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Earthquake hazard mitigation: Using science for safety decisions

by

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ABSTRACT

Earthquake-triggered landslides caused major economic losses during the October 17, 1989, Loma Prieta, California, earthquake. In the absence of regulations requiring that people have insurance or undertake mitigation to minimize the financial impact of earthquake-triggered hazards, individuals knowingly or unknowingly make choices about investments in loss-reduction measures. Ideally, consumer choices are made rationally with the most up-to-date hazard information and cost-effective loss-reduction measures. Using an expected utility framework, we demonstrate that refinements in pertinent hazard information can change individuals' risk-reduction decisions. Different information structures that examine the probability of damaging earthquake-triggered landslides are compared in a spatial risk-analysis procedure. Application of the method to mitigation strategies suggests that geologic and topographic maps and knowledge of geologic processes should be incorporated into mitigation planning by consumers and insurers. Secondly, consumer *ex ante* economic decisions to invest in hazard mitigation could change, depending on the types and the recency of information used in the analysis. Third, an asymmetry of information exists concerning local site conditions and the response of structures in those locations to earthquakes. This condition suggests that a moral hazard exists.

I. Introduction

After an earthquake occurs, government and business conduct mapping surveys and damage inventories to identify and assess the types and extent of personal and property damages and to evaluate the efficiency of loss reduction measures (insurance or mitigation). These hazard surveys postdating the earthquake may lead to the production of interpretive maps, such as those detailing the likelihood of hazard recurrence, represented by subjective categories (low-, medium-, or high-hazard likelihood). The surveys also can be used to formulate a public strategy to avoid future losses from similar types of hazards. Assessment of future risk, however, requires data from several events so that the spatial and temporal pattern of losses can be clarified. Although field evaluations are useful, information relating to the local effects of an earthquake cannot necessarily be adapted to other areas because the geologic conditions may not be sufficiently alike.

Individual consumers do not commonly evaluate risk in the same manner as governments or industry. Individuals make safety decisions concerning future earthquake hazards by purchasing earthquake insurance and employing engineering solutions. For example, California regulations require engineering study and review in areas within a specified distance from a fault known to be active in the last 10,000 years (Alquist-Priolo Special Study Zones Act, 1974). These zones, referred to as Alquist-Priolo Special Studies Zones (SSZ), can influence the residential housing market and the demand for self protection (Brookshire and others, 1985). SSZ's also have been identified as part of the risk communication policy in California, in the Seismic Hazards Mapping Act of 1990 (California Assembly Bill No. 3897, 1990). The Act mandates that maps delineate areas inside or outside of a fault (hazardous) zone. The success of this type of risk analysis is based, however, on anecdotal evidence from previous events and applications (BAREPP, 1992). Both this method and the mapping survey method of risk assessment are qualitative. Neither technique can form an adequate basis for a quantitative appraisal of consumer risk.

In this paper we describe a risk-analysis method based on the statistical analysis of geologic and topographic map information in a Geographic Information System (GIS). Using this approach, the relative susceptibility to a hazard can be assessed, for example, by producing a map of the probability of an earthquake-triggered hazard. Like the aforementioned techniques, a relative susceptibility-to-hazard map illustrates spatial vulnerability and can be updated as new information becomes available. Because these maps communicate hazard vulnerability in terms of a spatial probability, however, they provide a basis for a systematic approach to the quantification of earthquake-related risks: earthquake-triggered landslides, liquefaction, ground rupture, and strong shaking. The susceptibility-to-hazard maps can be applied in a Probabilistic Choice System (PCS) to evaluate consumer choice in the purchase of earthquake insurance.

We have chosen a risk-analysis method that is based on scientific information to examine the economic efficiency of different forms of damage-reduction procedures. The information in map form provides a basis to estimate a spatial damage function concerning potential earthquake losses (L) by combining the relative susceptibility-to-hazard with the value of the property at risk. An application of the approach is demonstrated in the central Santa Cruz Mountains in California, where extensive damage from earthquake-triggered landslides occurred during the 1989 Loma Prieta earthquake.

Our paper is divided into 6 sections. Section II contains applications of the expected utility model to earthquake insurance, to earthquake-related hazard mitigation, and to a consolidated program of earthquake insurance and mitigation. In addition, Section II includes the development of a probabilistic choice system for earthquake insurance. We then estimate three different types of probabilities that are integrated into information structures presented in the model in Section III. In Section IV we develop the decision framework for evaluating the cost effectiveness of individual loss-reduction measures. Section V contains the Loma Prieta earthquake application. We estimate expected losses that could be avoided for residential parcels and indicate the possibility of a moral hazard.[1] The example is based on insured values and losses in the vicinity of the epicenter of the October 17, 1989, magnitude (M_s) 7.1 Loma Prieta earthquake. The analysis is conducted in a 30-km^2 area in the vicinity of Summit Road, Santa Cruz County, CA. The application of the model demonstrates that for earthquake-triggered losses, (1) consumers are aware of local hazards when loss reduction choices are made, (2) insurance and/or mitigation can be cost effective in hazard prevention, and (3) hazards maps based on scientific data can be used by insurers to evaluate portfolio risks. The last section contains some observations for future policy consideration.

II. The Model

Recent analyses have demonstrated the applicability of expected utility theory to safety decisions regarding individual behavior toward earthquake risks (Schulze and others, 1987; Singh and others, 1992). These studies apply hedonic pricing models to illustrate how knowledge of an earthquake hazard can be incorporated into housing values; individuals' reactions to this information were found to be consistent with the expected utility hypothesis. Moreover, studies have shown that when a change in the probability of a natural-hazard recurrence is announced (i.e., as a warning based on improved or updated information), property investment decisions (Patz, 1985) and property values (Bernknopf and others, 1990) are affected. While these analyses incorporate scientific information about the recurrence of a natural hazard into a decision-oriented framework, they rely on simplifying assumptions

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[1]Moral hazard is an alleged deterrent of market insurance on self protection that increases the actual probabilities of hazardous events (Ehrlich and Becker, 1972).

that pertain to the precision of scientific data used in estimating the price gradient of residential structures. For example, in these studies, the hazard variable is either a probability of recurrence of an earthquake for a metropolitan area or a mean value for a geologic hazard on a county-wide basis. In contrast to these models, we incorporate a location-specific probability of an earthquake-triggered hazard into the analysis of consumer choice for earthquake insurance.

Expected utility

Consider a group of consumers i, where $i=1,\ldots,I$, whose individual endowed wealth (W_i^0) is at risk to earthquakes. The consumer is faced with two states of nature ($\omega=1,2$), no earthquake or earthquake (and consequent damage), with occurrence likelihood represented by probabilities $1\text{-}p$ and p. For these two states of nature, wealth is equal to W_i^1 with probability $1\text{-}p$ and W_i^2 with probability p, where W_i^1 and W_i^2 are the consumer's wealth endowment in the 2 states, and $W_i^1\text{-}W_i^2=L$.

L is a loss equal to earthquake-triggered damage in dollars. In maximizing expected utility *(EU)*, the consumer has multiple choices for loss reduction. Given available information about the state of nature, different forms of loss reduction such as market insurance and/or self protection lead to different consumer behavior.

By choosing market insurance, a consumer expresses a preference to redistribute income to the damage state. A consumer elects to reduce the loss in both W_i^1 and W_i^2 by purchasing earthquake insurance coverage Y_i for a premium of πY_i, where π is the "price of insurance" per unit in terms of a consumer's initial wealth endowment (Ehrlich and Becker, 1972). Earthquake insurance is defined as coverage minus premium and deductible. Wealth is

$$W_i^1 = W_i^0 - \pi Y_i \qquad \textit{if } \omega_1 \textit{ occurs, no earthquake;}$$

$$W_i^2 = W_i^0 - \pi Y_i - L_i + Y_i \quad \textit{if } \omega_2 \textit{ occurs, earthquake.}$$

To maximize end-of-period wealth, the consumer attempts to buy insurance wisely, optimizing expected utility in the following manner:

$$EU = \max(1-p)\,U(W_i^0 - \pi Y_i) + p\,U(W_i^0 - \pi Y_i - L_i + Y_i) \qquad (1)$$

U is the individual's utility of losses avoided from earthquake-triggered hazards. The optimal amount of insurance is characterized by the first-order condition:

$$\frac{\pi}{1-\pi} = \frac{p\,U'(W_i^0 - \pi Y_i^* - L_i + Y_i^*)}{(1-p)\,U'(W_i^0 - \pi Y_i^*)} \qquad (2)$$

where Y_i^* is the optimal level of insurance coverage.

