NONSTATIONARY ESTIMATES OF SEISMIC HAZARD USING THE CHINESE EARTHQUAKE CATALOG

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SUMMARY

Probabilistic seismic hazard analyses which use stationary models of seismicity lead to inaccurate estimates of the probability of damaging shaking during the last 700 years in north China. This inaccuracy results from the periodicity in seismic activity which is evident during these 700 years: the mean number of earthquakes per year varies by a factory of 10 in this region, with a period of about 300 years. More accurate estimates of the seismic hazard are obtained if (1) the maximum possible earthquake size in each seismogenic zone is determined from the entire seismic history rather than from a short time window, and (2) the future seismic activity can be estimated accurately. The first condition emphasizes the importance of realistically estimating the maximum possible size of earthquakes on faults. The second indicates the need to understand possible trends in seismic activity where these exist, or to develop an earthquake prediction capability with which to estimate future activity.

INTRODUCTION

The available history of earthquakes in China (Institute of Geophysics, 1970) is one of the longest in the world. Examination of this history by several investigators (Allen, 1975; Mei, 1960; Shi et al., 1975) has revealed periodicities in seismic activity, with periods ranging from several centuries to one thousand or more years. These periodicities have led to the view that the relatively short earthquake history available in many parts of the world may be inadequate to accurately assess seismic hazard (Allen, 1975) in particular because seismic activity in the future may differ substantially from that observed in the recent past.

The present study examines probabilities of occurrence of damaging shaking, using the most complete period of the Chinese catalog (1350 A.D. to 1949 A.D.). The occurrence of high intensities corresponding to building damage are (both observationally and computationally) highly dependent on the occurrence of large destructive shocks which appear particularly periodic in China. The purpose of the present study is to examine probabilistic seismic hazard analyses which use stationary seismicity models to calculate probabilities of damaging shaking, and to determine if and how these analyses should be modified to account for possible periodicities in seismic activity. The ultimate use of these results will be to make more accurate and consistent estimates of seismic hazard in parts of the world where only a short seismic history is available.

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CHINESE EARTHQUAKE DATA

The region of study consists of five provinces (Hopeh, Shantung, Honan, Shansi, and Shensi) in North China (see Fig. 1) and the surrounding provinces contained within the area bounded by latitudes 29.5° N and 44°N, and longitudes 104°E and 125°E. This is the "cradle of civilization" in China, the area with the longest cultural history, and is the area expected to have the most complete earthquake history.

The catalog of earthquakes in China consists of 1230 entries recorded between the years 1177 B.C. and 1949 A.D. (Institute of Geophysics, 1970). Earthquake epicenters reported in the catalog are plotted in Fig. 2, categorized into four magnitude ranges using the magnitudes listed in the catalog. For this investigation only earthquakes which have occurred since the year 1350 were used as described in the next section, because examination of the catalog indicates that earthquakes, particularly the smaller ones, were incompletely reported in prior years (McGuire, 1979).

The radius of damaging shaking for a given earthquake was determined using data reported by Lee (1958). The equation used to relate the damage radius Δ_d to epicentral intensity I_e was:

$$\ln \Delta_d = 0.88 + 0.43\, I_e \qquad (1)$$

For analysis Eq. 1 was transformed into a form typical of attenuation equations:

$$Z = 0.88 + 0.43\, I_e - \ln \Delta_d \qquad (2)$$

where, for a given Δ_d , $Z \geq 0$ implies damaging shaking and $Z < 0$ implies no damage.

HAZARD ANALYSIS FOR DAMAGING SHAKING

The method used for seismic hazard analysis is described elsewhere in detail (McGuire, 1976, 1979). Briefly, seismogenic zones were selected in the study region based on known or inferred fault locations and on topography; earthquakes were assumed to occur at random within each zone. The sizes and locations of successive earthquakes were assumed to be independent, and a Poisson process was used to model their occurrence in time. A truncated exponential distribution described the epicentral intensity associated with each earthquake. For the hazard analysis at each site of interest (described below), the probability of damaging shaking was determined from the probability that a seismic event with epicentral intensity $\geq I_e$ would occur within distance Δ_d (Eq. 1) of the site.

Integrating over all values of Δ_d and using a Poisson process to describe earthquake orcurrences in time, yielded the probability that damaging shaking would occur in a 50-year time period. A standard computer program (McGuire, 1976) was used for calculations.

Probabilities of damaging shaking during 50-year time windows (a typical design lifetime) were calculated at 62 cities in the study area. For the time window 1400 to 1449, earthquakes which occurred between 1350 and 1399 were used to determine the acitivity rates and maximum possible epicentral intensities I_{max} for each source. The b-value (the slope of the log number versus epicentral intensity relation) for all seismogenic zones was determined by the maximum likelihood method using all earthquakes which occurred in the study area between 1350 and 1949. As explained in McGuire (1979), this creates a more severe test for the hazard analysis than using a different b-value for each zone.

