A REGIONALIZED VARIABLES MODEL FOR SEISMIC HAZARD ASSESSMENT

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SUMMARY

Incorporating historical data into models for seismic hazard assessment is hampered by the spatially irregular nature of earthquake ground motion observations. By quantifying spatial relationships among ground motion observations, models for seismic hazard assessment can be developed. Spatial realtionships were found to exist among ground motion observations for southern California earthquakes in the period, 1930-1971. Using these spatial relationships, a microzonation model was developed which associated the highest seismic hazard in the southern California region with the Santa Barbara region.

INTRODUCTION

The seismic hazard of a region should incorporate the entire historical record of ground motion to define seismic patterns. The implicit assumption is that historical seismicity adequately describes future seismic patterns. Currently accepted approaches to seismic zonation make this assumption, either explicitly by relying on the historical record for zonation, or implicitly by using observations from past seismic events to develop theories that define future ground motion characteristics.

Incorporating the entire historical earthquake ground motion record into a program for earthquake microzonation is not trivial. The locations of historical observations, either instrument locations or felt reports, are spatially irregular. Random, spatially irregular observations make mapping of historical seismicity difficult. Futhermore, direct observations are seldom available for specific sites of interest and problems arise in utilizing spatially irregular observations to estimate the level of ground motion at these unsampled locations. Consequently, historical data on ground motion are often overlooked in favor of a theoretical approach based on attenuation functions.

When spatial relationships can be identified for ground motion data, however, they are valuable for estimating the level of ground motion at unsampled locations, enhancing the historical record. Such spatial relationships are useful in two fundamental ways. First, an estimate of the ground motion can be made at discrete, unsampled locations on the basis of their

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position relative to known ground motion measurements. Second, a measure of accuracy of the estimate can be made on the basis of this spatial relationship.

Earthquake ground motion data, specifically Modified Mercalli Intensity data, were shown to possess spatial structure in Ref. 1, for the 1872 Washington State earthquake. Spatially structured data are regionalized, and can be analyzed using the theory of regionalized variables (Ref. 2). Although the character of the spatial structure of earthquake data vary with geographic position and magnitude (Ref. 3), the theory of regionalized variables can adapt to this change, allowing a general, universally applicable seismic zonation model to be developed.

THEORY OF REGIONALIZED VARIABLES

The theory of regionalized variables was developed by Georges Matheron in the late 1950's. Matheron demonstrated that spatially dependent variables can be estimated on the basis of their spatial structure and known samples. This estimation is one aspect of geostatistics, a concept concerned with describing the distribution, in space, of geologic phenomena.

A random variable distributed in space is said to be regionalized. These variables, because of their spatial aspect, possess both random and structured components (Ref. 2). On a local scale, a regionalized variable is random and erratic. Two regionalized variables separated by a distance vector, h, however, are not independent, but are related by a structured aspect dependent upon h. Usually, as the length of h increases, the similarity between two regionalized variables decreases.

At first glance, a regionalized variable appears to be a contradiction. In one sense, it is a random variable which locally has no relation to surrounding variables. On the other hand, there is a structured aspect to a regionalized variable which depends on the distance separating the variables. Both of these characteristics can, however, be described by a random function for which each regionalized variable is but a single realization. By incorporating both the random and structured aspects of a regionalized variable in a single function, spatial variability can be accommodated on the basis of the spatial structure shown by these variables.

The Variogram

One way to examine the spatial structure of a regionalized variable is to analytically relate the change in samples, or measurements, of the variable as a function of distance separating the samples. In general, if the average difference between samples increases as their distance of separation increases, a spatial structure exists and the variable is regionalized.

The function which defines the spatial correlation, or structure, of a regionalized variable is the variogram. The variogram is given by

$$\gamma(h) = \frac{1}{2N} \sum_{N} [Z(x) - Z(x + h)]^2 , \tag{1}$$

where N is the total number of data pairs separated by a distance h. The variogram is one half the average square of the difference between samples $(z(x))$ separated by a distance, h. If a spatial relationship exists, the value of $\gamma(h)$ increases as the separation distance, h, increases. This also implies that samples located close in space are more similar in value than those separated by a considerable distance.

LINEAR ESTIMATION OF REGIONALIZED VARAIBLES: KRIGING

Once the spatial structure of a regionalized variable has been demonstrated through computation of the variogram, the spatial structure can be used to estimate the value of the variable at unsampled locations. This estimation process is known as kriging (Ref. 2).

