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Seismic Design Decision Analysis

Report No. 17

HOW DO WE EVALUATE AND CHOOSE BETWEEN ALTERNATIVE CODES FOR DESIGN AND PERFORMANCE?

by

Richard de Neufville

February 1975

Sponsored by National Science Foundation
Research Applied to National Needs (RANN)
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ABSTRACT

The choice of a design code depends on the values we place on the benefits or costs of greater safety or higher performance. Experimental data demonstrate that the public's evaluation of any protection, against earthquake damage for example, is both a highly nonlinear function of its level and of the level of other benefits, and varies between different elements of society. As shown by a case study, these facts mean that the most commonly discussed methods of evaluation for seismic codes - benefit-cost or risk-of-death analysis - may lead to incorrect and unacceptable recommendations. We propose criteria for deciding when approximate evaluations are appropriate and when a more complete assessment of the nonlinear values used by the different interest groups is required.

Preface

This is the 17th in a series of reports under the general title of Seismic Design Decision Analysis. The overall aim of the research is to develop data and procedures for balancing the increased cost of more resistant construction against the risk of losses due to possible future earthquakes. The research has been sponsored by the Earthquake Engineering Program of NSF-RANN under Grat GI-27955. A list of previous reports is included at the end of this report.

The report discusses the measurement of societal preferences and then demonstrates how these measurements can be incorporated into the process of choosing seismic codes.

The author is Professor of Civil Engineering at MIT. The principal investigator for the overall research project is Robert V. Whitman, Professor of Civil Engineering.

INTRODUCTION

The choice of national or regional design standards - for the strength of buildings, the levels of pollution, or the use of land and the location of facilities - represents a significant decision involving millions of dollars. The restrictions specified in any code may add only a small percentage to the cost of building a house or operating a car. But these small amounts can add together to truly enormous sums. The question is: How much should society spend to improve design?

Typically, this choice has not been based on any detailed understanding of the values at stake. There is little reason to believe that public policy toward design codes or performance standards really reflect the best interests of society. In particular, the choice of a seismic design code to protect us from earthquakes embodies a determination of how much society will have to spend to avoid deaths and other injuries, and to reduce the probability of future losses. Our practical problem is that the values of these important benefits are not at all obvious. There are no legitimate markets for lives: so there are no prices that we can use in our evaluation. This report shows how measures for societal preferences can be obtained and used, in the specific context of establishing construction codes for protection against earthquake damage.

DILEMMAS OF POLICY CHOICE

The incorporation of people's or societal values into the process of choosing a code requires that we face serious analytic and ethical problems. One dilemma is pragmatic. The value people place on any benefit generally depends nonlinearly both on its own level and the level of other factors.

Ignoring this complexity reduces the costs of measurement and analysis. But such simplifications will bias the results of the evaluation to some degree, and may lead to recommendations which are unacceptable to the public because they do not properly reflect societal values. To what extent is it then desirable to evaluate our choices using approximations, and when should we do a complete analysis?

The second dilemma stems from the fact that people differ considerably. What one expert believes is best for society is often quite different from what another feels, let alone from what the public desires. What procedures can we use that will incorporate the understanding of experts and be compatible with our sense of justice and democracy?

This report hopes to clarify these issues to help us face the immediate problem of revising seismic codes in the United States. Specifically, a criterion is suggested for indicating when the more complete analysis should be used, and when expert opinion as to levels of protection can - and cannot - be thought to be a reasonable approximation to societal preferences and guide for determination of public policy.

SEISMIC DESIGN PROCESS

The choice of a seismic code represents a decision about how much extra strength we should incorporate into buildings to protect us against earthquakes. Implicitly, it is thus a decision about how much we should spend now on some kind of insurance against an indeterminate threat. The problem involves:

-- uncertainty regarding the timing, intensity and frequency of earthquakes, and the transmission of these shocks to any building;

-- further uncertainty about the effectiveness of any extra strength in reducing damage to a building and its occupants;

-- tradeoffs between the costs of stronger design and the range of benefits it may provide if there is an earthquake.

The problem is so complex that it has generally not been subjected to detailed analysis.

Design codes have usually been proposed by committees of experts and governmental officials who subsequently urge city governments to accept their recommendations. Attention appears to have focused on resolving obvious problems as defined either by recent experience with a major earthquake, or by technological developments in construction procedures or seismology. Detailed estimation of the benefits of new codes does not ever seem to have been part of the process. Societal values only seem to have entered the deliberations insofar as major interests close to the construction industry were affected -- strong protests tend to arise, for example, if a proposed code gives steel construction significant new advantages over reinforced-concrete design.

This process has worked to a degree. The compromises that have been made between increased safety and extra cost have neither been so costly as to evoke public protest nor so inadequate as to lead to substantial losses. But we should be able to do better.

The MIT Seismic Design Decision Analysis project has thus been developing procedures for evaluating proposed codes in detail. We suppose that we are considering a limited number of distinct choices of code, each of which has specific implications for the design of a structure. Any earthquake will inflict various types of damage on the building, its contents and its occupants. Call this the vector of effects:

$$\text{Effects} \quad \underline{x} = [x_1, x_2, ----x_N] \tag{1}$$

where the x_N represent the different kinds of damage. Naturally the amount of damage of any type caused by an earthquake of specified intensity is probabilistically defined, as is the occurrence of earthquakes. The occurrence of any set of effects thus is also described by a probabilistic function which depends on the type of code k:

$$f_k(\underline{x}) = f_k\ [x_1,\ x_2,\ ----x_N] \tag{2}$$

The estimation of the distribution of each effect, say the annual probability of losing lives in a specific kind of building in a given area, is far from a trivial task. But much has already been done in this area, (see, for example, Whitman et al., 1974), so here we concentrate on the neglected aspect of the total problem, the question of evaluation.

The evaluation of each possible code requires that we define a value function which assigns a total value or ranking, $V(\underline{x})$, to any set of effects. The value of any code is then the expectation of the value of the probable consequences of using any code:

$$V_k = \sum_{\text{all } \underline{x}} f_k(\underline{x})\ V(\underline{x}) \tag{3}$$

The final step is to choose the code with the highest value.