The seismic hazard analysis was repeated for eleven 50-year time windows, the last being from 1900 to 1949. Thus, in total, 682 hazard analyses were performed (62 cities time 11 time windows) and used for comparison to observed occurrences of damaging shaking, as discussed in the next section. The entire set of calculations was repeated several times, using different methods of estimating activity rates, maximum intensities, and b values, as described below.

ACCURACY OF HAZARD ANALYSES

To assess the accuracy of the seismic hazard analyses performed, results from these analyses were compared to observed occurrences of damaging shaking in each city during the time windows examined. Damage descriptions in the catalog are incomplete or difficult to interpret in the engineering sense. Therefore, damaging shaking in each city during a 50-year period was assumed if, and only if, that city was closer than distance Δ_d (Eq. 1) to an earthquake with epicentral intensity I_e which occurred during that time period.

For comparison purposes, the probabilities of occurrence calculated at each city from the hazard analysis were divided into ranges (0.0 to 0.09, 0.10 to 0.19, and so on). For each range the fraction of cities which actually experienced damaging shaking during the 50-year period, as just described, was determined. Fig. 3 shows a comparison of the observed fractions (plotted as open squares) with the calculated probabilities. In general the hazard analysis gives a reasonable representation of the seismic hazard (the results are close to the one-to-one line) but fails to accurately assess small differences in hazard. It cannot, for example, distinguish cities with a 5 per cent probability of occurrence, from those with a 15 per cent or 25 per cent probability; it can, however, distinguish these from cities with 30 per cent or 50 per cent probability.

An important source of inaccuracy in the seismic hazard assessments lies in the periodicity of Chinese seismic activity. This is illustrated in Fig. 4, which shows the mean annual number of earthquakes (in a 50-year time window). The seismic activity varies by a factor of ten; when the numbers of earthquakes during the "observed damage periods" are significantly different from the activity rates used in the hazard analyses, some mis-estimation of seismic hazard results. The amount of mis-estimation due to changing seismic activity can be ascertained by "correcting" the rates used in the original hazard analysis to reflect the number of earthquakes which actually occur during the damage observation period. For example, if we are calculating probabilities of damage in cities for the period 1400 to 1449, we use, as activity rates for each seismogenic zone, the number of earthquakes which occur in that zone between 1400 and 1449. We also use, for the maximum possible intensities I_{max}, the maximum observed between 1400 and 1449. These results are shown as closed squares in Figure 3, and indicate generally better agreement between calculated probabilities and observed fractions.

A further source of error lies in uncertainty in the maximum intensities I_{max} for each seismogenic zone. As mentioned by McGuire (1979), it is more consistent to use, for I_{max} in each seismogenic zone, the largest epicentral intensity reported in the entire catalog, rather than that reported during a short time interval. In areas of the world with only a short earthquake history, determining I_{max} to be larger than the historical maximum implies having geological theories and data available on which to base this determination.

The accuracy of hazard analyses in which I_{max} is known from the entire catalog is illustrated in Fig. 5. These results show general conservatism in probability estimates; the results with activity rates corrected for the observed number of earthquakes show generally good agreement between calculated probabilities and observed fractions.

Even better agreement is obtained if b-values are determined for each seismogenic zone separately, rather than for the region as a whole. To illustrate, Fig. 6 shows results for both the stationary model and for the model with corrected activity rates, where b-values for each seismogenic zone were determined (by the maximum likelihood method) using all earthquakes between 1350 and 1949 which occurred in that zone. The results are more accurate than for a single b-value; for the model with corrected activity rates, the agreement between calculated probabilities and observed fractions is excellent (with the exception of the two points indicating the largest probability, which were determined with a small number of data). This verifies the appropriateness of many assumptions in the seismic hazard analysis, specifically that epicentral intensities are exponentially-distributed, that successive events are independent in size and locations, and that the Poisson process is appropriate for describing the occurrence of earthquakes in time.

These results should not be construed to mean that, for seismic hazard analysis in general, every seismogenic zone should have its own b-value. In fact the differences in calculated b-values for the zones used in this study are not statistically significant. Furthermore, even if the underlying earthquake generating process is the same for each zone, calculating a separate b-value for each zone will always result in more accurate results using the comparisons made in this study. Rather, the point is that if we can accurately estimate activity rates for the future, and if we can accurately determine b-values and maximum intensities (or can incorporate the uncertainty in these parameters into the analysis), we can make accurate determinations of seismic hazard.

