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ADEQUACY OF SIMPLE PROBABILITY MODELS FOR CALCULATING FELT-SHAKING HAZARD, USING THE CHINESE EARTHQUAKE CATALOG

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ABSTRACT

The Chinese earthquake catalog is used to evaluate the adequacy of simple methods for calculating seismic hazards. These simple methods use a time-stationary model for seismicity and an exponential distribution for earthquake size. Earthquake occurrences in five provinces of North China (the area with the most complete history) during time segments of three lengths (50, 100, and 200 years) are used as input to the hazard analysis. The probabilities of felt shaking in 62 cities in North China are calculated for the 50-year period following each time segment, and are compared to the observed occurrences of felt shaking during the 50-year period. Data intervals of 50 and 100 years suffice for accurate estimation of probabilities of felt shaking; 200 years of earthquake history lead to poorer estimates of these probabilities if the rate of earthquake occurrence is averaged over the entire 200 years. This inaccuracy results from the apparent periodicity of activity in North China, which has a cycle of about 300 years. The implication is that, at a specific time, the most recent seismic activity is the best data base to use for calculation of probabilities of felt shaking in the near future.

Introduction

The probabilistic assessment of seismic hazard is generally made using stochastic models which are stationary in time and space and which are calibrated with a limited set of historical earthquake data (for example, Cornell and Merz, 1975; Shah *et al.*, 1975; Algermissen and Perkins, 1976; McGuire, 1977a). These models do not reflect the temporal and spatial behavior of hypothesized tectonic processes which associate earthquakes with the release of elastic strain that has accumulated in the Earth's crust. Similarly, these models do not reflect possible time variations in the rate of strain accumulation and release. Some time-dependent models of earthquake occurrence have been examined, but these have involved either experimental studies without calibration to observed data (Veneziano and Cornell, 1974), studies calibrated with a relatively short, small magnitude catalog (Vere-Jones, 1970), or models using non-Poisson inter-arrival times with stationary (in time) parameters (Esteva, 1976).

The catalog of Chinese earthquakes, (Institute of Geophysics, 1970), dating from 1177 B.C. to 1950 A.D., has recently become available in the western world. This catalog spans a time period which far exceeds the available data base for North America. A summary of the catalog, and several pertinent observations, are available in Lee (1974) and in Lee *et al.* (1976). In examining the Chinese catalog, several authors (for example Mei, 1960; Shih *et al.*, 1974; Shi *et al.*, 1975; Allen, 1975) have noted apparent periodicities in the rate of seismic activity. Also, large earthquakes have been identified in areas that, both prior to and subsequent to these events, exhibited apparent quiescence. These observations have led to the conclusion that the use of stationary (time-independent) models and the short history of earthquakes available in North America may be inadequate to assess the real seismic hazard.

The purpose of this study is to use the Chinese earthquake catalog to quantitatively assess the effectiveness of various typical methods of estimating seismic hazard. No assertion is made there that the Chinese catalog is complete, that is, that it contains all earthquakes that occurred in the study area. In fact, printing in China did not become widespread until 1000 A.D. (Lee *et al.*, 1976); therefore, events before that year may have been less completely reported than those that occurred after. Also, at least one investigator (Mei, 1960) attributed part of the apparent increase in seismic activity after the year 1500 to the appearance of local chronicles, which resulted in more complete reporting. The purpose of this study is not to ascribe changes in reported seismicity to technological or social phenomena; rather, the purpose is to use the catalog of earthquakes in China to test the validity of simple methods of calculating seismic hazard.

Chinese Earthquake Catalog

The Chinese earthquake catalog (Institute of Geophysics, 1970) consists of 1,230 events recorded between the years 1177 B.C. and 1949 A.D. Maximum intensities (between VI and XII) have been assigned to the events on the basis of damage reports; for pre-instrumental earthquakes, magnitudes have been calculated from the intensities using an empirical relation derived from earthquakes that occurred after the year 1900. The catalog also lists, in addition to the date, intensity, and magnitude of each event, the epicentral coordinates (estimated from the damage descriptions for pre-instrumental earthquakes), descriptions of damage or felt effects in different cities and towns, and a map of the felt area for the larger shocks. A translation to English of the damage and felt effects is available in Guu (1976).