APPROXIMATE METHODS OF EVALUATION

The most commonly discussed methods for evaluating seismic design codes are both highly simplified. These are the benefit-cost and the "risk-of-death" methods. Both make strong assumptions about the nature of society's values for the possible effects of an earthquake.

The benefit-cost approach, as used in this context, assumes that each effect has a fixed value or price per unit. This assumption is acceptable when we consider items which are ordinarily manufactured or sold abundantly. The cost of replacing broken window panes, for example, is the cost of the pane and the cost of the labor, neither of which we expect to change due to an earthquake. But the assumption of fixed value is tenuous if not implausible when we consider irreplaceable objects and calamitous losses. Daily experience suggests, for instance, that society is not as concerned about the repeated loss of individual lives (as in the highway carnage) as about large loss of life in single events (as through a severe earthquake). To the extent that we actually face a serious possibility of loss of life, then, it may be quite inappropriate to assume that life lost has a fixed value, independent of the circumstances.

The risk-of-death approach focused on the number of deaths expected from different choices of codes. By implication, it places a value on each life, and none on all the other effects of an earthquake. This approach neglects the monetary costs associated with the structure, either of the damage inflicted or of the extra strength that must be provided in structures because of the code. It says, in effect, that we should reduce the death rate due to earthquakes regardless of cost, regardless even of other ways to spend money to save lives!

Despite the fact that their assumptions are questionable, both the benefit-cost and risk-of-death methods have a definite pragmatic appeal. These methods simplify the evaluation and lend themselves to formulas that can be easily applied. They can also be readily explained in popular terms, an evident plus for officials who must justify their decisions to the public. The simplified methods of evaluation thus cannot be totally dismissed.

MEASUREMENT OF VALUE

Value functions are inherently relative. In the firt place, there is no necessary zero point for our scale: we can define net value with respect to any convenient point. Second, we can also define our unit of measurement in terms of an arbitrary difference in value between two states; no particular difference is intrinsically better. This implies that our measurements of value, just like our measurements for temperature, are basically unaffected by changes in base or scale. We will, in short, obtain the same ranking for different sets of effects using either $V(\underline{x})$ or $V'(\underline{x})$, a different measurement of value using a different base and scale:

$$V'(\underline{x}) = a + b\,[V(\underline{x})], b > 0 \tag{4}$$

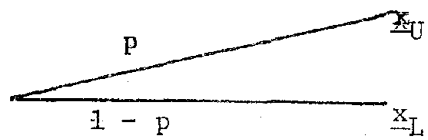
(This transformation is just like what we do to go between degrees centigrade and degrees Fahrenheit. Technically, it is known as a positive ($b > 0$), linear transformation.)

The practical implication of this fact is that we can assign arbitrary values to any two points or sets of effects. These are generally taken to be the lower and upper extremes of the range $\underline{x}_L$ and $\underline{x}_U$. Since their values are arbitrary, they might as well be convenient, just as we take the freezing point of water to be 0°C and boiling to be 100°C. In measuring the value of undesirable effects, such as the costs or damage due to earthquakes, it is convenient to set:

$$\begin{aligned} &\text{for} \quad \underline{x}_L = \text{no damage or cost}, && V(\underline{x}_L) = 0 \\ &\text{for} \quad \underline{x}_U = \text{maximum damage}, && V(\underline{x}_U) = -100 \end{aligned} \tag{5}$$

The value of all other points or sets of effects are scaled with respect to the predetermined base points. The procedures to do this have been perfected experimentally over the last decade and have been demonstrated to generate accurate, reproducible expressions for the value functions. (See Raiffa, 1968, for a detailed description of the procedure when $\underline{x}$ is a one-dimensional scalar quantity, and Keeney, 1971, for the theory and application of the procedure when $\underline{x}$ is a vector of effects.)

To determine the relative value of any set of effects, we compare it to a weighted average of two other sets of effects, whose value is known. Through a structured series of questions designed to eliminate bias, we determine when the value of the unknown point equals the known weighted value. The mechanism for weighting the value of two sets of effects is a lottery between the two sets, with arbitrary probabilities p and (1 - p) of obtaining each outcome. For example, we could have:



(6)

The value of this lottery is known if the value of its outcomes have been defined by assumption or previous computation.

In measuring a person's value for possible real situations, we naturally have to define realistic choices. For example, here is a sample question from the MIT study of people's values on earthquake codes:

> Sample Question: You can choose between two design strategies. Strategy A requires you to pay a fixed premium on your initial construction costs. Strategy B requires no premium, but has a probability p = 5% requiring repairs costing 50% of the initial costs, as well as a probability (1 - p) = 95% of requiring no extra expenses. What is the most you would pay in terms of a fixed premium, F, (as a percentage of the initial costs) before you would prefer strategy A to strategy B?

The answer to this question determines the value of F% of initial costs in terms of the values for paying no extra and 50% extra costs.

In practice, we usually construct the value function for all effects, $V(\underline{x})$, from measurements of values over one effect at a time, $V(x)$. The sample question, for instance, refers only to monetary costs. Similar questions would be asked concerning other effects, say, lives lost. Once these individual value functions have been measured, a further series of questions are asked to obtain the appropriate scaling factors, K_i, between them. The value function for all effects together is then determined by the formula developed by Keeney (1971):

$$K^{*}V(\underline{x}) + 1 = \prod_{i} [K^{*}K_{i} V(x_{i}) + 1] \tag{7}$$

which must be solved implicitly for the normalizing constant, K*, for any arbitrary definition of the value of the ranges of the scale, such as 0 and -100.

To determine a complete value function for an individual we obtain values for many points and construct the function by interpolation. To check for consistency and increase accuracy, we also calculate the value for the same point (or set of effects) by comparing it to different pairs of points of known value. The entire process is quite similar to a topological survey; points are triangulated independently from a baseline and contours are developed by interpolation. The assessment is fairly rapid. A complete measurement for an individual's preferences over a couple of dimensions takes less than two hours. First-order measurements for groups can be obtained in a half-hour.