One further set of results is shown in Fig. 6. If 100 years of data are used to estimate activitv rates. results are obtained which are less accurate than if 50 years of data are used. This reinforces the conclusion reached in the previous study (McGuire, 1979), that the most recent past is the best indicator of seismic activity for the near future.

CONCLUSIONS

Calculation of seismic ground motion hazard in China is accurate using 50 years of data if seismicity is modeled carefully. Specifically, realistic estimates of maximum possible earthquake sizes in seismogenic zones must be made rather than relying on the largest shock observed in a short time period. Accurate estimates of seismic activity during the exposure time of interest are required; less accurate but generally conservative results are obtained using seismic activity observed in the recent past assuming a time-stationary rate of activity, and accounting for statistical uncertainty in the rate. This sensitivity to rates of activity emphasizes the importance of methods of estimating future seismicity in areas of the world where activity may change dramatically (by a factor of ten) over a relatively short time (several centuries). No such changes in seismicity are evident in the United States, at least from analysis of the available earthquake record (McGuire and Barnhard, 1980). Methods of estimating future seismicity include examining available earthquake histories for trends in activity, and predicting earthquakes on specific faults on the basis of geological, geophysical, and seismological data.

ACKNOWLEDGEMENTS

This research was conducted with internal research funds of the U.S. Geological Survey and with research funds of the U.S. Nuclear Regulatory Commission, while the first author was associated with the U.S. Geological Survey. These sources of funding are greatly appreciated.

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FIGURE 1: People's Republic of China, and five provinces in study area.

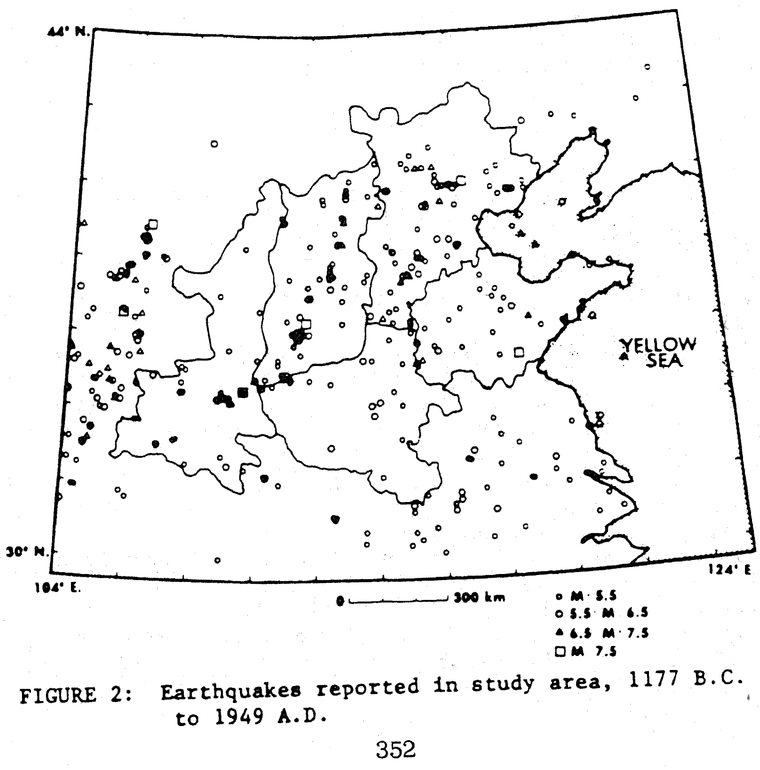

FIGURE 2: Earthquakes reported in study area, 1177 B.C. to 1949 A.D.

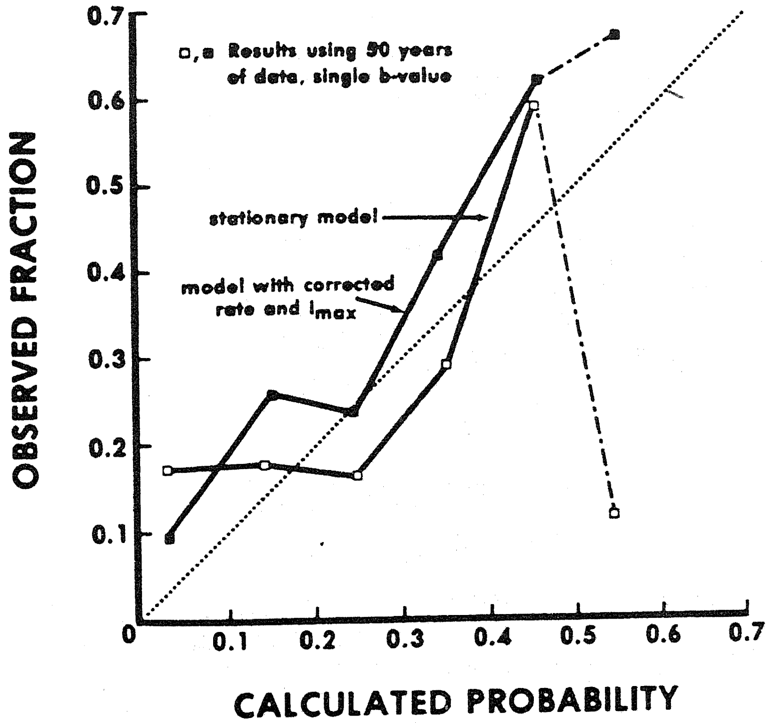

FIGURE 3: Observed fraction versus calculated probability, using 50 years of data and one b-value for all seismogenic zones.