Area of Study

For this investigation, the area known as North China comprising five provinces (Hopeh, Shantung, Honan, Shansi, and Shensi) and the surrounding area, was selected for study (Figure 1). This area is the "cradle of civilization" in China, that is, it is the area with the longest cultural history (Needham, 1954), containing the fertile valley and plains of the Yellow River. Thus, it is the area that has the greatest chance for having a complete list of earthquakes in the catalog.

A summary of earthquakes in and near these five provinces (between latitudes 30°N. and 44°N., and between longitudes 104°E. and 124°E.) is shown in Figure 2, plotted as a function of time, for the years 50 B.C. to 1949 A.D. The epicentral locations of these events are shown in Figure 3; thevents have been categorized into four magnitude ranges in Figure 3, using the magnitudes listed in the catalog, to facilitate identification of the large and small shocks.

Hazard Analysis

The Chinese earthquake catalog was divided into 100-year intervals; for each interval, the observed seismicity was used as input to a probabilistic hazard analysis (McGuire, 1976). For each of 62 cities, the probability that one or more earthquakes would be felt in that city during the succeeding 50 years was calculated. These probabilities were then compared to the actual number of cities in which earthquakes were felt during the subsequent 50 years, and the results were summarized for 1900 years of history. In the hazard analysis, it was assumed that earthquakes within each seismic source are uniformly distributed in space, exponentially distributed in size, independent in location and size, and occur as a Poisson process in time. Details of the methods used to determine input to the hazard analysis, and the cities chosen, are discussed below (and in McGuire, 1977b). The procedure was repeated with various modifications to the input and calculations, as discussed below.

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

Originally, it was hoped that the damage and felt reports from the catalog could be used to determine if earthquakes were felt in a certain city during a chosen 50 years. Unfortunately, upon translation of the catalog (Guu, 1976), it was found that reports of specific earthquakes in certain cities were not in the catalog when, in all likelihood, they should have been; these apparent omissions probably resulted either from lost records or from changes (or differences in translation) of city names. The felt-area maps in the catalog are neither of sufficient quality nor quantity to determine all cities in which earthquakes were felt during the study period. In light of these problems, the occurrence of felt shaking in cities was determined by drawing a circular felt area around each earthquake in the catalog, with the center of the

