240

PGA LEVEL =  6
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PROBABILITY OF FIRE =  .240
PROBABILITY OF S. S. FAILURE =  .200

DAMAGE STATE NO=          1          2          3          4
PROBABILITY=           .608       .192       .152       .048
STRL. DAM. RATIO       .064       .320       .280       .340
ARCH  DAM. RATIO       .080       .300       .280       .320
MECH  DAM. RATIO       .048       .220       .180       .260
ELEC. DAM. RATIO       .048       .240       .160       .280

PGA LEVEL =  7

PROBABILITY OF FIRE =  .350
PROBABILITY OF S. S. FAILURE =  .250

DAMAGE STATE NO=          1          2          3          4
PROBABILITY=           .488       .263       .163       .068
STRL. DAM. RATIO       .080       .340       .280       .360
ARCH  DAM. RATIO       .100       .300       .280       .360
MECH  DAM. RATIO       .056       .240       .180       .280
ELEC. DAM. RATIO       .064       .240       .180       .280

PGA LEVEL =  8

PROBABILITY OF FIRE =  .500
PROBABILITY OF S. S. FAILURE =  .300

DAMAGE STATE NO=          1          2          3          4
PROBABILITY=           .350       .350       .150       .150
STRL. DAM. RATIO       .100       .360       .280       .380
ARCH  DAM. RATIO       .110       .320       .300       .360
MECH  DAM. RATIO       .064       .280       .200       .300
ELEC. DAM. RATIO       .080       .280       .220       .320


CASE =  1
TOTAL EXPECTED DAMAGE WITH
FIRE AND SUBSTRUCTURE
FAILURE PROBABILITIES AS SHOWN  =     705147.98 DOLLARS.


CASE =  2
TOTAL EXPECTED DAMAGE WITH
PROBABILITY OF FIRE DISREGARDED =     480338.00 DOLLARS.


CASE =  3
TOTAL EXPECTED DAMAGE WITH
PROBABILITY OF SUBSTRUCTURE
FAILURE DISREGARDED             =     558414.40 DOLLARS.


CASE =  4
TOTAL EXPECTED DAMAGE WITH
PROBABILITY OF BOTH FIRE AND
SUBSTRUCTURE FAILURE DISREGARDED=     301920.00 DOLLARS.
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 SCHEME NO. =  3
AMBIENT PERIOD...


PGA LEVEL =  1

PROBABILITY OF FIRE =  .010
PROBABILITY OF S. S. FAILURE =  .010

DAMAGE STATE NO=           1          2          3          4
PROBABILITY=             .980       .010       .010       .000
STRL. DAM. RATIO         .008       .200       .200       .260
ARCH  DAM. RATIO         .008       .240       .240       .260
MECH  DAM. RATIO         .008       .080       .120       .160
ELEC. DAM. RATIO         .008       .160       .080       .200

PGA LEVEL =  2

PROBABILITY OF FIRE =  .050
PROBABILITY OF S. S. FAILURE =  .020

DAMAGE STATE NO=           1          2          3          4
PROBABILITY=             .931       .049       .019       .001
STRL. DAM. RATIO         .016       .220       .220       .280
ARCH  DAM. RATIO         .024       .260       .260       .280
MECH  DAM. RATIO         .016       .100       .140       .160
ELEC. DAM. RATIO         .016       .180       .100       .200

PGA LEVEL =  3

PROBABILITY OF FIRE =  .080
PROBABILITY OF S. S. FAILURE =  .050

DAMAGE STATE NO=           1          2          3          4
PROBABILITY=             .874       .076       .046       .004
STRL. DAM. RATIO         .024       .240       .240       .320
ARCH  DAM. RATIO         .032       .280       .280       .300
MECH  DAM. RATIO         .024       .120       .160       .200
ELEC. DAM. RATIO         .024       .200       .120       .220

PGA LEVEL =  4

PROBABILITY OF FIRE =  .120
PROBABILITY OF S. S. FAILURE =  .100

DAMAGE STATE NO=           1          2          3          4
PROBABILITY=             .792       .108       .088       .012
STRL. DAM. RATIO         .032       .260       .260       .320
ARCH  DAM. RATIO         .024       .280       .280       .300
MECH  DAM. RATIO         .032       .160       .160       .220
ELEC. DAM. RATIO         .032       .200       .120       .240

PGA LEVEL =  5

PROBABILITY OF FIRE =  .200
PROBABILITY OF S. S. FAILURE =  .150

DAMAGE STATE NO=           1          2          3          4
PROBABILITY=             .680       .170       .120       .030
STRL. DAM. RATIO         .048       .280       .280       .340
ARCH  DAM. RATIO         .064       .280       .280       .300
MECH  DAM. RATIO         .040       .200       .160       .240
ELEC. DAM. RATIO         .040       .200       .120       .240

PGA LEVEL =  6
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PROBABILITY OF FIRE =  .240
PROBABILITY OF S. S. FAILURE =  .200

DAMAGE STATE NO=              1          2          3          4
PROBABILITY=                .608       .192       .152       .048
STRL. DAM. RATIO            .064       .320       .280       .340
ARCH  DAM. RATIO            .080       .300       .280       .320
MECH  DAM. RATIO            .048       .220       .180       .260
ELEC. DAM. RATIO            .048       .240       .160       .280

