Optimum Seismic Protection for New Building Construction in Eastern Metropolitan Areas

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Internal Study Report No. 2

BACKGROUND FOR PRELIMINARY EXPECTED FUTURE LOSS COMPUTATIONS

October, 1971

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An example of expected future seismic loss computation together with suggested damage status and earthquake intensity categories for the Boston area are reported. The probabilities used in the example were chosen for illustrative purposes and no claim is made that they are reliable for the Boston area. The major components of uncertainty in the analysis of seismic design is the uncertainty of the effects of each earthquake on the structural system studies. A computational analysis model is proposed which relates damaged probabilities to Modified Mercalli intensities and to scatter in acceleration vs. intensity data. Damage state categories are based on probabilities for 8 to 13-story structures founded on firm ground and designed according to Boston building code requirements. A table of suggested damage states provides initial estimates which might apply for a particular type of building on firm ground in Boston.

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PREFACE

The informal report has two separate sections. In the first, Professor Vanmarcke provides an example of an expected future loss computation. The probabilities used in this example were chosen for illustrative purposes only; no claim is made that these probabilities are realistic for the Boston area. Professor Vanmarcke also suggests how damage probabilities might be related to Modified Mercalli intensities and to the scatter in acceleration VS. intensity data. In the second section, Professor Whitman suggests an array of damage categories, and provides initial estimates (guesses) as to the probabilities which might apply for a particular type of building on firm ground in Boston.

This report is intended as the starting point for preliminary expected future loss computations to be carried out during the first year of the study. These preliminary computations will serve to clarify basic ideas as to the nature of the study and to indicate the parameters having the greatest effect upon the final result. Further, it is hoped that the report will stimulate all staff to provide their own estimates of suitable input to the preliminary analyses.

PREVIOUS STUDY REPORTS

1. R.V. Whitman, "Preliminary Work Plans and Schedules," August 1971.

Section 1

EXAMPLE OF EXPECTED DISCOUNTED FUTURE COST COMPUTATION

Erik H. Vanmarcke

1. INTRODUCTION

Two major components of uncertainty enter into the analysis of seismic design decisions. The first, which is dealt with in part 2, is the uncertainty in the occurrence characteristics of earthquakes of various intensities (or peak accelerations). The second, the uncertainty in the effects of each earthquake on the structural system being studied, is studied in part 3. The complete formulation requires combining the uncertainties and the costs involved. This is done in part 4.

2. EARTHQUAKE PEAK ACCELERATIONS: RISKS AND RETURN PERIODS

Professor Cornell's seismic risk analysis method provides peak acceleration versus return period curves of the following form

$$T_a = c\ a^{\beta/b_2} \tag{1}$$

where

- a = peak ground acceleration (fraction of g)
- T_a = mean return period corresponding to level $\underline{a}$
- β = constant in Gutenberg and Richter's law relating magnitude and annual occurrence rate
- b_2 = constant in "attenuation law" ($a = b_1\ e^{b_2 m}\ r^{-b_3}$, where m = magnitude and r = focal distance)
- c = constant determined by seismic risk analysis (depends on location of sources w.r.t. site, attenuation, etc.)

Commonly used values, $\beta = 2$ and $b_2 = 0.8$, are adopted here. Assume the earthquake risk at the site to be such that the acceleration level $a = 0.01g$ (which would result in a negligible amount of damage) corresponds to a 10 year mean return period. From Eq. 1,

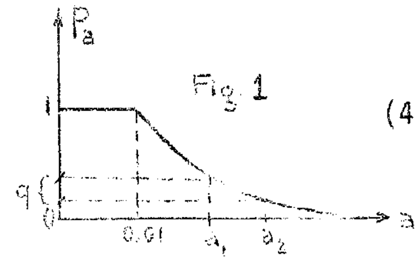
$$10 = c\ (0.01)^{2.5} \tag{2}$$

The mean return period T_a corresponding to some arbitrary level $\underline{a}$ can be computed from

$$T_a = 10 \left(\frac{a}{0.01}\right)^{2.5} \tag{3}$$

The probability, p_a, that an earthquake will cause a peak acceleration larger than (or equal to) some level a, given that it causes a peak acceleration in excess of 0.01g, is (see Fig.)

$$p_a = \begin{cases} 1 & a \leq 0.01 \\ \left(\frac{a}{0.01}\right)^{-2.5} & a \geq 0.01 \end{cases} \tag{4}$$



Finally, the probability that an earthquake will cause a peak acceleration in the interval a_1 to a_2, where $a_2 \geq a_1 \geq 0.01$, is given by

$$q = P[a_1 \leq a \leq a_2] = p_{a_1} - p_{a_2} = \left(\frac{a_1}{0.01}\right)^{-2.5} - \left(\frac{a_2}{0.01}\right)^{-2.5} \tag{5}$$

In particular, for the six acceleration intervals (j = 1 to 6) defined in Table 1, shown below, the corresponding occurrence probabilities are denoted by q_j, j = 1 to 6.