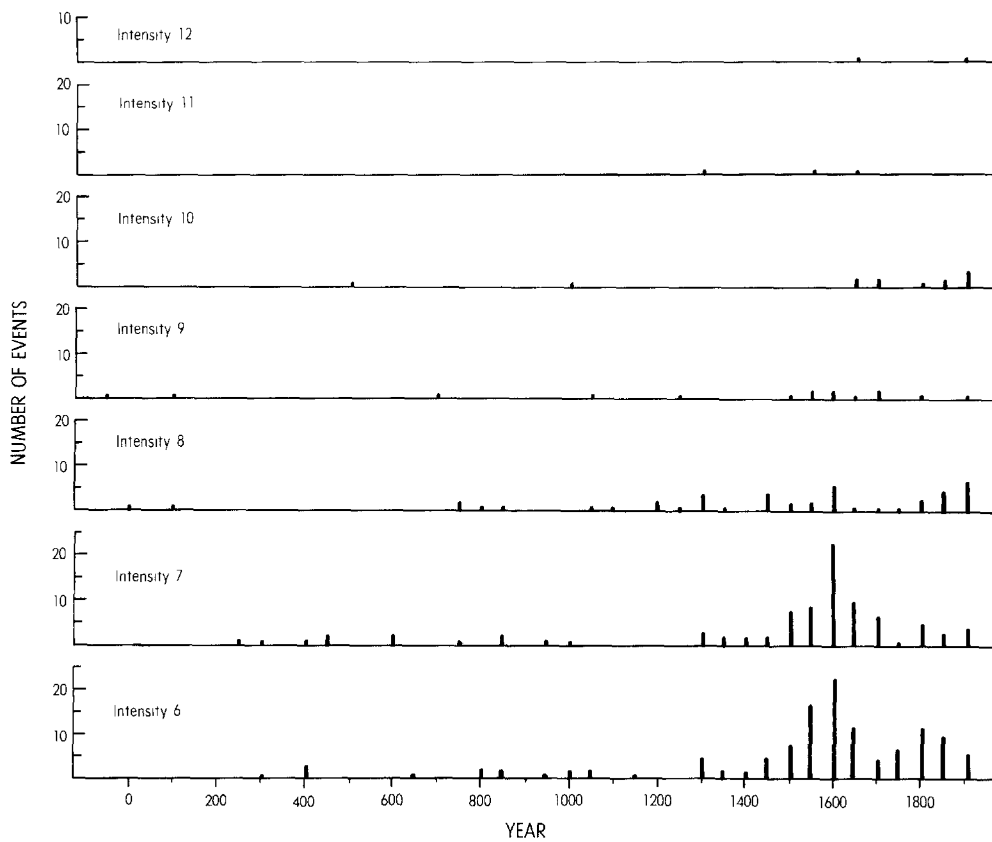

FIG. 2. Number of events with different maximum intensity, per 50-year interval, in study area, for years 50 B.C. to 1949 A.D. (Data for each 50-year interval are plotted at the year beginning the interval.)

circle located at the epicenter and the size of the circle a function of the maximum intensity (this function is described below). To be consistent with the deterministic felt areas, no dispersion in the felt radius-to-intensity relation was used in the hazard analysis. The alternative, using a probabilistic felt area to determine occurrences of felt shaking, and incorporating uncertainty in the hazard analysis attenuation function, would increase both observed and estimated risks, but would not greatly alter the comparison between the two.

Data Necessary for Hazard Analysis

For a seismic hazard analysis, several inputs must be determined: the seismicity of the area must be defined, a measure of the ground motion must be identified, and an attenuation function must be chosen relating that measure of the motion to earthquake size and distance. The methods used to determine these inputs are discussed below.

In this study, the desire was to avoid any "artificial" agreement between seismic hazard analysis and observed shaking which would result from using observed seismicity as input to the hazard analysis, and later comparing output of the hazard analysis with the observed seismicity. For this reason, the observed seismicity was not used in drawing seismic sources, although using seismicity to determine earthquake sources is the usual procedure in seismic hazard analysis. Similarly, the same

