AN APPROACH TO ESTABLISHING DESIGN SURFACE DISPLACEMENTS FOR ACTIVE FAULTS

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SYNOPSIS

The concept of subjective probability is suggested for defining the uncertainties associated with specification of seismic design criteria. Techniques for assessing the uncertainties associated with different amounts of surface fault displacement are discussed. It is argued that the explicit consideration of uncertainty is necessary for determining the risk associated with the location and design of structures in seismically active areas, especially those that must be located across active faults.

INTRODUCTION

There are many structures (e.g., lifelines) that have to cross active faults or must be located close enough to active faults to require that the structures be designed or positioned to accommodate or at least minimize the effects of surface fault displacements. In such cases, it is necessary to accurately identify and delineate the active faults and to develop realistic design values for the amount, distribution, and likelihood of the surface fault displacements. The basic premise applied in the assessment of surface faulting is that the type, amount, and location of future surface fault displacements will be similar to that which has occurred in the recent geologic past, as evidenced in the Quaternary geologic record.

Allen (1) has also argued convincingly in favor of the above premise. In addition, he states, "No amount of sophisticated statistics or extreme value theory can throw much light on the nature and frequency of large events based on a time sample that is too brief to include any such events unless a specific physical model is also assumed." The basic mechanisms that govern fault activity are measured in terms of geologic time (on the order of thousands to millions of years). Decisions made for most construction projects consider the design life of the structure (approximately 30-50 years), which is orders of magnitude smaller than the geologic time under consideration. Analytical models for estimating the probability and amount of future surface fault displacements have not been developed.

In spite of the lack of specific data and analytical models, geologists and seismologists have to provide design criteria that have an adequate degree of conservatism, do not result in unreasonable economic penalties, and can be justified under public and regulatory agency scrutiny. For certain structures where the consequences of failure can be catastrophic, society is demanding that the risks associated with failure be clearly specified. Uncertainties associated with various levels of seismic design criteria are one of the essential inputs to the evaluation of risk. One of these seismic design criteria is the design surface displacement along an active fault. If the geologist/seismologist gives single point estimates, he puts himself in the role of deciding the risk society should accept in terms of the amount of fault displacement. It is our view that his position should be one of assigning probabilities to different amounts of displacement, and the risks should be evaluated in the context of all parameters influencing performance and the consequences of failure. The decisions regarding acceptability of risk have to be made by the designer (decision maker) or, in some critical structures, by society as a whole.

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APPROACH

An approach based on Bayesian statistics which formally utilizes the judgment and experience of knowledgeable individuals is developed to establish design surface displacement values and their probability of occurrence. The objective of utilizing Bayesian statistics is to combine the subjective evaluations of experts with actual objective data to obtain a more complete state of knowledge concerning the magnitude and probability of occurrence of surface fault displacements.

The approach we suggest for specifying the uncertainty associated with different levels of displacement can, for discussion purposes, be divided into four steps: (a) Definition of the problem, e.g., design life, multiple events, etc.; (b) Assessing the probability associated with amount of displacement as judged by knowledgeable individuals; (c) Obtaining a consensus probability distribution; and (d) Updating the probabilities as new data become available. Because of the lack of data, we utilize the concept of subjective probability in implementing this approach. In the subjective approach, probability is defined as the quantified judgment of an individual, or as a degree of belief. Since this does not depend on repetitive trials, it is perfectly appropriate to assign such a probability to essentially nonrepetitive situations. It is because of this aspect that Winkler (2) considers the subjective interpretation "both conceptual and operational."

Consider two lotteries, L_1 and L_2, in which there are identical payoffs denoted by X^* and X° (Figure 1a). In L_1, X^* is received with probability p and X° with probability 1-p. In L_2 X^* is received if event E occurs and X° is received if E does not occur (E^c). The probability assessor is given the choice between lotteries for various values of p until he is indifferent between L_1 and L_2. At the indifference point the probability of E occurring p(E), is equal to p. It should be noted that $0 \leq p(E) \leq 1$ and the probabilities p(E) obey the axioms of probability theory.

Other operational techniques exist to elicit the subjective probability estimates of individuals. A detailed description of these techniques can be found in (2). The four steps in the suggested approach are discussed in the subsequent paragraphs.

Definition of Problem. In this step we wish to define the design life of the structure; whether we are concerned with multiple events; and how fine the subdivision should be if we divide the range of displacements into discrete events. Available data and field investigations should be reviewed and evaluated.

Assessing the Probability Associated with Different Levels of Displacement. To illustrate the idea of assessing subjective probabilities, we consider a hypothetical example. A pipeline has to cross a potentially active fault. It is necessary to determine the design surface displacement at a particular location. We first assume that we are dealing with a design life of 30 years and that the effects of displacement are not cumulative, so we need only be concerned with a single event.

The first series of questions deals with establishing the probability of the occurrence of any significant displacement; significant is interpreted to be greater than 1 ft. This assessment was done for a knowledgeable geologist; a hypothetical dialogue is indicated below.