If we assume that the marketplace is competitive, insurers will charge an actuarially fair premium forcing expected profits to 0, when $\pi = p$ (price per unit equals probability of earthquake occurrence). Under these conditions equation 2 reduces to

$$U'(W_i^0 - \pi Y_i^* - L_i + Y_i^*) = U'(W_i^0 - \pi Y_i^*) \qquad (3)$$

where $-p(Y_i - \pi Y_i) + (1-p)\pi Y_i = 0$. At market equilibrium, expected losses are equal to insurance coverage, and

$$L_i = Y_i^* \qquad (4)$$

If consumers instead undertake some form of mitigation to avoid a loss (self protection), they can alter the probability of loss $p_i = p(\omega, q)$ where $p(\omega)$ is the probability of an earthquake-related hazard and q is the amount invested in mitigation. Self-protection does not redistribute income to the damage state; instead, it reduces the probability of a loss in both states by the same amount (Ehrlich and Becker, 1972). The damage function for each consumer is $p_i = p(\omega, q_i)$ where $\partial p / \partial q < 0$, and $\partial^2 p / \partial q^2 > 0$. Wealth in the two states is

$$W_i^1 = W_i^0 - q_i \qquad \textit{if } \omega_1 \textit{ occurs, no earthquake;}$$

$$W_i^2 = W_i^0 - q_i - L_i \qquad \textit{if } \omega_2 \textit{ occurs, earthquake.}$$

If the consumer chooses to mitigate rather than purchase earthquake insurance, the optimal expenditure on structural modifications, for example, would maximize expected utility in the following manner:

$$EU = \max(1 - p_i)\, U(W_i^0 - q_i) + p_i\, U(W_i^0 - q_i - L_i) \qquad (5)$$

The optimal amount of mitigation satisfies the first order condition:

$$-\frac{\partial p_i}{\partial q_i}[U(W_i^0 - q_i) - U(W_i^0 - q_i - L_i)] = (1 - p_i)\, U'(W_i^0 - q_i) + p_i\, U'(W_i^0 - q_i - L_i) \quad (6)$$

The term on the left side of equation 6 is the benefit of the reduction in the probability of a loss, and the term on the right is the marginal cost of the decline in incomes in both states (Ehrlich and Becker, 1972).

An alternative to earthquake insurance or self protection is to combine the two. Consumer i can purchase Y_i dollars worth of insurance coverage for a premium of πY_i dollars and reduce the probability of the earthquake hazard by p_i by investing q_i dollars in mitigation. In this integrated approach to loss reduction, the consumer's end-of-period wealth now would be

$$W_i^1 = W_i^0 - q_i - \pi Y_i \quad \text{if } \omega_1 \text{ occurs, no earthquake;}$$

$$W_i^2 = W_i^0 - q_i - \pi Y_i - L_i + Y_i \quad \text{if } \omega_2 \text{ occurs, earthquake.}$$

The problem for the consumer is to determine the most efficient combination of earthquake mitigation and insurance to purchase. In order to make an optimal decision, the consumer would determine a utility-maximizing amount of q_i for every level of coverage Y_i and then choose the utility-maximizing level of Y_i, given the premium and the utility-maximizing level of q_i. The consumer's expected utility can be written as

$$EU = \max(1-p_i)\,U(W_i^0 - q_i - \pi Y_i) + p_i U(W_i^0 - q_i - \pi Y_i - L_i + Y_i) \qquad (7)$$

Taking the derivative of EU with respect to q to get the maximum expected utility for mitigation for consumer i yields

$$-\frac{\partial p_i}{\partial q_i}[\,U(W_i^0 - q_i - \pi Y_i) - U(W_i^0 - q_i - \pi Y_i - L_i + Y_i)]$$

$$= (1-p_i)\,U'(W_i^0 - q_i - \pi Y_i) + p_i U'(W_i^0 - q_i - \pi Y_i - L_i + Y_i) \qquad (8)$$

Like equation 6, the left-hand side of equation 8 is the benefit of the reduction in the probability of a loss, and the right-hand side is the marginal cost of the mitigation q_i. For example, the consumer will not be inclined to mitigate if $Y_i = L_i$, that is, if insurance provides full coverage of the earthquake loss and equation 8 reduces to the condition in equation 3. On the other hand, if $Y_i < L_i$, we would expect some utility-maximizing combination of mitigation and insurance. In general, the amount of mitigation is inversely related to the amount of insurance coverage purchased, because the consumer expects that as Y_i increases it will reduce the effect of mitigation q_i on W_i^0; thus, $\partial q_i/\partial Y_i \leq 0$.

To determine the optimal level of insurance, the consumer maximizes expected utility using the amount of q_i that is set in equation 8, while accounting for the dependence of q_i and πY_i on Y_i. Taking the total derivative of EU (equation 7), the first-order condition is[2]

$$\frac{\partial \pi Y_i}{\partial Y_i} = \frac{p_i U'(W_i^0 - q_i - \pi Y_i - L_i + Y_i)}{(1 - p_i) U'(W_i^0 - q_i - \pi Y_i) + p_i U'(W_i^0 - q_i - \pi Y_i - L_i + Y_i)} \tag{9}$$

Any earthquake insurance that the consumer purchases will therefore depend on $\partial \pi Y_i/\partial Y_i$, the cost for each level of protection. At the optimum the consumer would set $Y_i = L_i$ and choose the appropriate level of q_i so that $L\partial p/\partial q_i = 1$. This expression identifies the point at which the reduction in expected damages equals the cost of mitigation.

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[2]The total derivative of equation 7 yields:

$$\frac{\partial \pi Y_i}{\partial Y_i}[(1 - p_i) U'(W_i^0 - q_i - \pi Y_i) + p_i U'(W_i^0 - q_i - \pi Y_i - L_i + Y_i)] = p_i U'(W_i^0 - q_i - \pi Y_i$$

$$- L_i + Y_i) - \frac{\partial q_i}{\partial p_i}[(1 - p_i) U'(W_i^0 - q_i - \pi Y_i) + p_i U'(W_i^0 - q_i - \pi Y_i - L_i + Y_i)]$$

$$+ \frac{\partial p_i}{\partial q_i}\frac{\partial q_i}{\partial Y_i}[U(W_i^0 - q_i - \pi Y_i - L_i + Y_i) - U(W_i^0 - q_i - \pi Y_i)]$$

By cancelling terms, this total derivative reduces to equation 9.

If the insurer could observe q_i, the earthquake insurance premium would vary with q_i and p_i. In reality, however, we can assume the insurer is unaware of the amount of self protection purchased by the consumer. Because insurers do not know a consumer's investment in q, the firm is in a position to charge an equal premium across all i ($\partial \pi Y_i / \partial q_i = 0$) for a given level of coverage Y_i^*. Since q_i, is unobservable the market cannot attain a competitive optimum.

Under actual conditions (Pauly, 1974) a consumer buys an amount of earthquake insurance Y^* for a premium of $\pi Y_i = pY^*$, where $p = p(Y^*)$. Substituting pY^* for πY_i into equation 9, the optimal premium is determined by setting $\partial \pi Y / \partial Y = p + Y \partial p / \partial Y$. Because there is competition among insurers, the market sets a constant price $\hat{y}$ for earthquake insurance so that now $\partial \pi Y / \partial Y = \hat{y}$. The competition among insurers implies that the market-determined premium $\hat{y}$ is likely to be less than the consumer-determined premium $p + Y \partial p / \partial Y$. Most likely, there will be an underutilization of mitigation, because consumers are apt to believe that earthquake insurance is a bargain, and $q_i = 0$.