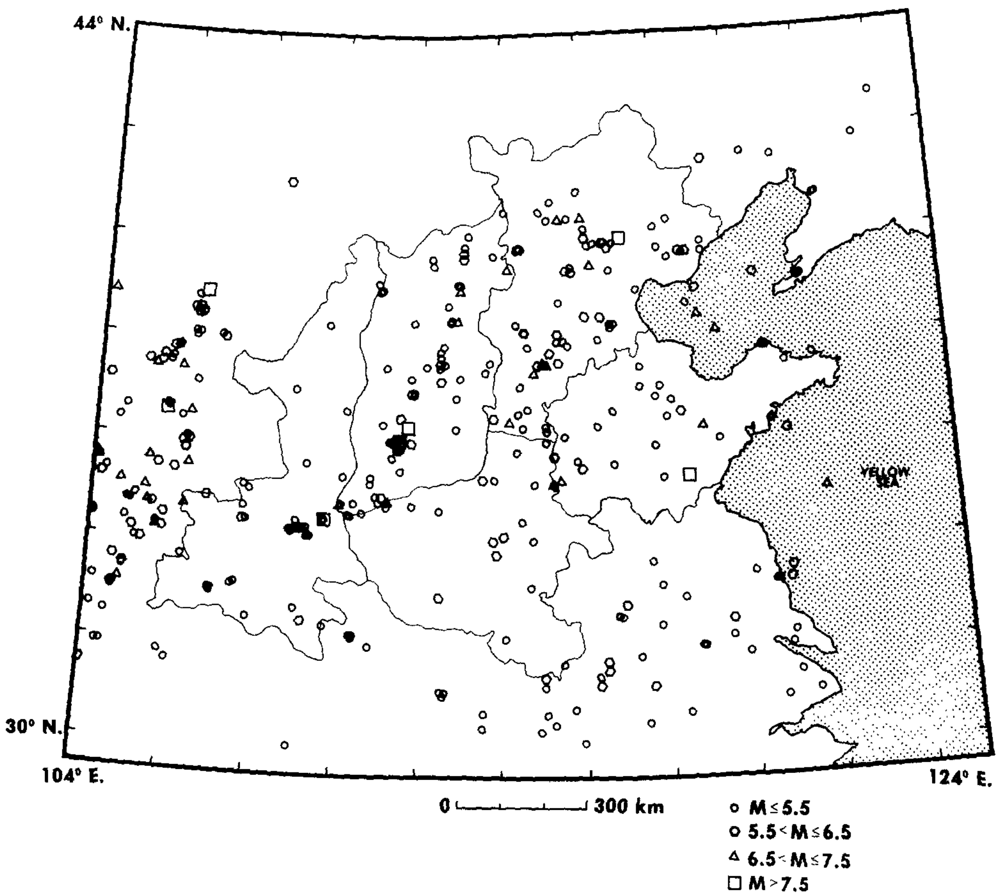

FIG. 3. Location of epicenters in study area.

b value (the slope of the log number versus intensity relation) was used for all seismic sources, rather than determining separate b values for each source. Both of these steps create a more severe test for the hazard analysis, in that alternate procedures (using seismicity to draw seismic sources, and using different b values for each source) would only *improve* the agreement between hazard analysis results and observed shaking.

Seismic sources. The locations of seismic sources, within which earthquakes were considered to be uniformly distributed in space, were selected using only the known fault locations and topography in the region. Epicenter locations were not used to draw seismic sources, for the reason discussed above. Figure 4 indicates the faults in the area as inferred by Lee *et al.* (1976) from Landsat (ERTS) images. Figure 5 indicates faults reported by the Tectonic Map Compiling Group (1974), and Figure 6 shows faults in the western part of the study area as reported by Tapponnier and Molnar (1977). These fault maps and the topography of the region formed the basis for the set of seismic-source areas shown in Figure 7. A significant amount of interpretation is necessary in drawing such seismic sources, particularly in determining the continuity of sources across discontinuous faults, and it is recognized that other investigators might draw somewhat different zones. However, the general pattern of faulting indicates that a series of north-to-northeast trending sources across the region, bounded by an east-to-southeast source across the southern part

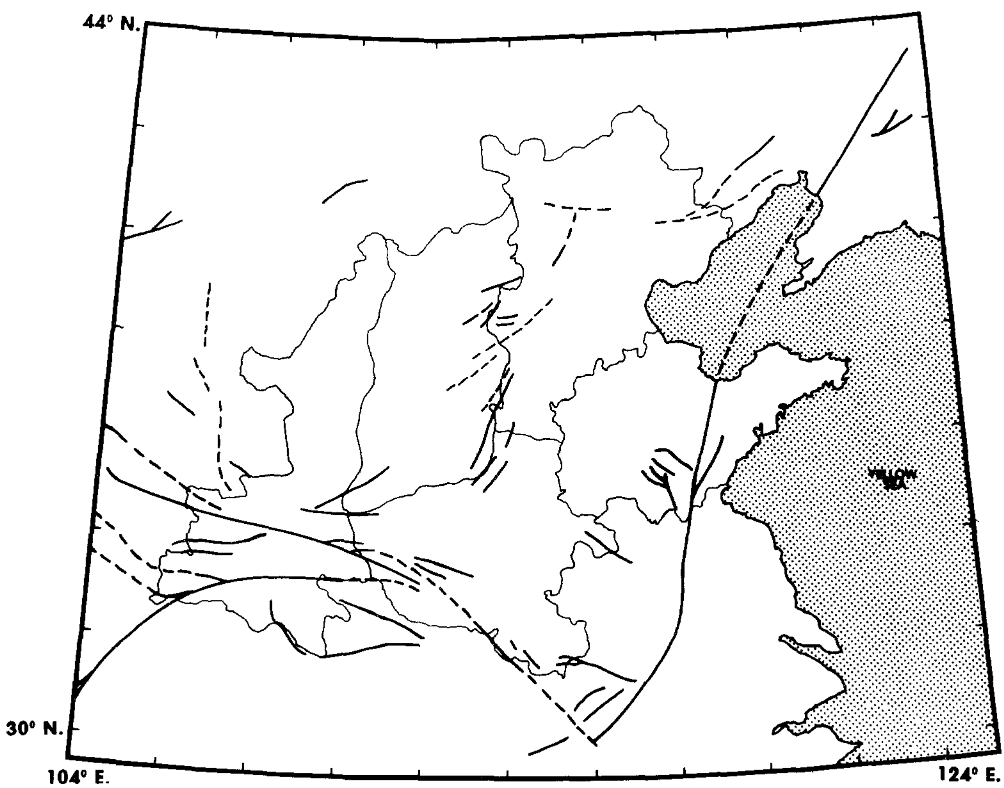

FIG. 4. Faults in study area derived from Landsat (ERTS) images (after Lee *et al.* 1976). (Dashed lines indicate inferred faults.)