RESULTS OF SOME MEASUREMENTS

We carried out measurements of people's values for the effects of earthquakes during 1973-74. Since this was an initial effort (to our knowledge, the first analytic assessment of values for seismic design) we considered a relatively simple case involving only two kinds of effects. These were monetary costs of damages that could be directly priced, and loss of life as a proxy for all human injury. These effects actually seem to account for most of the items of concern to people and society when thinking about protection against earthquakes.

The results first of all demonstrate that people's value functions are highly non-linear, as expected. Furthermore, most people apparently place a high value on avoiding calamitous vibrations with a large loss all at once, and find it easier to accept the same total loss spread out as many individual events.

Figure 1 illustrates these phenomena. The non-linearity is obvious, but the aversion to large losses requires some explanation. To visualize this aversion to calamity, focus on one of the curves in Figure 1, that of the planners, say. Their value for a 25 percent increase in cost is roughly -20. But, in the same relative scale, their value for a 50 percent increase in cost, a loss which is twice as great from a purely physical point of view, is -100. This means that they prefer to suffer up to approximately 5 losses of 25 percent rather than one loss of 50 percent.

Technically speaking, the measure of a person's aversion to calamity is the horizontal distance between the diagonal straight line and the curve of the value function. For planners, at a loss of 25 percent, this risk aversion is equivalent to about a 15 percent increase in loss. (That is, a 10% increase in loss implies, for a person with no non-linearity in the value function, a value of -20; the planners' 25 percent increase in cost is, then, higher by the 15 percent increase in cost.)

Different professional groups and interests appear to have quite measurably different values for different outcomes. While the specific curves portrayed in Figure 1 were not developed on the basis of controlled tests of well-classified groups (sufficient resources were not available to do this) but were obtained from professional groups that become accessible, these results are nonetheless generally borne out by everyday experience. Developers and tenants, for instance, do not seem willing to pay any substantial premium to avoid possible seismic damage. Structural engineers and governmental officials, and others who might feel more personally responsible for damage (as well as being insulated from paying the higher costs of stronger designs) may however feel that it is critical to pay a substantial premium as insurance against loss.

Finally, the values that people place on any effect also depends nonlinearly on the level or intensity of other effects. Figures 2 and 3 show this and also emphasize the nonlinearity of value functions and their differences between groups.

IMPLICATIONS OF ACTUAL VALUES

These nonlinear value functions significantly penalize heavier states of damage. This can be seen by looking at the function associated with structural engineers in Figure 1. Their relative value for a 50% extra cost is (at -100) about 10 times greater than their value for half the actual dollar amount (25% extra cost). This may seem strange at first but can be really quite rational: the bankruptcy and loss of reputation connected with a catastrophic failure may easily be seen as far worse than smaller damages that can be absorbed.

These values lead to the choice of more protective codes than would be chosen if we used constant values, for life lost say, as we would in a benefit-cost analysis. Conversely, since people actually do value money as well as life,(and since huge amounts have to be spent for each life we may expect to save from loss in an earthquake) these value functions might imply a less protective - and more economical - code than a risk-of-death analysis.

To understand the importance of the effect of the nonlinear value functions, we need to determine how much they change V_k, the perceived value of each code, k. This requires knowledge of the impact of any code on the initial costs of a building and the distribution of losses that may occur for any earthquake. This has been calculated at MIT for a prototype 10-story reinforced concrete building (see Whitman, et al., 1974). We can thus calculate the probability distribution of effects on such buildings designed according to various codes, $f_k(\underline{x})$, once we specify a probability distribution of earthquakes and for any set of values. This enables us to determine the preferred code for any distribution of earthquakes (the one with the best V_k). Conversely, this kind of result enables us to demonstrate the effect of different value functions on the choice of code.

We in fact calculated which codes would be optimal for a range of situations. Specifically, we examined the choices that 'government officials' and 'developers', with the value functions indicated in Figures 2 and 3, would make. To do this, we used a simple computer program to calculate which level of design code they would prefer for each of 90 situations with different distributions of earthquake intensity. These situations were defined by families of distributions with varying maximum intensities and rates of decrease in the probability of more intense earthquakes. Taleb-Agha (1974) describes the procedure in detail. We found that the same level of design code would be preferred for a continuous range of combinations of probabilities and intensities. The results then enable us to infer, by interpolation, which level of design code these groups might prefer for any probability distribuiton of earthquake intensities that might exist.

The codes that would be chosen for any site by our different groups are illustrated in Figures 4 and 5. To determine the code which is preferred, we draw on the diagram the significant tail of the probability distribution for earthquakes at a site and identify its intersection with the area associated with the highest code. As an example, consider the site which has the distribution of earthquakes indicated by the dashed line. Developers and others with essentially linear values for life lost (and for whom a benefit-cost analysis would be appropriate) would choose the code now associated with Zone 1, while government officials would choose the code for Zone 3.

The effect of using a nonlinear value function is seen by comparing Figures 4 and 5. The stronger the nonlinearity, that is, the heavier the weighting against calamitous effects and loss of life, the more the regions of optimal code shift to the left, implying more protective designs for safer sites. The figures show that this shift can be significant.

This approach to the evaluation of design codes is valid for many areas, not just seismic design. It is finding acceptance in several other sectors of the construction industry, notably for the specification of desirable levels of protection against fire damage (see Shpilburg et al., 1974). The Factory Mutual Insurance companies have, in fact, been investigating the possibility of rewriting their policies and rate books on the basis of similar analysis.

CRITERIA FOR SIGNIFICANCE

Different value functions do not always imply different policies. The ranking of codes generated by two value functions $V'(\underline{x})$ and $V''(\underline{x})$ may be identical either because these functions are not sufficiently different, or because of the shape of the probability distribution. So while we should recognize the essential nonlinearity of value functions and their difference between groups, it may not be worthwhile to insist on these distinctions in practice. The question is: when is it desirable to use a nonlinear value function?

A related question concerns the level of detail that is useful in the analysis. When should we look at several different effects together, such as both monetary costs and loss of life, and when might we reasonably simplify the analysis by considering only one or the other?