The analyst first familiarizes the geologist with the concepts of subjective probability and particularly the definition given earlier.

Analyst: Let us set up two lotteries following our definition of subjective probability (Figure 1b). The payoffs are arbitrary, and we assume, based on our discussions, that surface displacements less than 1 ft are not significant. First consider the case where p = 0.5. In other words, you would have a 50-50 chance of receiving $100,000 in L_1. Also, we want to eliminate any effects of different times of payoff. Would you prefer to play L_1 or L_2?

Geologist: I would prefer L_2.

Analyst: This means that you believe that a surface displacement greater than 1 ft has a probability greater than 0.5 of occurring.

Geologist: Yes.

Analyst: Suppose p in L_1 were changed to 0.95; would you still prefer L_2?

Geologist: No, I think I would take L_1. Does that mean that I think the chances of a surface displacement greater than 1 ft occurring are less than 0.95?

Analyst: That's right. What I now want to do is vary p such that you will be indifferent between the lotteries.

Geologist: I get the idea! At the value of p that I am indifferent between L_1 and L_2 is the probability with which I think E will occur.

After a series of questions, the answers to which are shown below, the geologist agrees that with p = 0.90 he would be indifferent.

$p = 0.5,\ L_2 > L_1;\ \ p = 0.95,\ L_2 < L_1;\ \ p = 0.7,\ L_2 > L_1;$

$p = 0.8,\ L_2 > L_1;\ \ p = 0.9,\ L_2 \sim L_1.$

Therefore in his opinion the probability of surface displacement greater than 1 ft occurring within 30 years is 0.9. Now assume that we are interested in the probability of the magnitude of displacement within certain intervals. Our next series of questions assesses conditional probability. The question is posed as, "Given that a displacement greater than 1 ft has occurred, what are the chances it will be greater than 5 ft?" The two lotteries are set up as shown in Figure 1c. The questioning process is the same as indicated earlier. The process is continued; for example, the next question would be, "Given that the displacement is greater than 5 ft, what are the chances it will be greater than 10 ft?" The results of such a series of questions can be presented in a probability tree, as shown in Figure 1d. It should be understood that probabilities shown on any branch of the tree are conditional on the probabilities of the prior branches of the tree leading to that branch. From this tree the absolute probabilities tabulated in Figure 1d can be calculated.

An alternative representation for probabilities is a probability distribution. There are several techniques for assessing probability distributions. The most common technique is often referred to as the fractile method (3). In this approach, one would obtain from the geologist a few points on the cumulative probability distribution function, and then fit a curve to these points. The derivative of this is the judgmental probability density function.

Developing Consensus Distributions. In practical problems there are often several geologists/seismologists working on the problem, and it is desirable to obtain a consensus distribution because "there will be honest differences of opinion among competent geologists specializing in this field as to the likelihood of displacements on a given fault." (4) A consensus distribution is a single summary distribution derived from a number of individual distributions.

The problem of determining a consensus distribution can be stated in the following terms. Assume that k geologists, $G_1, G_2, \ldots, G_k$, have been consulted and each has assessed a probability distribution for a parameter (or vector of parameters). Let $f_i(\Theta)$ represent the distribution of geologist G_i. The problem then becomes one of determining from the $f_i(\Theta)$'s a single distribution, denoted by $f(\Theta)$, to represent a "consensus." [1]

The weighted average technique can be used to derive a consensus distribution if the mathematical approach is adopted. The weighted average technique consists of assigning weights, w_i, to each of the k distributions and can be expressed as:

$$f(\Theta) = \sum_{i=1}^{k} w_i f_i(\Theta) \quad \text{where } w_i \geq 0 \quad \text{and } \sum_{i=1}^{k} w_i = 1$$

Several methods for determining the weights, w_i, are possible:

- Equal weights. $w_i = 1/k$; $i=1,2,\ldots,k$. In this case, it is assumed that there is no reason to think that one assessor is a "better" assessor than another.
- Weights proportional to a ranking. This involves the assignment of weights to each assessor in accordance with a ranking (e.g., by years of experience) of the k assessors. The assigned weights would be given by:

$$w_i = r_i / \sum_{j=1}^{k} r_j \quad \text{where } r_i = \text{number of years of experience of the i-th assessor}$$

- Weights proportional to self-rating. This procedure involves each assessor (G_i) rating himself on a scale from 1 to c, where c is the highest rating and 1 the lowest. The weights can then be assigned in accordance with each self-rating.

The behavioral approach for defining consensus distributions consists of two techniques; feedback and individual reassessment, and group reassessment. The behavioral methods depend on each expert reconsidering his assessments after being presented with feedback. Given feedback, each expert would have full knowledge of the assessments of the other (k-1) experts.