Acceleration Ranges ($a_1 \leftrightarrow a_2$)	$q_j = p_{a_1} - p_{a_2}$
0.01 - 0.02	0.83
0.02 - 0.05	0.152
0.05 - 0.01	0.015
0.1 - 0.2	0.0028
0.2 - ∞	0.0002

Table 1

3. COMPUTATION OF AVERAGE TRANSITION PROBABILITIES

To model the effects of earthquake ground motion, the structural system is idealized by a finite number of states. Before an earthquake the structure is assumed to be undamaged (stage 0). Immediately after the earthquake it is found in one of the following states ($i = 1$ to 5):

- state 1 : minor nonstructural damage
- state 2 : major nonstructural damage
- state 3 : structural damage and major nonstructural damage
- state 4 : building declared unsafe
- state 5 : building collapse

It will be assumed here that the policy is to repair damage and replace the structure, if necessary, by a (nominally) identical one, after each earthquake. In this case, the only transitions we need to consider are those from state 0 to some other state. As will be seen in part 4, expected future costs depend importantly on the average probabilities of transition from state 0 to state i, p^*_{oi}. These can be computed from the vector of probabilities q_j (see part 2) and the matrix of probabilities f_{ij}. We have

$$p^*_{oi} = \sum_{\text{all } j} f_{ij} \, q_j \qquad (6)$$

where f_{ij} is the fraction of buildings expected to be found in state i immediately after an earthquake with a peak acceleration in range j.

A typical set of values for f_{ij} and the resulting values of p^*_{oi} are shown in Table 2.

f_{ij} = Fraction of Buildings Expected to be Found in State i after Quake with Peak Acceleration in Range j

Acceleration Ranges j	0.01-0.02 1	0.02-0.05 2	0.05-0.1 3	0.1-0.2 4	>0.2 5	p^*_{oi}
q_j	0.83	0.152	0.015	0.0028	0.0002	
State i = 0	f_{11}=0.95	0.75	0.30	0.01	0	0.905
1	0.05	0.20	0.40	0.14	0.01	0.078
2	0	0.04	0.20	0.30	0.14	0.012
3	0	0.01	0.07	0.40	0.25	0.004
4	0	0	0.02	0.10	0.30	0.00065
5	0	0	0.01	0.05	0.30	0.00035

Table 2

The probability assignments must always satisfy

$$\sum_{\text{all } j} q_j = 1$$

$$\sum_{\text{all } i} f_{ij} = 1 \qquad \text{for every } j \qquad (7)$$

$$\sum_{\text{all } i} p^*_{oi} = 1$$

The f_{ij} values in Table 2 are rough estimates referring to "average" buildings in Boston. A different set of values exists for each type of building, for different age categories, different code provisions, etc. For example, an increased base shear coefficient may be expected to give rise to an "upward shift" in the tabulated f_{ij} values (for example, we might have $f^{new}_{03} > f^{old}_{03}$ and $f^{new}_{05} < f^{old}_{05}$).

4. ECONOMIC ANALYSIS

If one's policy is to repair or replace the structure (if necessary) following each earthquake, then the Expected Discounted Future Cost (EDFC) takes the form

$$\text{EDFC} = \frac{\lambda}{\delta} \sum_{\text{all } i} p^*_{oi}\, c_{oi} \tag{8}$$

where λ = average rate of occurrence of earthquakes causing a peak acceleration $a \geq 0.01g$ ($\lambda = 1/10 = 0.1/\text{yr}$)

δ = continuous discount rate--say, $\delta = 0.04$ (δ^{-1} can be interpreted as the "effective life" or the decision "horizon "; earthquakes which might occur more than δ^{-1} years from now contribute only negligibly to EDFC).

c_{oi} = the average loss suffered as a result of a "transition" from state 0 to state i. It can be expressed as a fraction of the replacement cost C_o. Estimates for the ratios c_{oi}/C_o are tabulated below:

State i	c_{oi}/C_o
0	0
1	0.01
2	0.05
3	0.20
4	1.0
5	5.0

Table 3

In this example:

λ = 0.1 per year

δ^{-1} = 1/0.04 = 25 years

$$\sum_{\text{all } i} = p^*_{oi}\, c_{oi} = (0 + 0.078 \times 0.01 + 0.012 \times 0.05 + 0.004 \times 0.2 + 0.00065 \times 1.0 + 0.00035 \times 5.0)\, C_o$$

$$= (0 + 0.00078 + 0.0006 + 0.0008 + 0.00065 + 0.00175)\, C_o$$

$$= 0.00458\, C_o$$

Finally, $\text{EDFC} = (0.1) \times (25) \times (0.00458\,C_0) \approx 0.0115\,C_0$

- (0.1): Average Annual No. of Quakes Causing $a \geq 0.01g$
- (25): Effective Lifetime in Years
- ($0.00458\,C_0$): Average Cost if Quake (causing $a \geq 0.01g$) Happens
- ($0.0115\,C_0$): About 1% of Initial Cost

5. SOME COMMENTS AND SUGGESTIONS

(i) Matrix formulation

To perform a decision analysis, one needs, besides λ and δ,

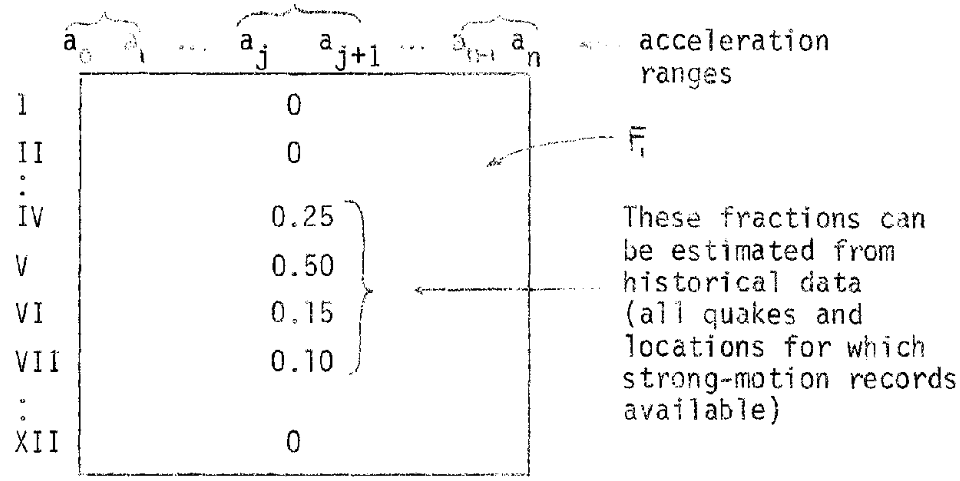
- a vector of probabilities (related to ground acceleration), $\underset{\sim}{q} = \{q_j\}$
- a vector of cost fractions, $\underset{\sim}{c} = \{c_{oi}\}$
- a m x n matrix F relating n acceleration intervals to m (average) cost quantities

Eq. 8 can be rewritten in matrix notation

$$\text{EDFC} = \lambda\,\delta^{-1} C_0 \underset{1\times m}{\underset{\sim}{c}}\;\underset{m\times n}{F}\;\underset{n\times 1}{\underset{\sim}{q}^T} \qquad (9)$$

(ii) Another Way of Arriving at Reasonable Values for EDFC:

M.M. Intensities can be related to damage and an approximate relationship exists between MMI and peak ground acceleration. One can set up a matrix F_1, relating MMI values (states correspond to units on the scale) to ground acceleration levels.



A second matrix F_2 relates MMI levels to structural damage states (and associated average fractions of initial cost). It can be shown that EFDC now takes the form

$$\text{EFDC} = \lambda\, \delta^{-1} C_0 \underbrace{\underset{\sim}{c}}_{1\times m} \overbrace{\underbrace{F_2}_{m\times 12} \underbrace{F_1}_{12\times n}}^{F \;\; m\times n} \underbrace{\underset{\sim}{c}^T}_{n\times 1} \qquad (10)$$

(iii) λ is obtained from a local seismic risk analysis, of course. The sensitivity of the probabilities q_j and EDFC w.r.t, the occurrence and attenuation parameters β and b_2, respectively, needs to be studied. Values between 1.5 and 2.8 have been suggested for the ratio β/b_2.

(iv) When code requirements are changed for a given category of buildings, the matrix F will be affected, but not the vectors $\underset{\sim}{q}$ and $\underset{\sim}{c}$ and λ and δ. It is, in principle, straightforward to evaluate proposed code changes: compare old and new EDFC values and estimate the change in first cost.