PGA LEVEL =  7

PROBABILITY OF FIRE =  .350
PROBABILITY OF S. S. FAILURE =  .250

DAMAGE STATE NO=              1          2          3          4
PROBABILITY=                .488       .263       .163       .088
STRL. DAM. RATIO            .080       .340       .280       .360
ARCH  DAM. RATIO            .100       .300       .280       .360
MECH  DAM. RATIO            .056       .240       .180       .280
ELEC. DAM. RATIO            .064       .240       .180       .280

PGA LEVEL =  8

PROBABILITY OF FIRE =  .500
PROBABILITY OF S. S. FAILURE =  .300

DAMAGE STATE NO=              1          2          3          4
PROBABILITY=                .350       .350       .150       .150
STRL. DAM. RATIO            .100       .360       .280       .380
ARCH  DAM. RATIO            .110       .320       .300       .380
MECH  DAM. RATIO            .064       .280       .200       .300
ELEC. DAM. RATIO            .080       .280       .220       .320


CASE =  1
TOTAL EXPECTED DAMAGE WITH
FIRE AND SUBSTRUCTURE
FAILURE PROBABILITIES AS SHOWN  =     319602.94 DOLLARS.


CASE =  2
TOTAL EXPECTED DAMAGE WITH
PROBABILITY OF FIRE DISREGARDED =     221707.20 DOLLARS.


CASE =  3
TOTAL EXPECTED DAMAGE WITH
PROBABILITY OF SUBSTRUCTURE
FAILURE DISREGARDED             =     256685.20 DOLLARS.


CASE =  4
TOTAL EXPECTED DAMAGE WITH
PROBABILITY OF BOTH FIRE AND
SUBSTRUCTURE FAILURE DISREGARDED=     150560.00 DOLLARS.
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SUMMARY OF ANALYSIS FOLLOWS

CASE = 1
FIRE AND SUBSTRUCTURE FAILURE CONSIDERED

SCHEME NO. =                              1              2              3

COST OF MODIFICATION                   0.00      500000.00     2000000.00

DAMAGE FROM PRED. E. Q.          2235429.88      814215.42      599375.78
DAMAGE FROM AMB. PER. = 1        1246029.44      407056.23      300990.72
DAMAGE FROM AMB. PER. = 2        1105128.98      361026.49      266954.82
DAMAGE FROM AMB. PER. = 3         980161.48      320201.77      236767.68
DAMAGE FROM AMB. PER. = 4         869325.24      283993.49      209994.10
DAMAGE FROM AMB. PER. = 5         771022.32      251879.63      186248.06

TOTAL EXPECTED LOSS              7207097.34     2938373.04     3800331.16


CASE = 2
PROBABILITY OF FIRE DISREGARDED

SCHEME NO. =                              1              2              3

COST OF MODIFICATION                   0.00      500000.00     2000000.00

DAMAGE FROM PRED. E. Q.          1863646.25      519337.25      408287.30
DAMAGE FROM AMB. PER. = 1        1044186.14      269025.40      208795.98
DAMAGE FROM AMB. PER. = 2         926110.02      238604.12      185185.42
DAMAGE FROM AMB. PER. = 3         821385.91      211622.87      164244.73
DAMAGE FROM AMB. PER. = 4         728503.95      187692.65      145672.01
DAMAGE FROM AMB. PER. = 5         646125.04      166469.45      129199.48

TOTAL EXPECTED LOSS              6029957.30     2092750.75     3241384.93


CASE = 3
PROBABILITY OF SUBSTRUCTURE FAILURE DISREGARDED

SCHEME NO. =                              1              2              3

COST OF MODIFICATION                   0.00      500000.00     2000000.00

DAMAGE FROM PRED. E. Q.          2057127.50      666128.00      474652.24
DAMAGE FROM AMB. PER. = 1        1143518.75      335590.26      241737.02
DAMAGE FROM AMB. PER. = 2        1014210.15      297641.86      214401.50
DAMAGE FROM AMB. PER. = 3         899523.71      263984.65      190157.07
DAMAGE FROM AMB. PER. = 4         797805.96      234133.38      168654.19
DAMAGE FROM AMB. PER. = 5         707590.41      207657.68      149582.85

TOTAL EXPECTED LOSS              6619776.48     2505135.82     3439184.88


CASE = 4
PROBABILITY OF BOTH FIRE AND SUBSTRUCTURE FAILURE DISREGARDED

SCHEME NO. =                              1              2              3

COST OF MODIFICATION                   0.00      500000.00     2000000.00

DAMAGE FROM PRED. E. Q.          1650700.00      330140.00      256632.00
DAMAGE FROM AMB. PER. = 1         928579.83      185715.97      141792.07
DAMAGE FROM AMB. PER. = 2         823576.43      164715.29      125758.28
DAMAGE FROM AMB. PER. = 3         730446.77      146089.35      111537.59
DAMAGE FROM AMB. PER. = 4         647848.16      129569.63       98924.97
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DAMAGE FROM AMB. PER. = 5            574589.78       114917.96        87738.58

TOTAL EXPECTED LOSS                 5355740.97      1571148.19      2822383.49
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