of the region, is appropriate. Previous research (McGuire, 1977a) has shown that, when all of the other relevant uncertainties in the problem are accounted for, seismic-hazard estimates are not highly sensitive to the set of seismic sources chosen.

The seismic sources used here can be compared to the earthquake hazard zones determined by Shih *et al.* (1974) and shown in Figure 8. These zones are intended to depict earthquake hazards and were determined using both known faulting and locations of historical epicenters; these zones thus reflect any inaccuracies in the catalog, such as the location of an earthquake at the city that was shaken hardest rather than at the real epicenter. The seismic sources of this study were drawn independently but are generally consistent with the shapes and locations of the zones determined by Shih *et al.* (1974) with the exception of the southern east-to-southeast zone.

Earthquake distribution. The activity rate, b value, and maximum possible intensity for each seismic source were determined using the events which occurred in that source during a limited time interval. The manner in which these parameters were determined from the data is discussed below.

The occurrence of earthquakes was assumed to conform to a Poisson process; the activity rate of each source was taken to be uncertain and was estimated by the rate of activity during a limited time interval. If $G_1(i_s)$ is the probability that intensity i_s will be exceeded at a site, given that a single event of random size and location has

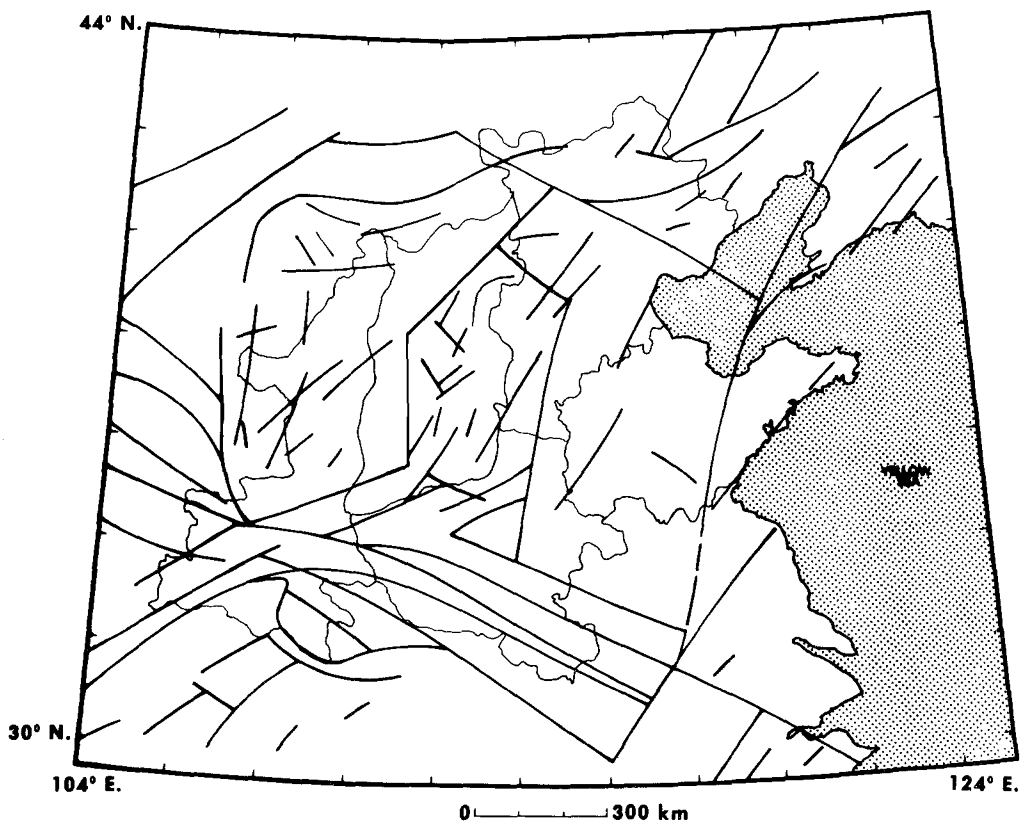

FIG. 5. Faults in study area (after Tectonic Map Compiling Group, 1974).