Section 2

DAMAGE STATES AND PROBABILITIES

Robert V. Whitman

1. INTRODUCTION

The damage states and earthquake intensity categories suggested herein are intended to be general in their applicability. The earthquake intensity probabilities are for the Boston area. The damage probabilities are for 8 to 13 story structures founded on firm ground and designed according to the building code requirements in effect in Boston prior to 1 July 1971.

The suggested probabilities are little more than guesses. The intention is to suggest the general level of probabilities which might apply.

2. DAMAGE STATES

Table 2.1 lists suggested damage state categories, described both by words and in terms of the direct cost of repairs. Repair cost expressed as a ratio to replacement cost appears to be the most meaningful quantitative description of damage state, although this is not necessarily the cost which should be used in loss computations.

In particular, the costs in Table 2.1 do not include non-physical costs: loss of occupancy of the building, loss of life or psychological effects upon individuals or upon population as a whole. There is a range of possible viewpoints concerning such costs, ranging from that of insurance companies who are concerned only with dollar losses to that of a politician who dreads any loss of life which might be attributed to one of his decisions. It may be desirable to keep the technical and non-technical costs separate until a very late stage in the computations, and even to delay trying to express the non-technical costs in dollars. Research will be needed into the difficult problem of optimizing with regard to both physical and non-physical costs.

3. EARTHQUAKE INTENSITY CATEGORIES

It seems desirable to use categories corresponding to the various levels of modified Mercalli intensity. The range of accelerations shown in Table 2.2 were obtained by applying the Hershberger correlation at intensities of IV and less, the Gutenberg and Richter correlation at intensities of IX and greater, and using a transition curve at intermediate intensities. The transition curve is the one which NOAA has recently suggested to the AEC.

In computations, it may well be meaningless to treat categories I, II and III separately. Possibly even I, II, III and IV should be lumped together.

4. PROBABILITY ESTIMATES

Table 2.3 gives probability estimates for modern 8 to 13 reinforced concrete buildings built on firm ground in Boston, assuming no specific provision has been made for earthquake resistance but that wind resistance has been provided. The numbers in this table are intended as "best guesses". I suspect that the estimates are pessimistic. That is, the probabilities assigned to intensities VI, VII and VIII probably are too high, and for these intensities the probabilities of levels 4, 5, 6 and 7 damage are also probably too large.

The attempt to assign the probabilities in this table suggests to the writer that intensities VI, VII and VIII possibly should be subdividied.

Table 2.1

SUGGESTED DAMAGE STATES

Description of Level of Damage	Ratio to Replacement Cost
0. No damage	0
1. Minor non-structural damage - a few walls and partitions cracked, incidental mechanical and electrical damage	0.0005
2. Small non-structural damage - more extensive cracking (but still not widespread); damage to elevators and other mechanical/electrical damage	0.002
3. Minor structural damage - a few beams and columns cracked or yielded; substantial non-structural damage - widespread cracking on lower floors, elevators damaged	0.01
4. Substantial structural damage requiring repair or replacement to numerous structural members; associated extensive non-structural damage	0.05
5. Major structural damage requiring repair or replacement of many main structural members; associated non-structural damage requiring repairs to major portion of interior; building vacated during repairs	0.25
6. Building condemned	1.00
7. Collapse	1.00

Table 2.2

EARTHQUAKE INTENSITY CATEGORIES

MM Intensity	Acceleration Range
I	$<0.001g$
II	0.001g - 0.003g
III	0.003g - 0.008g
IV	0.008g - 0.02g
V	0.02g - 0.04g
VI	0.04g - 0.08g
VII	0.08g - 0.16g
VIII	0.16g - 0.33g
$\geq$IX	$>0.33g$

		EARTHQUAKE INTENSITY							
LEVEL		I	II	III	IV	V	VI	VII	VIII
PROB.		0.67	0.20	0.06	0.04	0.025	0.0045	0.00045	0.00005
DAMAGE STATE	0	1.00	1.00	0.99	0.98	0.90	0.20	0	0
	1	0	0	0.01	0.02	0.09	0.25	0	0
	2	0	0	0	0	0.01	0.25	0.05	0
	3	0	0	0	0	0	0.20	0.20	0.05
	4	0	0	0	0	0	0.09	0.50	0.20
	5	0	0	0	0	0	0.01	0.20	0.50
	6	0	0	0	0	0	0	0.04	0.20
	7	0	0	0	0	0	0	0.01	0.05

Table 2.3

FIRST GUESS AT INTENSITY AND DAMAGE PROBABILITIES FOR 15-20 STORY RC BUILDINGS ON FIRM GROUND IN BOSTON