Probabilistic choice

If this discussion accurately depicts the current state of the earthquake insurance market, we should be able to improve consumer utility by identifying locations where consumers could invest in specific strategies for mitigation that would be a welfare improvement over the insurance-only solution. We develop a probabilistic-choice model for earthquake insurance to test the implications of the expected utility model. A random utility model provides a convenient empirical mechanism to evaluate consumer behavior in relation to the purchase of earthquake insurance. Probabilistic-choice models have been applied to many problems that involve discrete economic decisions (McFadden, 1976; Hausman and Wise, 1978; Amemiya, 1981). We apply this formulation to the purchase of earthquake insurance.

Let U_i denote consumer utility that is based on earthquake insurance coverage of Y^* at a cost of $\bar{y}$ and on other goods z_i, yielding a utility function (Mason and Quigley, 1990)

$$U_i = U(Y^*, z_i) = U(Y^*, W_i^0 - \bar{y}) \qquad (10)$$

subject to the budget constraint

$$W_i^0 = \bar{y} + z_i$$

Next, suppose the utility for consumer i of earthquake insurance can be partitioned into a mean utility V_i denoting the level of indirect utility associated with purchasing earthquake insurance, and a random component ϵ_i denoting a random component in utility that includes unobserved variations in tastes and perceptions by the individual. Substituting these terms into equation 10 yields

$$U_i = V_i(Y^*, W_i^0 - \bar{y}) + \epsilon_i = V_i + \epsilon_i \qquad (11)$$

Buying earthquake insurance corresponds to the probability that a choice to "protect" from a loss yields a higher utility than other available choices; *Prob* $[(V_i^1 + \epsilon_i^1) > (V_i^0 + \epsilon_i^0)]$. V_i^1 is the consumer's indirect utility derived from purchasing earthquake insurance and V_i^0 is the indirect utility of doing nothing. If the ϵ_i are distributed according to a normal distribution, then, based on McFadden (1976), we can approach the problem by applying a multinomial probit model. The probit model is a linear combination of the attributes of the indirect utility function

$$p(Y^* | \bar{y})_i = \Phi(\beta' V_i) \qquad (12)$$

where $\Phi(\epsilon, \Psi)$ is the multivariate normal cumulative distribution, with zero mean and covariance Ψ, and β is a vector of coefficients of consumer attributes.

III. Information Structures that Define States of Nature

We develop a risk-analysis procedure to evaluate whether consumers behaved in a manner consistent with the expected utility model, in an area near the epicenter of the 1989 Loma Prieta earthquake. An information structure can be a probability map, P, that denotes the likelihood of a change in a state of nature. P can be considered an abstract description of observations made and information gathered and interpreted to learn something about the true value of the state of nature ω and the possible consequences (McGuire, 1972). Maps that depict the odds of specific outcomes for hazards such as landslides can be considered information signals in a safety decision. $P_a = [p(\omega m, L)]$, where $a = \{1, \ldots, A\}$ different structures, is defined as a transition probability (Markov) matrix of expected losses for each state of nature ω, where $p(\omega)$ is the probability of the occurrence of damages resulting from an adverse physical state such as an earthquake. An earthquake is a particular physical state among a set of possible adverse physical conditions (floods, hurricanes, etc.). There are m maps, $m = 1, \ldots, M$, that describe, according to different criteria, the probability of a state. There are $s = 1, \ldots, S$, types of landslides, where $s \in \omega$ (other information structures, P_a, $a \neq s$, represent other types of earthquake-related hazards (liquefaction, strong shaking, etc.)).[3] Each information structure is a map of a different interpretation of the susceptibility to an earthquake hazard. The information is a combination of map recency (scientific understanding has improved during the last several decades), map scale, and description of physical attributes. For this study, there are three information structures P_a, where a=1,2,3.

P_1 contains a spatial probability $p(s)$ at a given map scale. This information structure illustrates a range of physical conditions that contribute to a hazard in similar physical environments. P_1 combines static physical attributes (e.g., the slope angle of the land surface and the friction angle of the near-surface geology) with the property value at risk. The physical information is derived from topographic maps and geotechnical measurements. In contrast, information structure P_2 considers the property value at risk and a probabilistic hazard estimate $p(EQ)$ of the magnitude and time to recurrence of a damaging earthquake that is derived from geophysical and seismologic measurements. That estimate is uniform for the entire map area. P_1 and P_2 are considered to be independent probabilities of earthquake-related hazards.

Information structure P_3 is a hazard map of the probability of an earthquake-triggered landslide. It incorporates both the relative susceptibility of particular locations, $p(s)$, and the probability of earthquake-triggered landslides, $p(s \mid EQ)$, that result from specific earthquakes.

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[3]A landslide state of nature is characterized as an outcome of a physical process that can occur on a hillside. A physical model for an earthquake-triggered landslide is contained in the appendix. The individual's risk is determined by a mapping $L(\omega;C,s)$, where $C=C(Y,q)$, a mapping into L. Therefore L is related to ω as a cumulative distribution function F and density function f: $F(L(\omega);C,s)=\omega$, and $f= \partial F/\partial C=(\partial L/\partial C)/(\partial L/\partial \omega)$.

To reflect this additional refinement in information, Bayes theorem is applied so that $p(s \mid EQ) = p(EQ \cap s)/p(s)$.

To accommodate a probabilistic estimate of the hazard in the Probabilistic Choice System, we substitute each P_a into equation 11

$$U_i = V_i[P_a(Y^*, W_i^0 - \bar{y})] + e_i \qquad \forall\, i \qquad (13)$$

Estimating the probabilities

The probability of earthquake-triggered landslide activity can be estimated as a function of physical variables that include hillside attributes and earthquake shaking. Data from maps provide the static spatial attributes and inventories of slope movements associated with earthquakes which, along with physical process models of hillside stability, form the basis of the conditional probability of earthquake-triggered landslides. A derivation of the physical process model is found in the appendix. Our information structures have the general form

$$P_a = (p_s(g_n, h_n, a_n)_k, L) \qquad n=(1,\ldots,N) \qquad (14)$$

where P_a is a function, in part, of n physical characteristics of the hillside that can be grouped into three broad categories: geologic attributes *(g)*, topographic attributes *(h)*, and components or effects of earthquake acceleration *(a)*. All of these physical variables can be mapped for each parcel of land, k, where k=1,...,K. For example, *g* may be the shear strength of the geologic material, *h* may be the slope of the hillside, and *a* may be observed ground failure resulting from the duration and intensity of shaking during an earthquake. The current approach to specifying hazardous locations includes the identification of Special Studies Zones that delineate areas around faults where the earthquake hazard is presumed to be greatest. These zones can be represented as a dummy variable in g.

In information structure P_1, the probability $p_k(s)$ is the relative susceptibility of a location k to sliding from all triggering mechanisms (earthquake, rainfall, construction, etc.). Specifically, $p_k(\omega m)$ is the occurrence of old landslide deposits, $p_k(s)=1$, where s_k is identified on existing maps, $p_k(s)=0$ otherwise. $p_k(s)$ can be estimated as a function of the observed physical characteristics of the hillside: friction angle *(FA)*, maximum slope angle *(MS)*, and elevation *(DEM)*. P_1 is estimated using a probit model and is represented on a map in figure 1.

Information structure P_2 includes the probability of a specific magnitude earthquake $p_k(EQ)$ that is estimated as a function of fault segmentation and displacement, time of the most recent fault rupture, and estimated earthquake recurrence interval. $p_k(EQ)$ has been estimated as a Poisson renewal process. A detailed description of this type of model can be found in the Working Group On California Earthquake Probabilities (1988). Because the Working Group report was published prior to the Loma Prieta earthquake, we use the probability that predates the event, $p_k(EQ)=0.3$, for a 30-year period for the recurrence of a $M_s \geq 6.5$ earthquake along the central Santa Cruz Mountains segment of the San Andreas fault.