Simple numerical criteria can help answer these two questions. Basically, we can use the general parameters of the value functions and probability distributions - which are easy to obtain - to develop tests of significance of the nonlinearity of the value functions and the importance of each effect in any situation. We do this right at the start and use the result to screen out dimensions of the problem and degrees of sophistication that are not important for this situation. The subsequent detailed analysis then focuses only on what is likely to be important. This screening procedure gives us confidence that we are not wasting time and money on irrelevant detail, and also that we do include everything that is important.

The criteria for significance are first-order estimates of the maximum expected difference between the true value of the recommended policy that could result from making both the complete and the simpler assumptions. These differences are expressed in terms of one of the effects, such as monetary costs, chosen arbitrarily for convenience.

To use the criteria, we compare them to the first-order estimate of the total value of the recommended policy. If our upper bound on the possible difference in total value is relatively insignificant, we presume that the change in ranking that might occur, by making the simplifying assumptions, is equally insignificant.

Estimates of the test criteria are easily obtained through the use of standard approximations to both the value functions and the marginal (or unconditional) probability distributions for each effect x_i. Probability functions for the effects can likewise be approximated by obtaining a priori estimates of only the two or three parameters needed to specify a particular member of any of the few important families of distributions that could reasonably represent a situation with which we might be concerned. Value functions can be approximated for each effect either in terms of $a_i + b_i e^{c_i x_i}$ if they are nonlinear or of $a_i + b_i y_i$ if they happen to be linear. The value function over the vector of all effects, $V(\underline{x})$, is then a combination of these individual value functions requiring scaling constants K_i as indicated by Equation 7. Since the base a_i , and the scale, b_i, of any individual value function are arbitrary, the approximation of $V(\underline{x})$ only requires us to obtain twice as many parameters as there are different effects. We have to ask at least one question each to determine the degree of risk aversion, c_i, for each effect, and the scaling constant, K_i. The base constants, a_i, are set by the value arbitrarily assigned to the origin of the scale, for example $V(0) = 0$; and the scale constants b_i, can equal 1.0 except for linear function of value over a given dimension.

The test criteria can, thus, be calculated once a handful of parameters have been specified. Table 1 illustrates what is involved. For any of the combinations of values and probability distribution functions shown, it displays the specific parameters that must be estimated and the formulas for the measures of value used to generate the test criteria. The column labeled $|x_e - \bar{x}|$ contains the equations for the maximum difference that might arise from using a linear value function instead of the more accurate nonlinear ones. The $\bar{x}$ is the mean of the distribution; x_e is the level of the effect whose value equals the value of the expectation obtained by multiplying the distribution and the nonlinear value function. This latter quantity is known technically as the certainty equivalent, and thus $|x_e - \bar{x}|$ is simply what is known as the risk premium implicit in the nonlinear value function for a particular situation. The column headed $\bar{V}$ contains the formulas for the expected value associated with any effect, and this provides the basis for judging whether it is worthwhile to include that effect in a more detailed analysis.

The procedure for using the measures of value shown in Table 1 is the following. We search for the sets of probability distributions of the effects (which vary with the design policies reflected in each building code) that maximize $|x_e - \bar{x}|$, and that maximize and minimize $\bar{V}$. $|x_e - \bar{x}|$ is the criteria of significance for linearity, and the range on the $\bar{V}$ determines the criteria for including an attribute, as indicated previously. Byer (1975) provides complete details. Meanwhile, we proceed to illustrate the use of the criteria by means of a case study.

CASE STUDY

This example looks at the evaluation of building codes for 5 to 20 story reinforced concrete buildings. Its purpose is to illustrate how we might go about choosing the appropriate level of complexity and detail for an evaluation. The complete case is developed in Byer (1975). We only present the highlights.

Conforming to the data collected as part of the MIT Seismic Design Decision Analysis project, we assume that two groups, characterized by significantly different notions of value, are concerned with the design: developers and government officials. Two different kinds of effects are also taken to be potentially important: monetary costs and lives lost. The possible design spanned the usual range, that is, from the least protection given by the 1970 U.S. Uniform Building Code to that given by a Superzone having twice the lateral force requirements of Zone 3 of the Code. Finally, the analysis for two seismic risk areas is made; the low risk area corresponds approximately to Boston, Massachusetts, while the high risk area is hypothetical and might occur at only a very few locations on the earth. This definition of the situation allows us to show how evaluation procedures with different degrees of complexity are suitable for different groups and different locations.

The parameters needed to determine the approximate functional representations of the value functions were extrapolated from the data plotted in Figures 2 and 3. These parameters are listed in Table 2. The degree of nonlinearity of the value functions for each effect is captured by the risk aversion coefficients, c. (A positive c indicates aversion to risk; a negarive c indicates a willingness to gamble more than the expected value - presumably for the chance to win big eventually; and c = 0 suggests indifference to risk.) The subscripts M and L refer to the dimensions of monetary cost and lives lost. M is the percent increase in present value of monetary costs, capital and repair, over the initial cost of a building without seismic protection, assessed over 50 years at a discount rate (net of inflation) of 5 percent. L is the percent of the building occupants killed over 50 years.

To obtain the parameters of the probability distributions of the effects for a building designed according to any code, we need first to multiply the probability of occurrence of earthquakes of different intensities by the probability of damage to a structure for several levels of possible shaking. These data are given in Tables 3 and 4, and were adapted from those developed by the MIT Seismic Design Decision Analysis effort (see Whitman et al., 1974). The product gives the annual probability that different levels of damage will occur and hence that dollars and lives will be lost. A shifted, inverted, exponential distribution was fitted to these distributions.

The parameters of the estimated distribution of effects appear in Table 5. The $(x_M)_*$ and $(x_L)_*$ represent the lower bounds on the distribution of effects, that is the initial costs and no lives lost. Since we define our baseline in measuring costs as the building without any protection, $(x_M)_*$ for the least stringent code is zero by definition. For the most stringent code, $(x_M)_* = -6.7$ means that the estimated cost of beefing our building up to that level is 6.7% of the initial costs. The B_M and B_L are the expected additional effects over 50 years, discounted as indicated above. The mean of the distribution is then the sum of these two quantities.