occurred in the source, the probability that the maximum intensity during time t exceeds i_s (Benjamin, 1968; McGuire, 1977a) is

$$G_{\max}(i_s) = 1 - \left[\frac{\tau}{\tau + tG_1(i_s)}\right]^{n+1}, \tag{1}$$

where n is the number of events observed in the limited time τ during which the rate has been estimated. Thus, even if no events have been observed ($n = 0$), there is a risk at the site resulting from uncertainty in the activity rate.

The b value describing the slope of the log number versus intensity relationship was determined from the observed frequency of events in the study area during the period 50 B.C. to 1949 A.D. In a previous study (McGuire, 1977a), differences in b values from source to source for the eastern United States could be attributed to small numbers of events available for analysis; as the numbers increased, the calculated b values approached the same value. Thus, it was considered reasonable in this study to use a single b value for the entire catalog. This value, determined from a log-number versus intensity graph, was 0.43. As discussed above, the alternative procedure of calculating different b values for each seismic source could have been followed, but this would have artificially improved the agreement between calculated hazard and observed shaking if the differences in b values among sources was statistically insignificant. Along a similar vein, using short time periods to

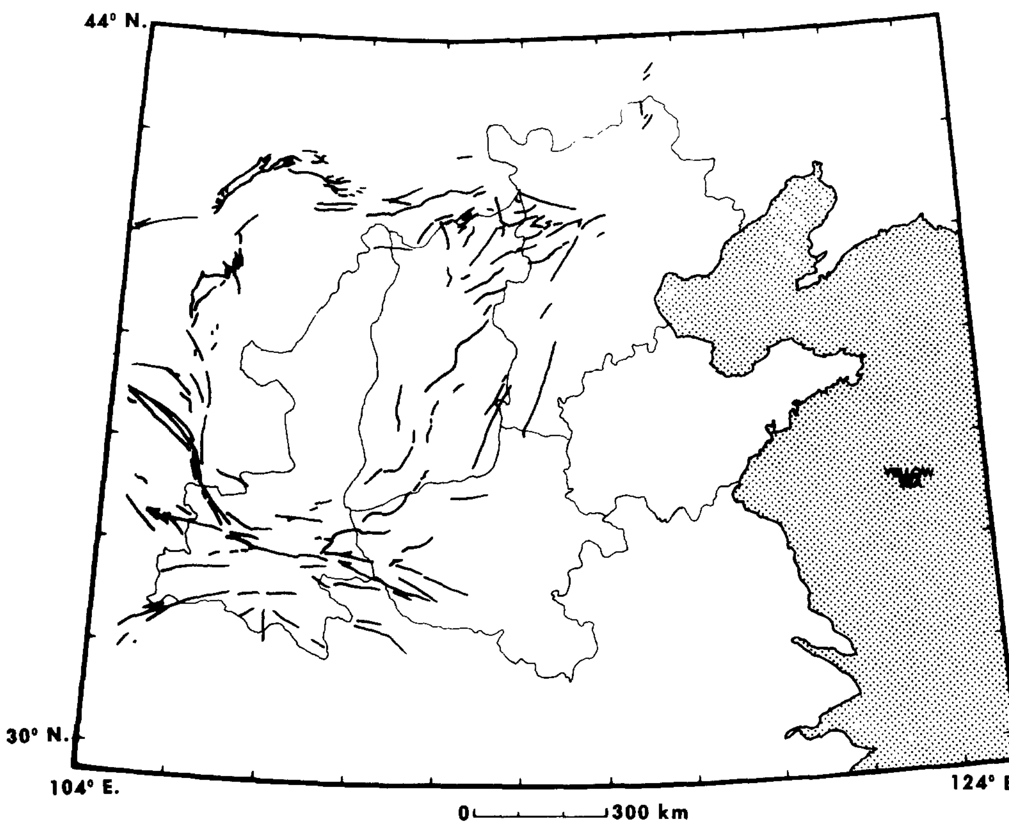

FIG. 6. Faults in western part of study area (after Tapponier and Molnar, 1977).

calculate b values would improve agreement between results because (for example) incomplete reporting of small earthquakes before the year 1300 would decrease the estimated b value and allow estimation of the higher fraction of large earthquakes in the catalog before that year. The procedure followed (using a single b value) is a more severe test of the hazard analysis.