The third information structure includes the conditional probability for earthquake-triggered landslides $p_k(s|EQ)$. The probability in P_3 uses a probit two-stage estimation procedure (Maddala, 1983). The first stage is $p_k(s)$ from information structure P_1. A probit equation also is used in the second stage to estimate the probability of an earthquake-triggered landslide. In the second stage, $p_k(s|EQ)$ is a function of $p_k(s)$ and RD_k, where RD is road locations (areas where roads have been constructed that tend to create over-steepened slopes and/or weak roadbed foundations that can fail in landslides). s_k is a discrete variable ($s_k=1$; 0 otherwise) that identifies whether a landslide or related tectonic feature is reactivated during the Loma Prieta earthquake in k (Keefer and others, 1991, and Spittler and Harp, 1991). P_3 is represented as a map in figure 2.

Results for the regression equations along with the relevant test statistics are listed in table 1. Special Studies Zones in the current regulatory scheme delineate areas of greatest earthquake hazard, which are defined as likely fault rupture zones. In that usage they have served as a surrogate for all geologic and other physical attributes (Brookshire and others, 1985). Many types of earthquake damage (e.g., landsliding or liquefaction) are not, however, limited to these areas. Special Studies Zones were tested in the equations and were found to be insignificant in predicting the locations of both new and reactivated landslide deposits.

Table 1.
Regression coefficients and test statistics for P_a
k=2443 (t statistic)

Model	FA_k	MS_k	DEM_k	$p_k(s)$	RD_k	CONSTANT	LLR*
P_1	-0.0906 (-18.87)	-0.0109 (-6.21)	0.0008 (2.55)			2.209 (10.41)	477.97
P_3				0.882 (6.15)	0.609 (10.44)	-1.11 (-19.61)	143.29

* LLR=Log Likelihood Ratio

All of the variables included in both models are statistically significant at the 0.01 level except for *DEM*, which is significant at the 0.05 level. In addition, all variables exhibit the expected signs. The sign on the maximum slope variable is negative and expected because we are estimating the probability of activating old landslide deposits. A priori we expect locations with landslides to be somewhat flatter than other types of rock on hillsides because the materials in these locations most likely slid to their current locations during previous landslide-triggering events. In locations with very high slopes, strong "bedrock" commonly is found at the surface, and large, mappable landslides are less likely.

The probability in information structure P_1 assumes that the probability of a landslide is equal across all triggering mechanisms. If this were true, then we would expect that failures during rainstorms and earthquakes would occur in the same locations. There is no physical or historical evidence to support this notion. The probability in structure P_2 is an estimate of the probability of the recurrence of a large, damaging earthquake in the central Santa Cruz Mountains segment of the San Andreas fault. $p_k(EQ)$ captures the general effect of an earthquake, but it does not account for the relative susceptibility of different locations to landsliding. $p_k(s \mid EQ)$ captures the relative susceptibility to lansliding from all triggering mechanisms as in model P_1, but, in addition, it accounts for the effects of earthquakes as in P_2. Spatially, the patterns for the high probability-of-failure locations identified by P_1 and P_3 bear out these results (figures 1 and 2). Each model is evaluated in Section V.

IV. Approach for Comparing the Decisions to Mitigate among Information Structures

Earthquakes recur in the same general regions of the United States. Their effects on humans vary depending on specific site responses that are influenced by the composition of the earth's crust and the distance to the earthquake epicenter and its depth. Following an earthquake, individuals are most aware of the potential for losses and are most likely to purchase earthquake insurance to minimize future losses (Palm and others, 1990). While people are most likely to invest in loss avoidance at these points in time, any time period represents an opportunity to choose some form of loss reduction. Here we consider the choice of mitigation in the decision with the three information structures.

Cost Effectiveness of Landslide Mitigation

For many environmental risks, hazard mitigation has been shown to provide benefits and savings to individuals (FEMA, 1993). Estimation of expected losses avoided has two components based on map information: a probabilistic-hazard estimate and a loss assessment. The hazard component of the model is embodied in the different probabilities in the information structures. The loss-assessment component is a map of the expected losses avoided $p(\omega m, L)$. The benefits of mitigation are the expected losses avoided for a given mitigatory solution $\mathrm{E}[L(q)_i]$. If the solution q_i is 100% effective and the consumer suffers no property loss, then $\mathrm{E}[L(q)_i]=\mathrm{E}(L(0)_i)$, where $\mathrm{E}(L(0)_i)$ is expected losses. However, the effectiveness of mitigation can be less than 100%, thus expected losses avoided can be represented as a fraction, α, of the total expected property loss avoided, $\mathrm{E}(\alpha L(0)_i)$, where $0\leq\alpha\leq1$. Therefore, $\mathrm{E}[L(q)_i]=\mathrm{E}(\alpha L(0)_i)$ for all i. For example, the benefit of mitigation based on piers and grading is the difference in the expected losses avoided with and without structural modifications.

In general, the decision rule for the consumer is that mitigation is undertaken only if $E(\alpha L(0))-C>0$, the difference between the expected losses avoided $E(\alpha L(0))$ that derive from the plan and the cost of that plan C. Thus, if location k is classified as benefiting from mitigation in time t, t=1,...,T, there is a net gain in consumer welfare. It is assumed that decisions are made at discrete points in time and that the cost effectiveness of mitigation is evaluated independently by consumers at those times.[4] Within this framework, the consumer attempts to maximize $E[L(q)_i]$ in the following manner:

$$\max_j E[L(q_j)_i] = \int_0^T \sum_{a=1}^{A} \sum_{j=0}^{J} (\alpha(P_a) - C)_{ijkt}] e^{-rt} dt \qquad \forall\, i,k \quad (15)$$

where $j=1,..,J$ choices of plans for mitigation, $E(\alpha L(0)_i)=(\alpha P_a)_i$, r is the discount rate, t is time in years, and T is a future time when an earthquake occurs.

Even though there is some level of uncertainty about future payoff from the investment, a decision to mitigate, d (yes or no; 1 or 0), must be made that expresses a consumer choice. The decision to mitigate a landslide hazard is expressed by the binary variable d_i for a given cell k in equation 16:

$$d_i | P_{ak} = 1 \quad \mathit{if} \max_j \, [E[L(q_j)_i]_k > 0 \qquad (16)$$

$$= 0 \quad \mathit{otherwise}$$

Thus the plan for mitigation that maximizes consumer welfare is accepted when the risk of an

[4]This approach presumes that mitigation decisionmaking over some planning horizon is a Bernoulli process.

earthquake-triggered landslide is high enough to meet the expected loss avoided threshold.

Cost estimation and landslide hazards

Earthquake insurance and building codes are accepted loss-reduction measures and provide some protection against landslide damage. Earthquake insurance policies have seemingly large deductibles and substantial annual premiums; we apply a representative deductible of 10% of insured value and an annual premium of $2 per $1000 of coverage (Palm and others, 1990). Earthquake-related building codes generally are minimum provisions that are necessary for structural integrity during shaking and do not address the collateral effects of earthquakes (such as landsliding) that temporarily exacerbate the potential for damage. Additional structural modifications that exceed the minimum code provisions specific to earthquake-triggered landslides also can be undertaken to ameliorate some if not all of the hazard. Mitigation for a specific hazard involves construction activity, such as slope alteration, retaining walls or piers, or extraordinary foundation structures. Each strategy for mitigation has a planned effect and a known cost to achieve the selected level of self protection. Table 2 contains some representative measures for mitigation and capital costs C_j for landslide-resistant foundations in mountainous terrane.