Let us now apply our screening procedures to help us judge what degree of sophistication is appropriate for which users and in what situations. We first turn to the question of whether it is desirable, as a practical matter, to use nonlinear value functions.

The simpler assumption of a linear value function has several advantages. Most obviously, it permits one to assign a fixed price or cost to each effect, and avoids the necessity of interviewing members of the different groups interested in the policy. The simpler assumption may also permit us to focus on the mean of a distribution rather than to work always with the more complicated probability distributions of the effects.

The formula for the criterion for significance of a nonlinear value function appears in Table 1. Since we are considering the implications of assuming linear values for each factor separately, we calculate the criterion for each factor in terms of that factor. Table 6 shows the results of these calculations. In viewing them, one should remember that the criterion does not estimate the actual expected effect but, rather, the maximum perception of a person or group of what it means to neglect the nonlinearity. The 60.6 for officials are deemed to weight calamitous losses very heavily, and to perceive a neglect of this feeling to be potentially equivalent, at the maximum, to neglecting about 60% of the initial costs.

The criteria for significance indicate that considerable accuracy could be lost in the evaluation if one disregards the inherent nonlinearity of the value functions of officials for monetary losses. The maximal difference of 60% is large both absolutely and relative to the potential size of the effects in the high risk area.

It appears reasonable, on the other hand, to use linear values for loss of both money and lives in the low risk area. Working with a nonlinear value function in these cases would change our perception of the value of any code so minimally that it would only have a trivial - if any - effect on our ranking of alternatives.

This procedure for determining how detailed and complex the evaluation should be rests on judgment, of course. It is, consequently, not altogether unambiguous. Consider, for example, the criteria for significance for monetary losses for developers in high risk areas. Although a 2.9% increase in costs is reasonably large absolutely, it is small compared to the potential magnitude of the losses, which could be total. The coefficients are an aid to judgment - where no other quantitative measures exist - but not a substitute for judgment.

We now turn to the question of what effects it is worthwhile considering in the evaluation of different policies. We thus calculate the criteria for significance of the effects. To compare their relative importance, we must place them all on the same scale. This is arbitrary. For convenience, we chose the percent of initial costs of a building without extra protection.

The calculated criteria for significance of the effects appear in Table 7. In viewing them, remember that they reflect the maximum potential effect, as mediated by nonlinear value functions, of omitting each effect from the evaluation. The figures are, thus, much larger than the actual expected losses for several reasons. First, the nonlinear value functions give enormous weight to high losses, and push the perceived amount of loss considerably higher. Second, the expected losses for some policies are much higher than what we would obtain for an optimal policy. For example, the expected monetary losses over 50 years for a building without protection in a high risk area is 74% of initial costs, as Table 5 indicates. Finally, recall that the cost of preparing our building for the most stringent code is 6.7% of initial costs, so that the lowest values of the criteria - for developers in low risk areas - are of that size.

The criteria indicate that monetary losses always constitute an important aspect of the evaluation of seismic codes. For developers, omission of this factor - as might happen in a risk-of-death analysis, could affect the perceived value of any policy for 54% of the initial costs of construction in a high risk area, and by about 6% in a low risk area. These figures are large both absolutely and relative to the 6.7% that would have to be paid to design the building according to the most stringent code. The differences in perception of the value of a code is even greater for officials. Consequently, it could appear that monetary costs should, indeed, be part of the evaluation.

Loss of life likewise also appears to be a significant factor in the evaluation. As the likelihood of an earthquake decreases, however, the consideration becomes less important. It may then be reasonable to exclude it from the evaluation for developers in a very low risk area. For officials, this exclusion would be warranted only for the areas of essentially no risk to life, since they value this effect quite heavily.

The procedure outlined and illustrated here is a pragmatic guide to what kind of evaluation is needed in any situation. It provides a mechanism for objectively addressing the question of whether particular aspects of a problem, which we know to exist, are worth taking into account in a practical situation.

As regards seismic design in particular, the analysis leads to two fairly strong conclusions. First, it seems quite clear that both monetary losses and fatalities should be incorporated into the evaluation. This implies that the risk-of-death method is inappropriate. The second conclusion is that nonlinear value functions should be used in the evaluation of designs for high risk areas.

For low risk areas, however, nonlinear value functions would appear to be superfluous, and a standard benefit-cost analysis would seem quite adequate.

HOW SHOULD WE ESTABLISH PUBLIC POLICY ON SETTING DESIGN CODES?

Taking for granted that our choice of code can be improved by a careful, detailed investigation of the consequences of any code, the real difficulties in choice center on the evaluation of these consequences. If the values of the different groups concerned with the choice are sufficiently similar they will all prefer the same choice. For these special cases it appears reasonable to have the technical experts analyze the situations and recommend a policy for society.

In general, however, significant disagreement over values and choices may exist between groups, and in particular between the experts and society at large. In a democratic society, we should not assume that the opinion of experts should prevail, especially when their expertise concerns technology and not values. How then should we use expert advice to choose design standards for society?

First, the technical experts should identify plausible choices and identify their consequences. Second, they should make available means to determine which alternatives are preferable for any particular value function that may be appropriate. For typical functions, they should determine the choices that would be made as a way of informing the public. Finally, rather than presume that any special set of values (as embodied either in benefit-cost or risk-of-death analyses) is appropriate, they should work with local communities to help them determine the choice which most closely matches their preferences.

The public ultimately pays for the insurance against earthquakes and for any damage they may cause. The choices are thus ultimately their responsibility. As experts we have a duty to alert them to the possibilities and the consequences. We do not necessarily have either the right or duty to impose our own prejudices or values. We need to work with the public on this, recognizing that it often will not be easy.