The estimate, Z^*, of a regionalized variable at a point, x_o, is

$$Z^*(x_o) = \sum_{i=1}^{N} \lambda_i Z(x_i) \ , \tag{2}$$

where N is the number of points located within a distance, R, of x_o, each $Z(x_i)$ is the value of a ground motion observation at the i^{th} location, and λ is a vector of weights, a function of intersample spatial structure.

Once the weighting vector, λ, is known, the kriging variance, which is the variance of the estimation error, is computed as

$$\text{Krig Var} = SV - \sum_i \lambda_i \sigma_{oi} - \mu \ , \tag{3}$$

where SV is the sample variance, σ_{oi} is intersample covariance, and μ is a Lagrangian multiplier to constrain the weights to sum to one $(\Sigma\lambda_i = 1)$. In a practical sense, the kriging variance is analogous to the mean square error of the estimate.

THE REGIONALIZED ASPECT OF EARTHQUAKE GROUND MOTION DATA

In developing a regionalized variables model for earthquake microzonation, southern California was chosen as the geographic region of interest. The historical record for this region is extensive. For this study, Modified Mercalli Intensity (MMI) data for earthquakes in the time period, 1930-1971, provided the historical record (Ref. 4).

Extensive examples of variograms for these data are given in Ref. 3. An example variogram for the 1933 Long Beach earthquake is shown in Figure 1. The spatial structure for these data is spherical (Ref. 5). Using this variogram, kriging resulted in the isoseismal map shown in Figure 2. This map was produced using a 55 by 55 element raster, hence 3025 estimates were made to result in spatially regular data for this earthquake. All southern California earthquakes for which a spatial structure could be defined were treated in an identical manner, using a grid of the same dimension and

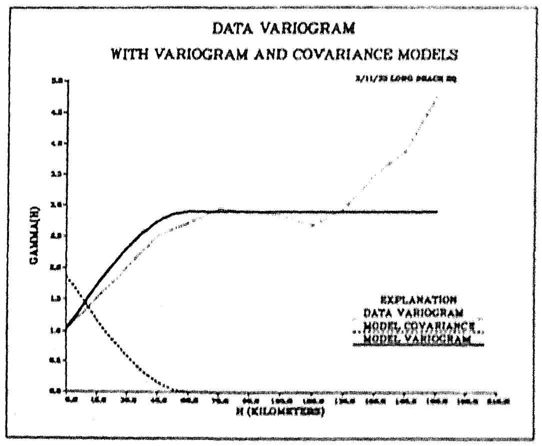

Figure 1. Variogram for 3/11/33 Long Beach Earthquake Intensity Data

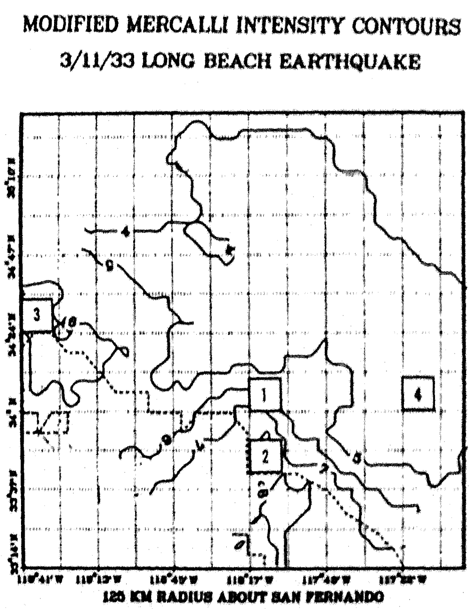

Figure 2. Kriged isoseismal map, 3/11/33 Long Beach earthquake. Location Index: (1)- Los Angeles; (2) - Long Beach; (3)- Santa Barbara; (4) - San Bernardino.

geographical registration. In this way a history of estimated ground motions was developed for each of the 3025 intersections for the 50-year period.

DEFINING THE HAZARD

Earthquake hazard is defined herein as the probability of exceeding a threshold value of Modified Mercalli Intensity over a fifty year period. Gumbel's method of extremes (Ref. 6) is used to define this probability, using the maximum annual intensity at each of the grid intersections.

The probability of experiencing ground motion below a given threshold can be defined as (Ref. 6)

$$P(x_N \leq T) = EXP\left[-EXP[-\beta(T - \mu)]\right] , \qquad (4)$$

and the probability of exceeding a threshold is 1 - P, where T is the threshold value, and β and μ are parameters of the data distribution (Ref. 7).

Seismic hazard was computed using equation (4). This hazard was computed first for the historical period, 1930-1970, prior to the occurrence of the 9 February 1971 San Fernando earthquake. The hazard was then recomputed for the time period, 1930-1971, to evaluate the influence of the San Fernando earthquake on the computed regional hazard for southern California. If the hazard map for the period, 1930-1970, is adequate (resistant), the influence of the San Fernando earthquake on the regional seismic hazard should be minimal. As shown in Figure 3, the seismic hazard for southern California did not change significantly when including the 1971 San Fernando earthquake, suggesting that the maps are resistant to limited changes in, or additions to, the data set.