Table 2. Hypothetical costs for new foundations and repairs in a seismically active area for a 2000-square-foot house

SETTING	TYPE OF MITIGATION	NEW FOUNDATION	REPAIRS
Level Ridge Top-Bedrock at or near surface	Shallow Spread Footing	\$28,000 ± 10%	Underpinning \$150,000 ± 50%
Slope-Bedrock near surface	Pier & Grade 10-foot piers	\$38,000 ± 10%	Underpinning \$150,000 ± 50%
Slope-Soil 10 feet deep or thinner	Pier & Grade 20-foot piers	\$60,000 ± 10%	Underpinning \$150,000 ± 50%
Slope-Soil greater than 10 feet Deep	Mat or Rigid Grid	\$55,000 ± 10%	Minor Operation \$15,000 ± 10% Major Operation \$100,000 ± 25%

source: William Cole, William Cotton & Associates, Inc., Los Gatos, California, 1990.

V. The Application

In this section we apply the risk-analysis procedure to evaluate how each information structure can be used to influence decisions related to insurance purchases and mitigation. In developing the spatial econometric models, we apply an instrumental variables approach (Anselin, 1988). The probability of purchasing earthquake insurance is a 2-stage model where the first stage is the probability of a landslide, $p_k(s)$. Estimation of insurance claims is a 3-stage model based on $p_k(s \mid EQ)$.

The setting

The study area for this analysis is known as the Summit Ridge area in the central Santa Cruz Mountains, California. The area is underlain by steeply inclined sedimentary rocks of the Butano, San Lorenzo, and Vaqueros Formations (Brabb, 1989; Clark and others, 1989; William Cotton and Associates, Inc., 1990; McLaughlin and others, 1991). Large landslide masses overlie the bedrock in part of the area. The landslide terrane is characterized by stepped topography, including very steep scarps and steep slopes. Data on earthquake-triggered landslides also have been collected to inventory the location, frequency, and size of landslides that occurred during the 1989 Loma Prieta earthquake (Spittler and Harp, 1990; Manson and others, 1992). Fresh ground fissures indicate that parts of these large landslide complexes moved as a result of the 1989 earthquake (William Cotton and Associates, Inc., 1990; Keefer and others, 1991).

Consumer hazard-protection choices: Which information structure is best?

We evaluate whether the utility of consumer decisions regarding mitigation can vary with a change in the refinement with which earthquake-hazard information is communicated to those consumers. In order to examine this notion, we test to see if changes in the information structure affect the estimate of $p(Y^* \mid \bar{y})_i$ and $E[L_i(q_i)]$ and hence improve the reliability of the decision to purchase earthquake insurance and/or invest in mitigation. We expect that a refinement in information reduces the uncertainty associated with this decision. In order to evaluate whether refinements in the hazard information significantly affect consumer decisions, we test two hypotheses. First, we test the probability that purchasing earthquake insurance is based solely on the insured value of the structure. This is a basic test of consumer awareness of the local physical conditions and the potential geologic hazard.

$$H_0\colon p_{EI}|P_1 = p_{EI}|P_2 = p_{EI}|P_3$$

where p_{EI} is the probability of purchasing earthquake insurance.

Second, we evaluate whether the estimate of expected losses avoided varies significantly as the information changes.

$$H_0\colon E[L(q)_i]|P_1 = E[L(q)_i]|P_2 = E[L(q)_i]|P_3$$

In testing the first hypothesis we apply our Probabilistic Choice System (PCS). On the basis of insured values and probability estimates of the hazard in each parcel in the study area, we estimate the probability of purchasing earthquake insurance in a spatial discrete choice model:

$$p_{EI_k} = p(p_k(\omega m), INS_k) \qquad (17)$$

where *INS* is the insured value in parcel k.

In our evaluation, indirect utility in the PCS is normally distributed. We chose this type of PCS on the basis of data for homeowners' and earthquake insurance policy holders in the general area prior to the Loma Prieta earthquake. To test whether our data are normally distributed, we gathered information on 2416 consumers in the study area, 1140 of whom purchased earthquake insurance in addition to a homeowners' policy (insurance data were compiled for the 95030 Zip Code in Santa Cruz County, California). Figure 3 illustrates the frequency distribution of those consumers who purchased insurance protection according to insured value. Using a chi-squared test we evaluate whether consumers who purchased insurance are randomly distributed according to insured value. We cannot reject the null hypothesis that consumers purchased insurance according to a normal distribution ($\chi^2=0.17$, where the critical value at the 95% confidence level is 5.99).[5] Because insurance purchasers in the study area can be represented by a normal distribution, a probit model is appropriate for estimating mitigative choice in the PCS.

Results for the PCS model are listed in the top three rows of table 3. The insured value variable has the expected sign and is significant in all equations in determining whether a consumer is apt to purchase earthquake insurance (this is consistent with our chi-square test for insurance purchasers in the area). The coefficient for this variable is stable across all information structures. On the other hand, as we vary the probability information, only P_1, which contains the relative susceptibility to landslides, is statistically significant (t statistic of 1.73 for the $p_k s$ variable in model $p_{EI} \mid P_1$ in table 3). We find that information structure P_3 is not statistically significant in predicting the purchase of earthquake insurance and exhibits the wrong sign. This is expected because people living in the area had not experienced the 1989 event and had not, therefore, had the opportunity to update their strategies for mitigation.

[5]We also examine subsets of the data. One subset is those consumers who purchased only homeowners' policies according to insured value, a second subset is those consumers who purchased earthquake policies in addition to homeowners' policies according to insured value. Using a chi-squared test, we evaluate whether consumers who purchased only homeowners' policies and those who purchased earthquake policies are randomly distributed according to insured value. Like the entire sample, we cannot reject the null hypothesis that consumers purchased insurance according to a normal distribution in the homeowners'-insurance-only subset ($\chi^2=4.22$), whereas we can reject the null hypothesis for the earthquake insurance purchasers subset ($\chi^2=8.31$). The difference in the frequency distributions between the homeowners'-policies-only subset and the earthquake policies subset is consistent with the first-order condition $dL/dq<0$.

Because information structure P_2 does not vary across the study area and is equally probable at any point in a 30-year time interval, the probability for recurrence cannot be included as an independent variable and tested explicitly in a spatial PCS. This variable could be included explicitly in the model if consumer panel data for long periods of time were available. The dummy variable for the current SSZ regulation is insignificant in all models. The SSZ variable does not represent landslide hazards.

Table 3.
Regression coefficients and test statistics for probability of purchasing insurance and expected losses avoided
k=139 (t statistic)

Model	$INSUR_k$	$p_k(s)$	$p_k(s \mid EQ)$	EQ_k	Constant	R^2	LLR	AIC*
$p_{EI} \mid P_1$	0.000005 (2.92)	0.986 (1.73)			-1.043 (-2.71)		11.0	
$p_{EI} \mid P_2$	0.000005 (2.79)				-0.646 (-2.11)		7.98	
$p_{EI} \mid P_3$	0.000005 (2.78)		-0.693 (-0.76)		-0.443 (-1.09)		8.55	
$CL_{k(1)}$		23778.0 (0.82)		79933.0 (7.16)	-4298.8 (-0.34)	0.28		42511×10^5
$CL_{k(3)}$			146040.0 (3.24)	83462.0 (7.78)	-39759.0 (-2.47)	0.33		40039×10^5

*AIC=Akaike Information Criterion

We can, therefore, reject the null hypothesis that the probability of purchasing earthquake insurance is based solely on the insured value of the structure. From our results we conclude that consumers are aware of local physical conditions and use this knowledge when deciding whether to buy earthquake insurance. The probability of purchasing earthquake insurance is found to be a function of insured value at risk and the relative susceptibility to the landslide hazard.

Our second hypothesis tests for variations in losses avoided among the information structures. We assess the differences in the distributions of $E(L(O)_i)$ for each P_a, where $E(L(O)_i) \mid P_a = P_a(INS)$. If we accept the null hypothesis, we can assume that the structure of the information has little or no bearing on estimating the benefits of mitigation. To test the appropriateness of the individual P_a's for benefit estimation, we perform a Wilcoxon matched-pairs signed-ranks test. On the basis of this test, we can reject the null hypothesis that expected losses avoided are equal across information structures. Test results indicate we can reject the null hypothesis that $P_1[INS] = P_3[INS]$ ($P = 0.06$ for a 2-tailed test), and $P_2[INS] = P_3[INS]$ ($P = 0.03$ for a 2-tailed test). On the other hand, we cannot reject the null hypothesis that $P_1[INS] = P_2[INS]$; that is, these two samples can be considered to come from the same population.