Table 1: Measures of Values Used to Calculate the Test Criteria for Significance for Each Effort, x_i (subscripts omitted for clarity)

Functions Assumed: Value	Functions Assumed: Distribution	Parameters of Distribution	Measures of Value of Nonlinearity $\lvert x_e - \bar{x} \rvert$	Measures of Value of Each Effort $\bar{V}$
	Normal	mean, $\bar{x}$ variance, σ^2	$\lvert c\sigma^2/2 \rvert$	$a+be^{(c^2\sigma^2/2) - c\bar{x}}$
	Exponential (Shifted and inverted)	lower bound, x_* β	$\left\lvert \frac{\rho+\ell n(1-c\beta)}{c} \right\rvert$	$\frac{a+be^{-cx_*}}{(1-c\beta)}$
$a+be^{-cx}$	Gamma (Shifted)	lower bound, x_* β,ρ	$\alpha\left\lvert \frac{\beta+\ell n(1+c\beta)}{c} \right\rvert$	$\frac{a+be^{-cx_*}}{(1+c\beta)^{\alpha}}$

Table 2: Parameters of the Value Functions for Developers and Officials

Parameters		Group	
Type	Symbol	Developers	Officials
Risk Aversion	c_M	0.001	0.01
Coefficients	c_L	-0.4	0
Scaling	K_M	0.96	0.99
Factors	K_L	0.32	0.99
Base and	a_M	-1.0	-1.0
Scale	b_M	1.0	1.0
Constants	a_L	-1.0	1.0
	b_L	1.0	0.05

Table 3: Probability of Earthquakes of Different Intensity in High and Low Risk Areas

Modified Mercalli Intensity	Annual Probability Assumed for Risk Area High	Low
≤ V	0	0.975
VI	0.600	0.020
VII	0.350	0.004
VIII	0.045	0.001
IX	0.004	0
X	0.001	0

Table 4: Probability of Effects of Specific Earthquakes on Most and Least Stringent Designs

Design level	Money Lost (% of Initial Cost)	Lives Lost (% of Total)	Probability of Damage Associated with Modified Mercalli Intensity $\leq$ V	VI	VII	VIII	IX	X
	0	0	1.00	0.27	0.15			
Least	0.3	0		0.73	0.48			
Stringent;	5.0	0			0.33	0.20		
UBC	30.0	0.25			0.04	0.41		
Zone 0	100.0	1.0				0.34	0.75	0.25
	100.0	20.00				0.05	0.25	0.75
	0	0	1.00	0.67	0.30			
Most	0.3	0		0.33	0.49	0.40	0.10	
Stringent;	5.0	0			0.21	0.52	0.30	
	30.0	0.25				0.08	0.58	
Superzone	100.0	1.00					0.02	0.90
	100.0	20.00						0.10

Table 5: Parameters for the Exponential Probability Functions for Damage

Design Level	Risk Area	Money $(x_M)_*$	Money β_M	Lives $(x_L)_*$	Lives β_L
UBC 0	High	0	-74.0	0	-5.33
	Low	0	- 1.25	0	-0.074
Superzone	High	-6.7	-16.3	0	-0.22
	Low	-6.7	-0.22	0	-0.001

Table 6: Criteria for Significance for the Nonlinearity of the Value Functions for the Effects for Different Groups in Different Areas

Risk Area	Loss Type	Loss As % of	Criteria for Developers	Criteria for Officials
High	Money	Initial Costs	2.9	60.6
	Lives	Occupants	2.9	0
Low	Money	Initial Costs	0.001	0.01
	Lives	Occupants	0.001	0

Table 7: Criteria for Significance of Various Effects for Different Groups in Different Areas

Risk Area	Type of Effect	Criteria as % of Initial Costs for Developers	Officials
High	Money	53.8	110
	Lives	66.0	280
Low	Money	5.67	5.66
	Lives	4.05	85.3