Also noteworthy is the identification by these maps of seismic hazard in the Santa Barbara, California area (34°24' N-lat, 119°41' W-long). This hazard is directly attributable to seismic activity within the Santa Barbara Channel (Ref. 9) and indirectly attributable to activity on adjacent faults, such as the White Wolf and Oak Ridge faults. These hazard maps are, of course, a reflection of historical seismicity in the period, 1930-1971. It is interesting, however, that very little seismicity in this period is attributable to activity on the San Andreas fault. Ironically, the area of lowest seismic hazard was found to be East Los Angeles.

CONCLUSION

There are several advantages to more completely using historical data for defining earthquake hazard. First, directional attenuation characteristics are implicitly included. This is apparent in the kriged isoseismal map for the 11 March 1933 Long Beach earthquake. A rapid, northeast attenuation is evident for the Long Beach earthquake.

In addition to directional affects, local spatial variability in ground motion is also accounted for. This is implicit in the kriging technique which relies on a random function describing a dichotomous, regionalized variable.

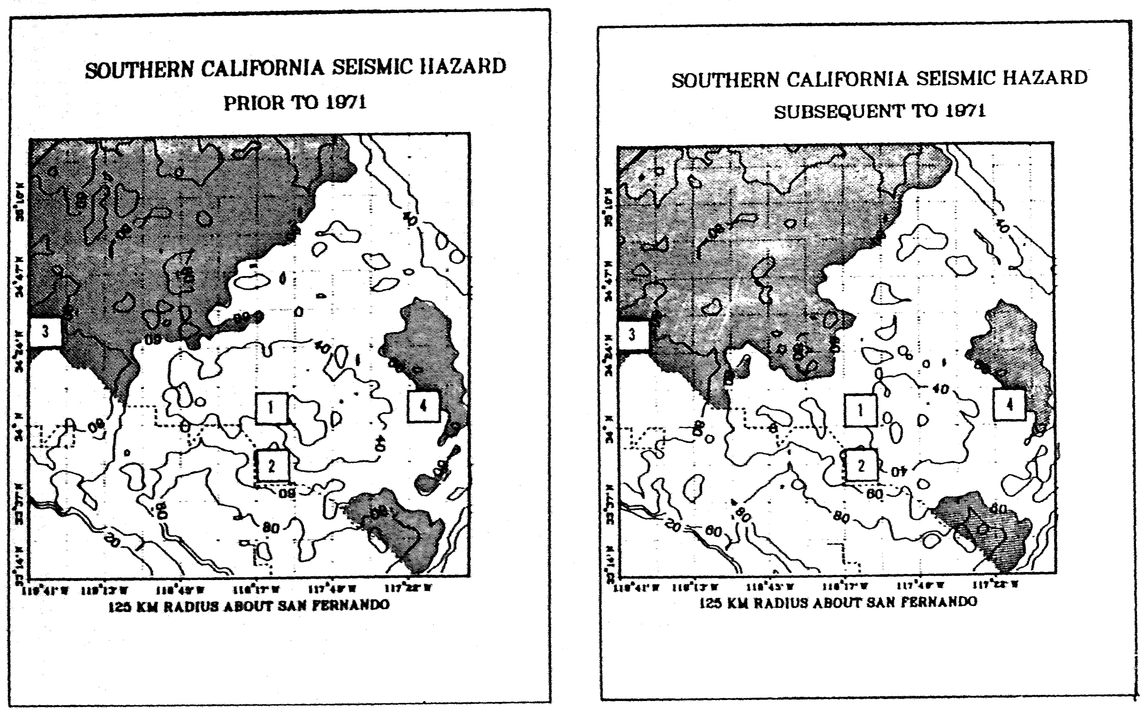

Figure 3. Southern California seismic hazard maps computed prior to, the subsequent to, the 2/9/71 San Fernando earthquake. Maps were produced using Gumbel's statistics of extremes relying on kriged intensity data. The gray region accentuates areas having at least a 60% probability of exceeding an intensity VI. Location index: (1)- Los Angeles; (2) - Long Beach; (3) - Santa Barbara; (4) - San Bernardino.

Local, site-specific behavior is partially accounted for by using nearest, neighboring samples in this random function. This is better than a point source-attenuation approach, a regression analysis, which can only account for regional ground motion characteristics and is incapable of accounting for source, and geologic effects.

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