Now that we have rejected the second test hypothesis, we should identify which information structure is best suited for application in the risk-analysis procedure. We use two criteria for choosing the information structure: (1) estimating the significance of the hazard-map variable in predicting damage claims as a result of the Loma Prieta earthquake and (2) identifying which structure most closely approximates the actual claims. For the first criterion, insurance claims following the Loma Prieta earthquake (including the deductible) CL_k are estimated in an ordinary least squares (OLS) regression equation (equation 18) as a function of whether the consumer had an earthquake policy (yes or no; 1 or 0) at the time of the earthquake EQ_k, and the probability estimate from the information structure P_a:[6]

$$CL_k = f_L(EQ_k, p_k(\omega m)) \qquad (18)$$

Since $P_1[INS] = P_2[INS]$, we need only compare P_1 and P_3. Table 3 contains the regression results for the two CL_k models. Model $CL_{k(3)}$ is found to be a better estimate of insurance claims than model $CL_{k(1)}$ because the probability information in P_3 is statistically significant at the 0.01 level while the probability information in P_1 is statistically insignificant in predicting earthquake insurance claims.

Using our second criterion, we compare the expected losses avoided for each P_a to actual claims. The statistics for each of the $P_a[INS]$ distributions are compared with insured values and actual claims in table 4.

Table 4.
Statistics for actual claims and expected losses avoided
k=139

	Mean	Standard deviation	Range	Mean of residual (Claim-P_a)	Standard deviation of the residual (Claim-P_a)
Insured Value	$176,479	$67,355	$15,200 - 421,000		
Claim	49,126	76,102	0 - 374,939		
P_1(INS)	62,818	43,395	2,378 - 194,138	$-13,691	$73,330
P_2(INS)	52,943	20,206	4,560 - 126,300	-3,817	71,671
P_3(INS)	50,638	29,725	3,433 - 167,918	-1,512	69,580

[6]In equation 18, we included damage claims for those homeowners who had purchased earthquake insurance and for those who had not. Of the 139 parcels in our sample, 45 had no earthquake insurance but submitted a claim and 5 had earthquake insurance but did not submit a claim.

The ranges for each P_a in table 4 are much smaller than for actual claims, which cause significant differences in the standard deviations. Because the difference between actual claim and expected losses avoided in each cell, or the residual, provides a more realistic assessment, the mean and standard deviation of the residuals also are shown in table 4. Inspection of the table suggests that $P_3[INS]$ is the most appropriate measure of expected losses avoided for the risk analysis because it best approximates the average actual earthquake damage claim. We conclude that insurers should employ the most up-to-date hazard mapping information that reflects recent earthquake events (i.e., P_3) in determining portfolio exposure and setting policy premiums and deductibles.

Optimizing the decision for investment in mitigation

In the process of using the method to identify a choice for mitigation, consumers consider market earthquake insurance, self protection in lieu of purchasing insurance, or a combination of both. We show that, depending on the information contained in P_a, the cost effectiveness of specific plans for mitigation, for the same location, can be sufficiently different to alter a consumer's strategy. Applying equation 15 yields the number of parcels where each loss-reduction strategy would be cost effective. The combinations are listed in table 5.

Table 5.
Number of parcels where mitigation is cost effective[a]
[Parenthetical entries assume the case of 50% damage.]

Model	Insurance available: no mitigation	Insurance not available: new construction	Insurance not available: retrofit	Insurance available: new construction	Insurance available: retrofit	Insurance with capped coverage[b] available: new construction	Insurance with capped coverage[b] available: retrofit
P_1	134[c] (114)	68 (18)	18 (0)	53 (7)	12 (0)	54 (11)	13 (0)
P_2	139 (139)	60 (6)	0 (0)	42 (0)	0 (0)	45 (1)	0 (0)
P_3	139 (139)	49 (14)	6 (0)	33 (4)	4 (0)	36 (5)	5 (0)

[a] All parcels (139) are considered for the "insurance available: no mitigation" case because we assume earthquake insurance always is available. However, prospective homesites on steep slopes (we use a slope angle of 34° for the threshold) require variances in construction, therefore such locations (23 parcels) are excluded from the other columns in the table.
[b] Insurance coverage is capped at $100,000 loss.
[c] Denotes number of parcels satisfying the criterion for the case of 100% damage.

The purchase of earthquake insurance is found to be cost effective in 96% of the parcels using information structure P_1 and for all parcels using P_2 and P_3 in the study area. This is not the case, however, for construction activities associated with self-protection alternatives. Depending on the hillside setting of the parcel, differences in the payoffs from different plans for mitigation are found. These differences in potential investment decisions depend on hillside setting, structure condition, and physical model. On the basis of our procedure, consumers in the study area, assuming risk neutrality, would prefer to purchase market insurance over structural modifications (table 5, column 2 - "Insurance available: no mitigation"). If mitigation were mandatory as a condition for purchasing earthquake insurance or if insurance were restricted or unavailable, mitigation would be cost effective in a number of parcels in the study area. Further inspection of table 5 shows that as the hazard information structure becomes more refined, the number of parcels where mitigation would be cost effective declines. For example, if P_2 were used by consumers, our model forecasts that, where new construction is applicable, all would purchase earthquake insurance whereas 42 also would mitigate. On the other hand, application of P_3 forecasts mitigation for new construction to be appropriate in 33 parcels, and all would purchase earthquake insurance. Because there is no assurance that the construction alternatives are 100% effective ($\alpha=1$), the number of parcels where mitigation has a positive expected payoff could be an overestimate. Therefore, for comparison we vary the damage outcome. In cases where mitigation is 50% effective or if losses are 50% of insured value, the figures in parentheses in table 5 show, as expected, that market insurance remains the preferred option for the consumer.

In characterizing the process of decisionmaking related to earthquake-loss reduction, we note that a moral hazard problem could arise. That is, the availability of earthquake insurance at premiums near \$2 per \$1000 of coverage reduces the consumer's exposure to property damages associated with an earthquake-triggered landslide and consequently reduces the consumer's willingness to pay for self protection, q_l. Even though self-protection options (table 5) can be cost effective, insurance at the market price of \$2 per \$1000 of coverage independent of q_l is almost always preferred. Because an insurance company cannot observe the investment in mitigation, the possibility of a moral hazard becomes evident. Using column 5 in table 5 and information structure P_3, of the 33 parcels where mitigation for new construction is permissable and cost effective, claims equaled at least three-fourths of insured value 23 times. We believe that a loss greater than 75% of insured value can be considered a total loss. In these cases, either self protection was rejected or mitigation failed to adequately protect against loss. If we assume mitigation were rejected, then a moral hazard seems to exist. Both the insured, by reducing the probability of a loss, and the insurer, by reducing the damage claims, would be better off if mitigation were undertaken. Premiums could rise to a level more consistent with the hazard, or individuals would improve their safety. Similar conclusions to varying extents can be reached for the remaining alternatives.

VI. Conclusions and Observations

The risk-analysis procedure developed here provides a means for consumers and insurers to make welfare comparisons among safety strategies for earthquake-triggered landslides. We applied three types of information structures to assess the efficiency of self protection. The results of the application demonstrate that the informational content of a particular map can make a significant difference in decisions related to earthquake-hazard mitigation. On the basis of the risk-analysis procedure, we measured the gains in consumer benefits of self protection by estimating the differences in expected losses avoided with different structures of information. We found that the information contained in P_1 assists consumers in making earthquake insurance decisions and that the information contained in P_3 is superior in evaluating expected losses avoided for making mitigative investment decisions. In any case, scientific data clearly play an important role in consumer choices concerning loss avoidance from earthquake-triggered landslides. Further refinement of earth-science information for this type of model, however, is required for successful implementation of risk-based regulations or for insurance programs containing provisions for mitigation as a qualification for participation. With more detailed geotechnical measurements, improved understanding of earthquake and landslide processes, and maps of earthquake-triggered landslides in a variety of "at risk" physical environments, regional (and somewhat general) hazard probabilities could be translated to site-specific forecasts useful for decisions by the public.