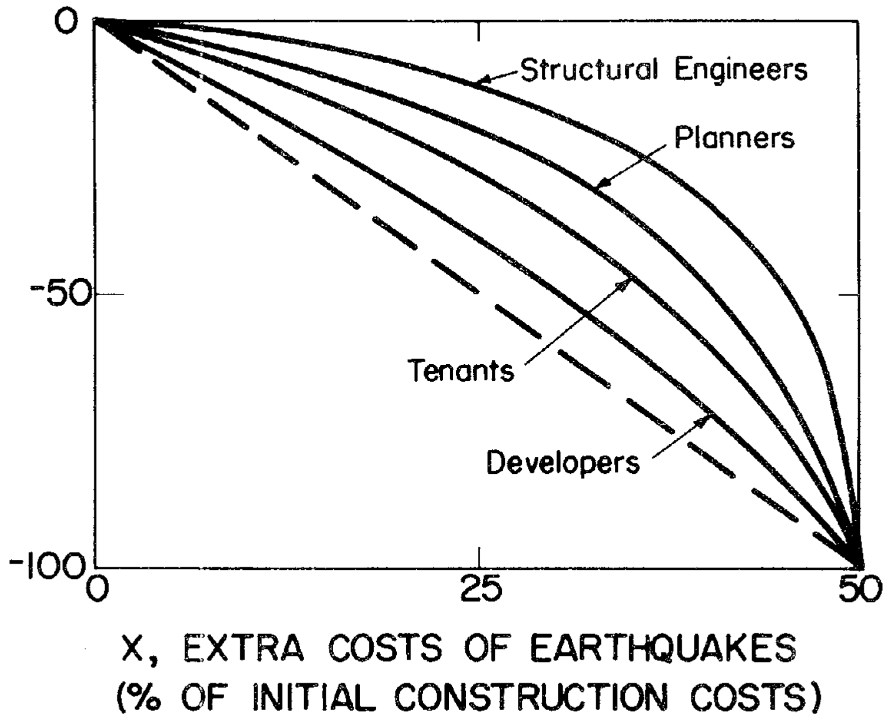


FIGURE 1 TYPICAL UTILITY FUNCTIONS FOR DIFFERENT GROUPS

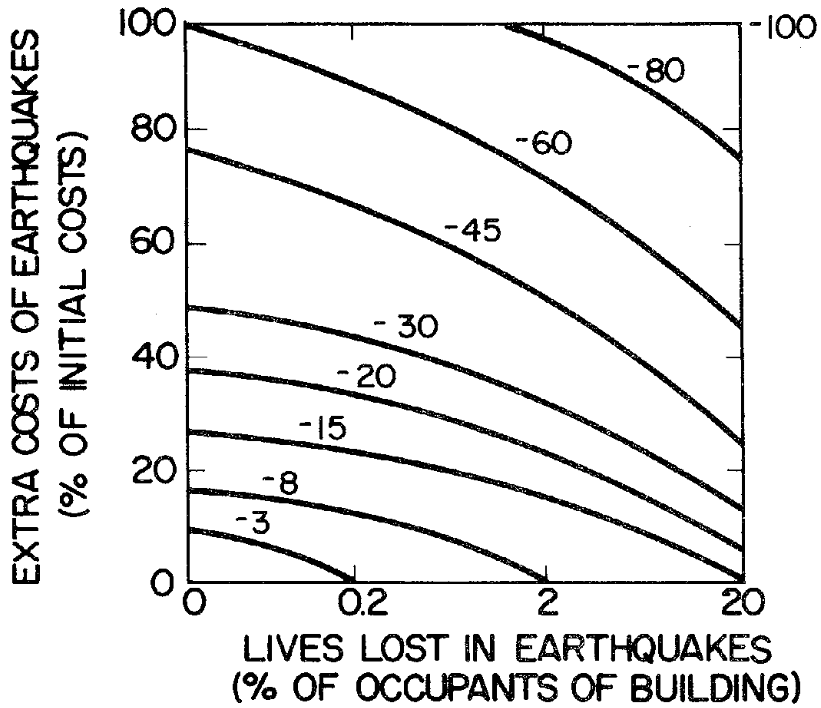


FIGURE 2 TYPICAL UTILITY FUNCTION OVER COSTS AND LOSS OF LIFE (DEVELOPERS)

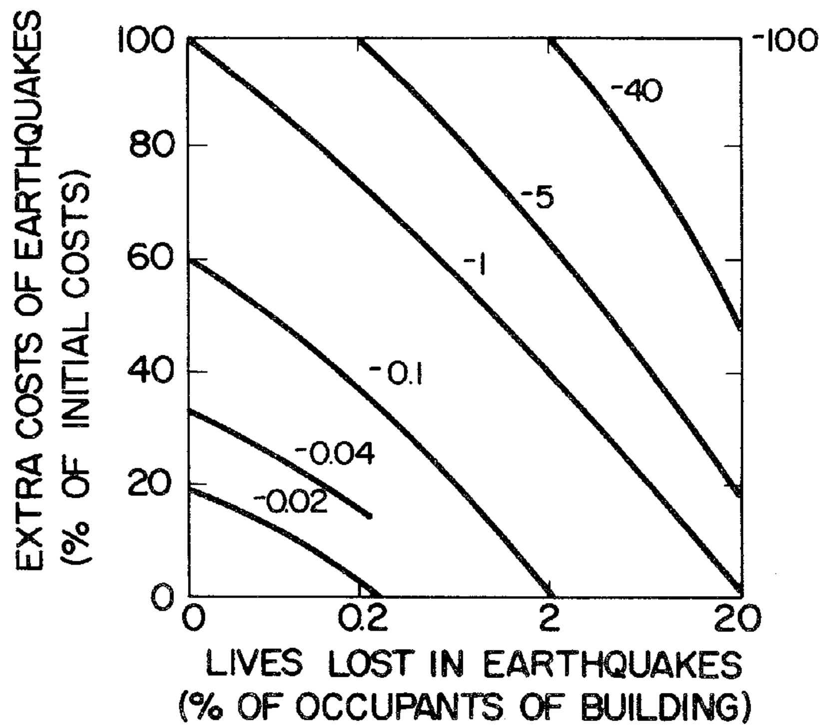


FIGURE 3 TYPICAL UTILITY FUNCTION OVER COSTS AND LOSS OF LIFE (GOVERNMENT OFFICIALS)