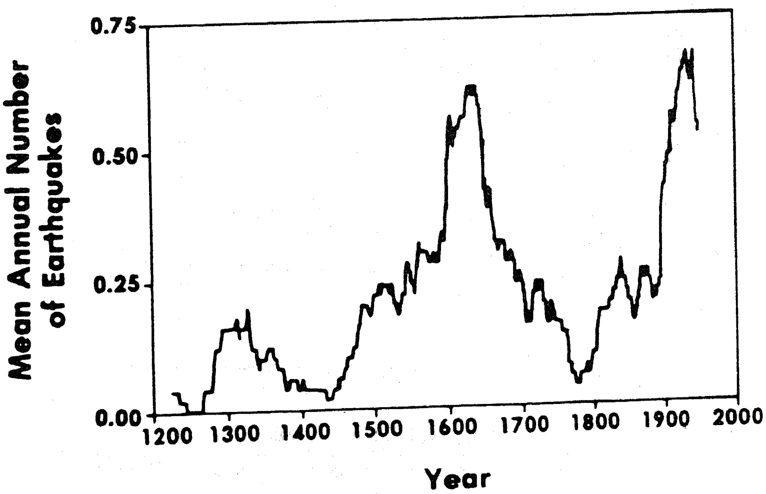

FIGURE 4: Mean annual number of earthquakes (using a 50-year time window) with intensity $\geq$ VII in study area.

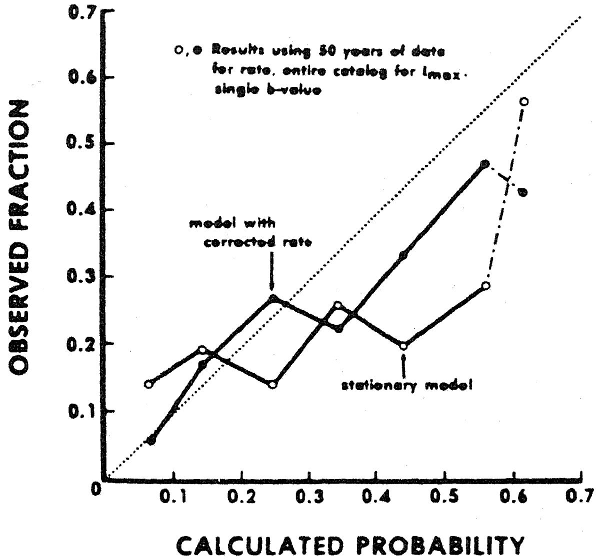

FIGURE 5: Observed fraction versus calculated probability, using 50 years to estimate seismic activity rates, entire catalog to estimate I_{max}, and one b-value for all seismogenic zones.

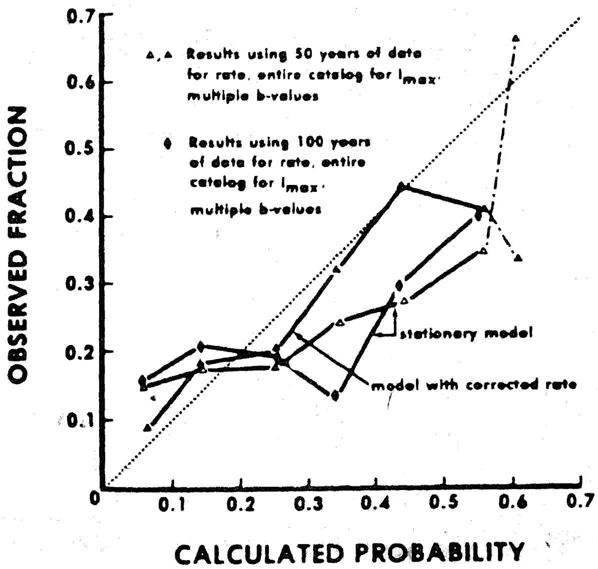

FIGURE 6: Observed fraction versus calculated probability, using 50 and 100 years to estimate seismic activity rates, entire catalog to estimate I_{max}, and different b-values for each siesmogenic zone.