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Appendix: A simple yet effective physical model

This appendix is a mathematical derivation of a physical-process model that characterizes landslide hazards by a failure criterion called the factor of safety. The factor of safety comprises a set of physical attributes that describe the current state of a hillside. First, we specify a static factor of safety in terms of earthquake acceleration and then derive the change in the factor of safety as a function of the duration of an earthquake.

The factor of safety (F) in equation A1 is a function of the soil cohesion (c), hillside slope angle (β), density of hillside material (γ), height of the water table (m), density of water ($\gamma_w = 1$), piezometric head (z), friction angle (ϕ), g=9.8 cm/s, and earthquake acceleration (a):

$$F = \left[\frac{c+(\gamma-m\gamma_w)z\cos^2\beta\tan\phi}{\gamma z\sin\beta\cos\beta} - 1\right]\cdot\frac{g\sin\beta}{a(t)} \qquad (A1)$$

In order to measure the change in the factor of safety with regard to changes in acceleration during an earthquake, we take the total differential of the factor of safety with respect to acceleration during an earthquake and obtain

$$\frac{dF}{da(t)} = \frac{g}{a(t)}\left(\frac{c\tan\beta-(\gamma-m\gamma_w)z\tan\phi\sin\beta\cos\beta}{\gamma z\cos\beta} - \cos\beta\right)\bullet\frac{d\beta}{da(t)}$$

$$-\frac{g}{a(t)}\left(\frac{c+m\gamma_w z\cos^2\beta\tan\phi}{z\cos\beta}\right)\frac{1}{\gamma^2}\bullet\frac{d\gamma}{da(t)} - \frac{gc}{\gamma\cos\beta\, a(t)}\bullet\frac{1}{z^2}\bullet\frac{dz}{da(t)}$$

$$+\frac{g(\gamma-m\gamma_w)\cos\beta}{\gamma a(t)\cos^2\phi}\bullet\frac{d\phi}{da(t)} + \frac{g}{\gamma z\cos\beta\, a(t)}\bullet\frac{dc}{da(t)} + \frac{g\gamma_w\cos\beta\tan\phi}{\gamma a(t)}\bullet\frac{dm}{da(t)}$$

$$+\left(\frac{c+(\gamma-m\gamma_w)z\cos^2\beta\tan\phi}{\gamma z\sin\beta\cos\beta} - 1\right)g\sin\beta\bullet\frac{-1}{a^2(t)} \qquad (A2)$$

Holding acceleration constant for a small geographic area like the Santa Cruz Mountain hillside used in this study and simplifying equation A2 yields

$$\frac{dF}{da(t)} = \frac{-9.8\left[\left(\frac{c+(\gamma-m\gamma_w)z\cos^2\beta\tan\phi}{\gamma z\sin\beta\cos\beta} - 1\right)\sin\beta\right]}{a^2(t)} \qquad (A3)$$

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Figure captions

1. Susceptibility to landsliding in the southern Santa Cruz Mountains, Calif. No triggering mechanism is assumed.

2. Conditional probability of earthquake-triggered landslides in the southern Santa Cruz Mountains, Calif.

3. Distribution of insured values for the 95030 Zip Code in Santa Cruz County, Calif. Includes all types of homeowners' policies.

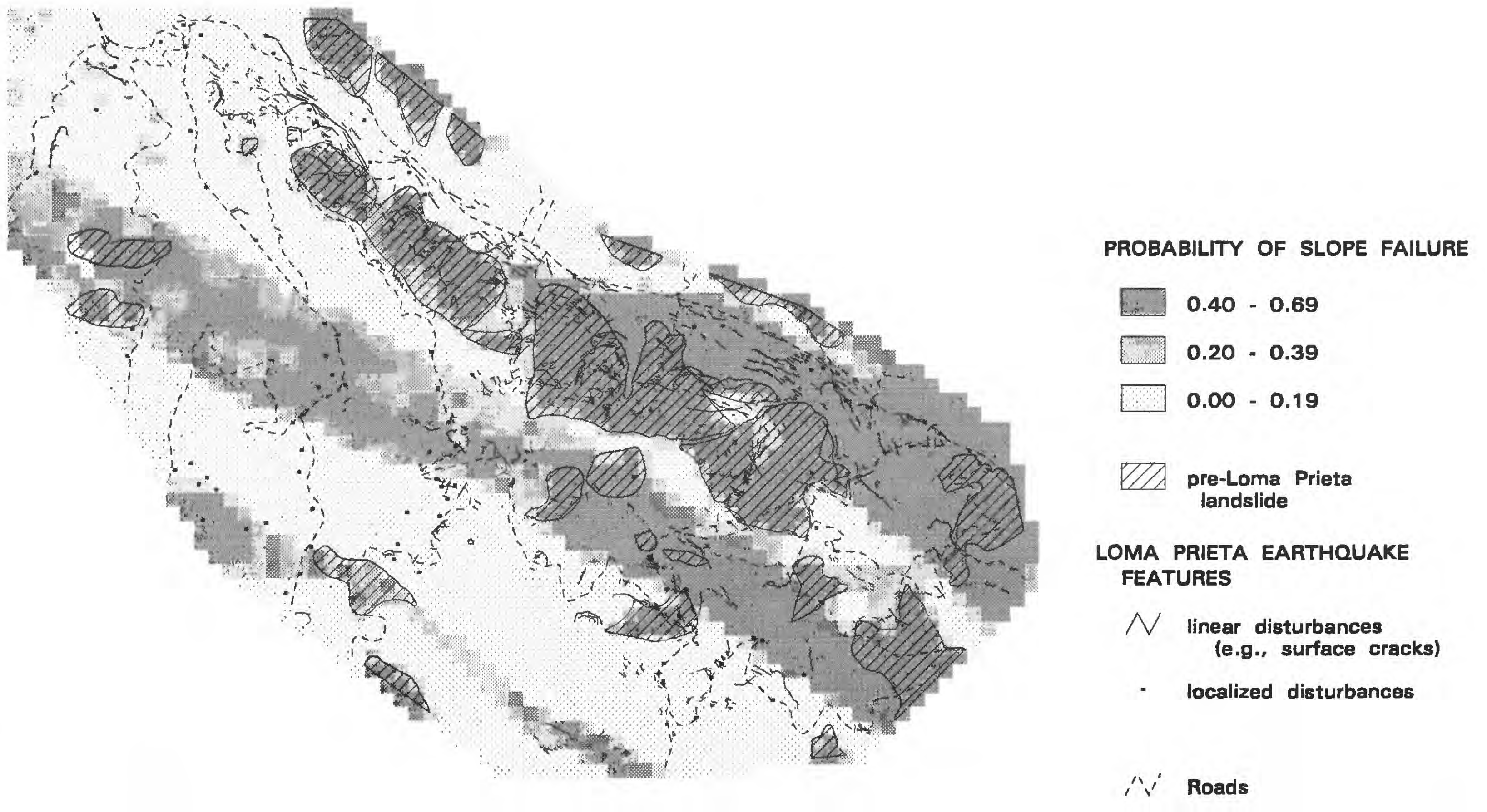
PROBABILITY OF SLOPE FAILURE
0.40 - 0.69
0.20 - 0.39
0.00 - 0.19
pre-Loma Prieta landslide
LOMA PRIETA EARTHQUAKE FEATURES
linear disturbances (e.g., surface cracks)
localized disturbances
Roads