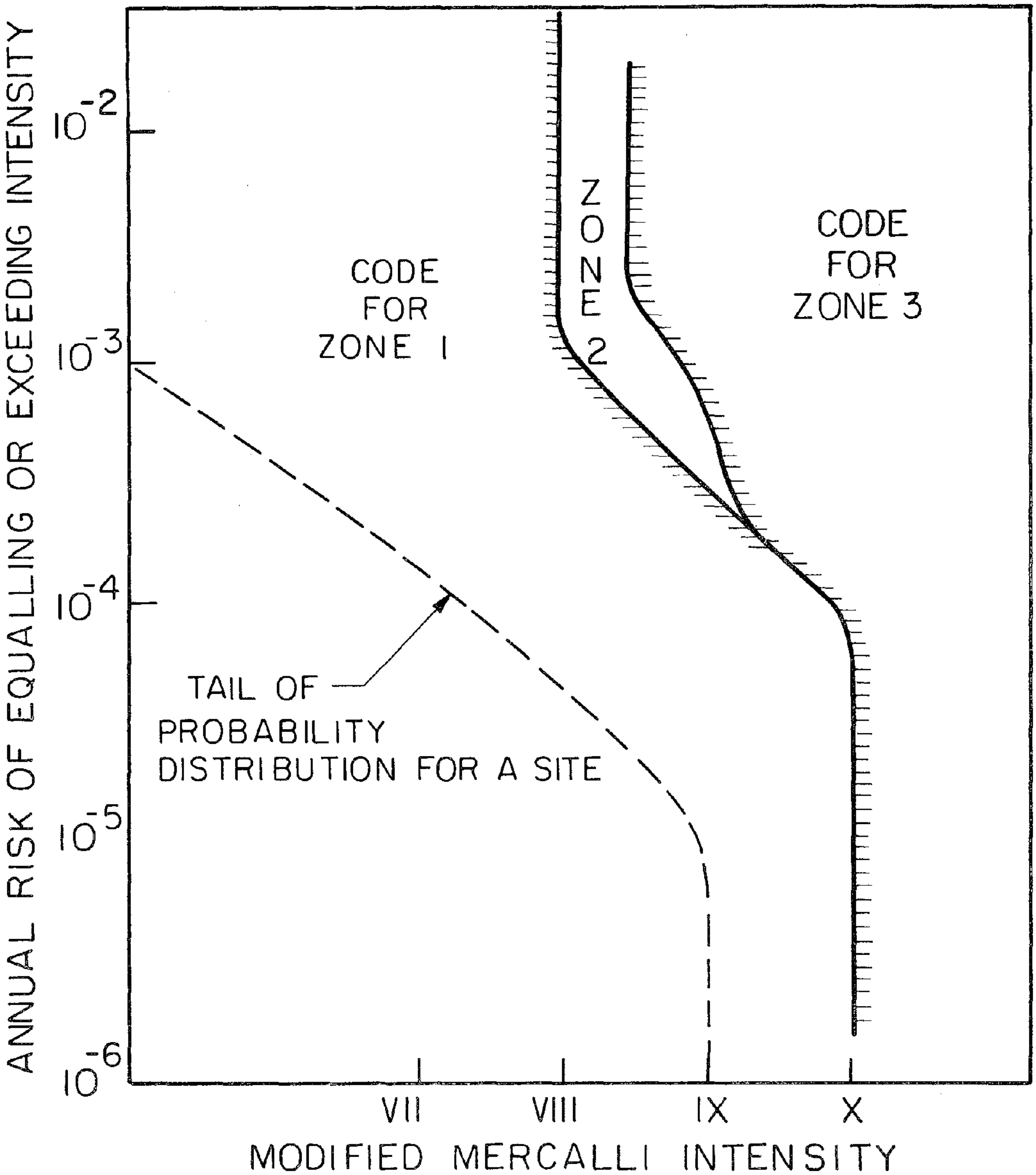


FIGURE 4 LEVEL OF SEISMIC PROTECTION THAT WOULD BE CHOSEN BY PERSONS WITH VALUES SIMILAR TO THOSE SHOWN IN FIGURE 2

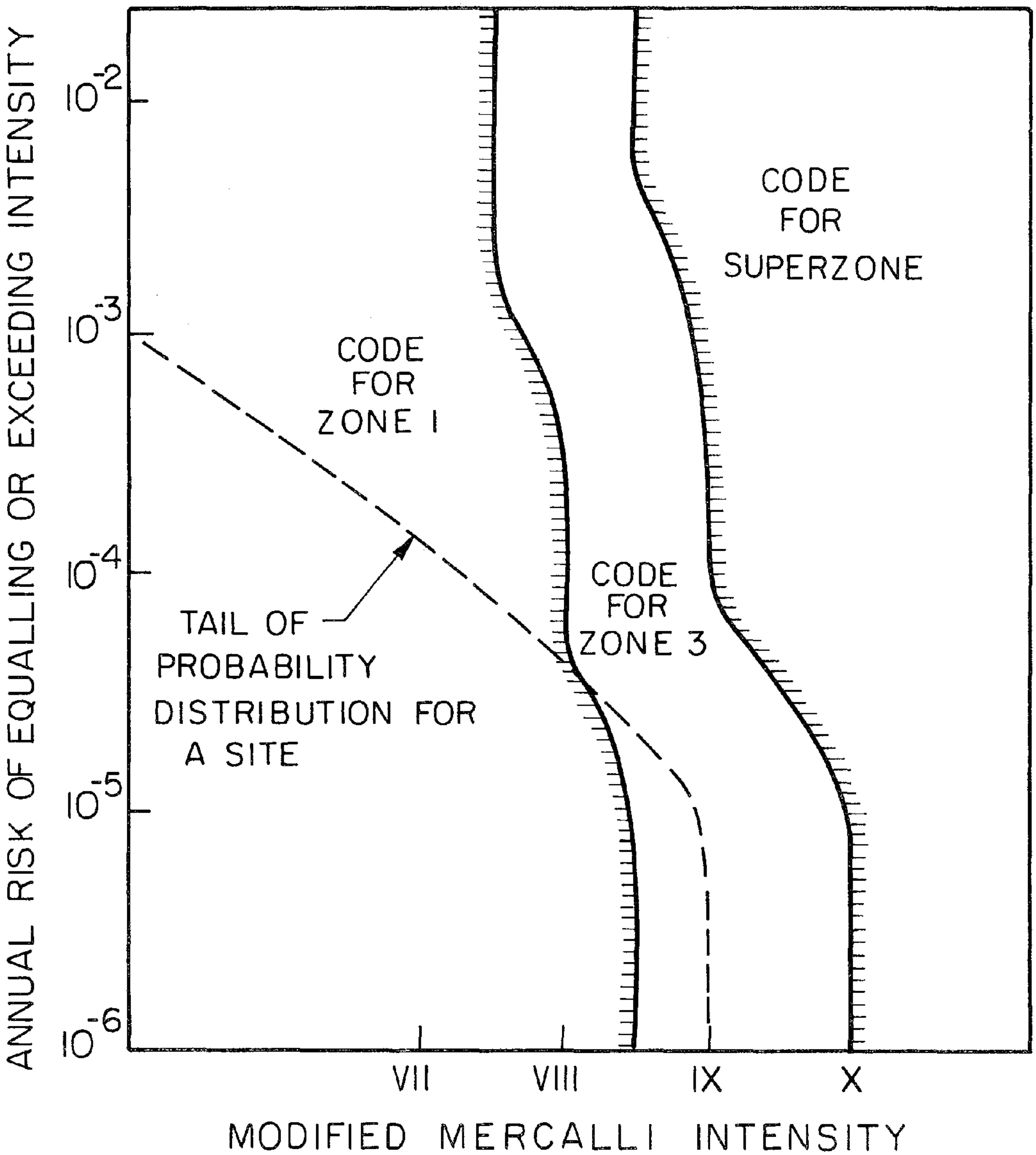


FIGURE 5 LEVEL OF SEISMIC PROTECTION THAT WOULD BE CHOSEN BY PERSONS WITH VALUES SIMILAR TO THOSE SHOWN IN FIGURE 3

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