The feedback and individual reassessment method would allow each assessor to reassess his distribution after examining the feedback and would probably still result in k distributions rather than one distribution. However, the process could be repeated and in many cases would result in the convergence to agreement among the k experts (although there is no guarantee of convergence). In this sense, the feedback and individual reassessment method is similar to the Delphi technique.

Updating the Probabilities on the Basis of Data. Often it may be important to combine judgmental assessments with relevant data. Bayes' theorem is a relationship that allows us to revise probabilistic assessments to incorporate new information that has become available. From an analytical viewpoint, it is often difficult to use the results of the assessment directly because of the complexities associated with combining judgmental information and data. Simplifications are possible if $p(E)$ or $f(x)$ can be approximated using certain forms of probability functions that make the mathematics more tractable (2,5).

Practical Considerations in Assessing Probabilities. The major practical consideration in assessing probabilities is to ensure that we are getting a genuine estimate of the assessor's beliefs. It is important that the assessor be careful and consistent in his assessment. In many cases, the assessor has limited knowledge of probability; therefore, an explanation of some of these concepts may be necessary. Assessors are seldom able to develop a consistent set of probability assessments. The analyst must always check for internal consistency. Inconsistencies should be explicitly pointed out to the assessor and resolved (2,3). Consistent probability assessments still do not imply that these subjective probability assessments are comparable with the assessor's set of beliefs. An individual's heuristic biases in making such judgments play an important role (6). An understanding of these can assist in avoiding errors.

CONCLUSIONS

It is our view that the risk associated with structures located in seismic areas should be explicitly defined. Definition of risk requires making judgments about the likelihood of occurrence of various seismic events. The subjective definition of probability is an appropriate concept for quantifying such judgments. The techniques for assessing subjective probability are well developed and the theoretical basis sound. These techniques have been used in many problems ranging from weather forecasting and oil drilling to foreign policy and business decisions (7). If uncertainties are specified explicitly, it is possible, using techniques of decision analysis, to evaluate the nature and extent of additional studies that need to be conducted to reduce these uncertainties. It is our view that the concept of subjective probability should be more widely used by the geologic and engineering professions and that the concept is particularly appropriate for considering the uncertainties inherent in criteria controlled by long-term geologic phenomena.

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Fig. 1a

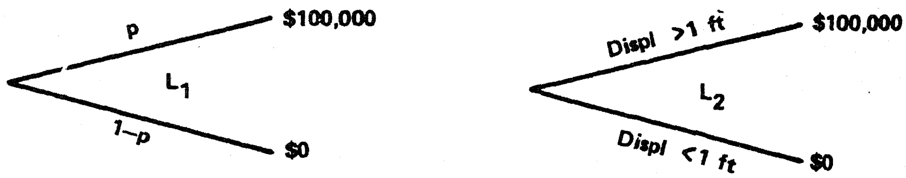


Fig. 1b

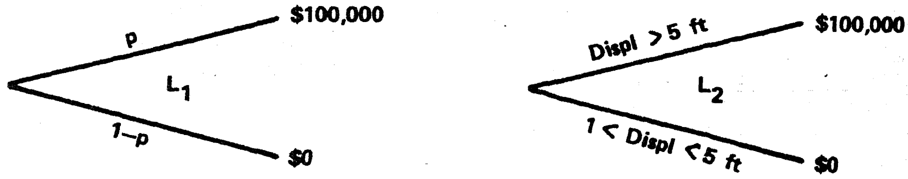
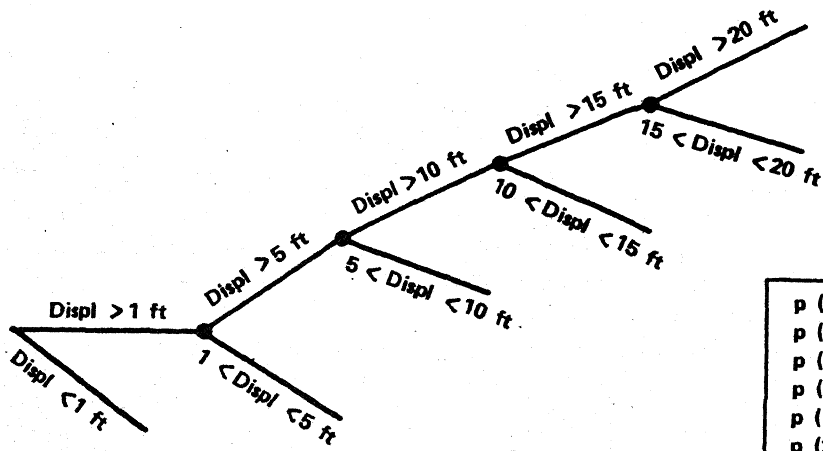


Fig. 1c



p (Displ < 1)	= .1
p (1 < D < 5)	= .27
p (5 < D < 10)	= .252
p (10 < D < 15)	= .3024
p (15 < D < 20)	= .07182
p (20 < D)	= .00378

Fig. 1d