FIGURE 1

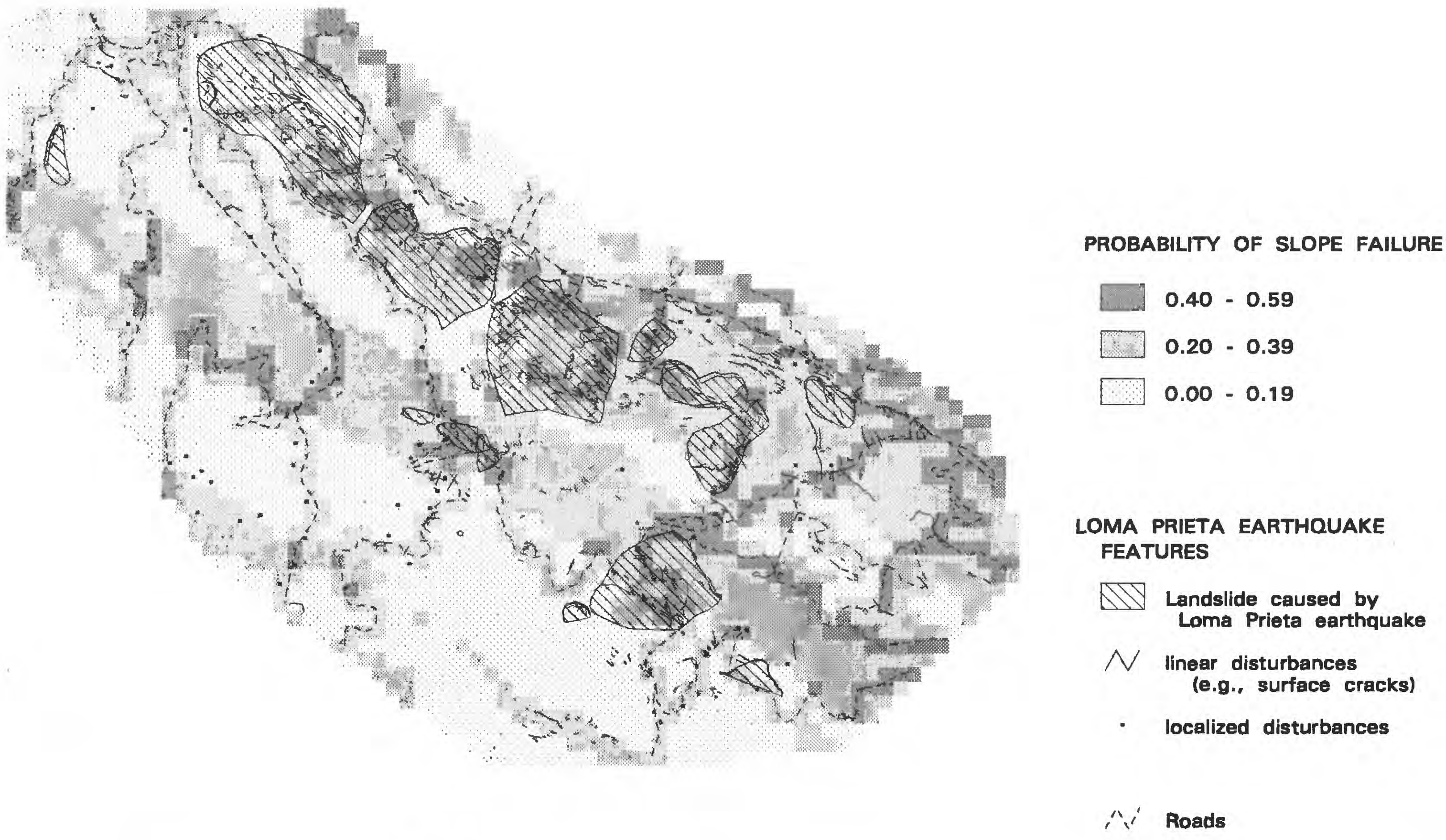
PROBABILITY OF SLOPE FAILURE
0.40 - 0.59
0.20 - 0.39
0.00 - 0.19
LOMA PRIETA EARTHQUAKE FEATURES
Landslide caused by Loma Prieta earthquake
linear disturbances (e.g., surface cracks)
localized disturbances
Roads

FIGURE 2

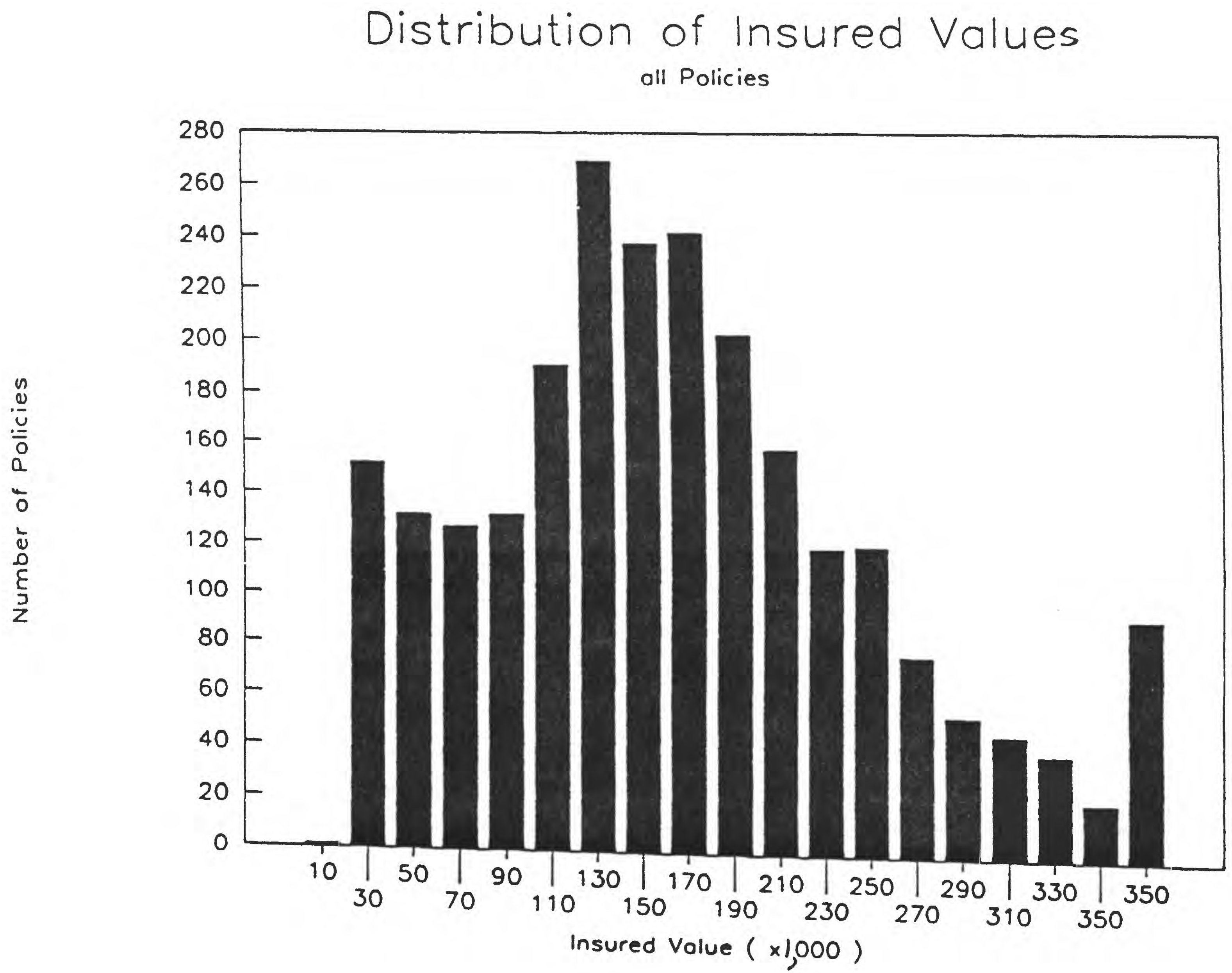
Distribution of Insured Values
all Policies
Number of Policies
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
10
30
50
70
90
110
130
150
170
190
210
230
250
270
290
310
330
350
350
Insured Value (x1,000)

Figure 3