The maximum possible intensity for each seismic source was determined using the seismicity during the limited time interval (50, 100, or 200 years, as described below). Use of this procedure implies that definitive geological or geophysical theories are not available to estimate the maximum earthquake size in an area, as is the case in many parts of the United States. If such theories are assumed to be available, this availability can be simulated using the entire catalog to determine maximum intensities for each seismic source. Following this procedure results in probability estimates that are more accurate; one example of this increased accuracy is described below.

Attenuation of ground motion. The distance to the felt limits of earthquakes of different epicentral intensities was estimated using the maps available in the Chinese catalog. Eighty-seven maps were examined; for each map, the felt area was determined by planimeter, if possible, or by estimating the radius of the felt limits if an incomplete or close-to-shore map was given. The felt-area data, plotted as a function of epicentral intensity I_e, are shown in Figure 9 with the regression line. The standard deviation of ln (area) about the regression line was found to be 0.88, which

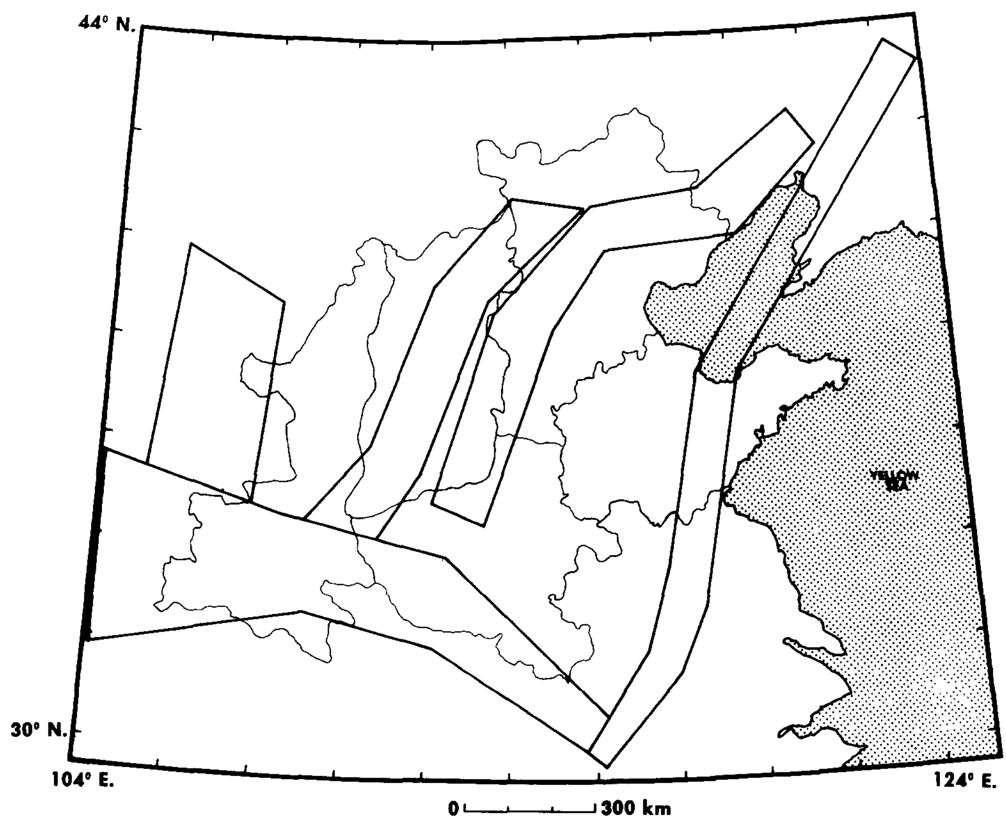

FIG. 7. Seismic sources selected.

is the same order as the error in similar regressions made using data from the eastern, central, and mountain regions of the United States (Brazee, 1976). Converting the felt area to a felt radius R_f yielded the equation

$$\ln R_f = 2.97 + 0.312 I_e. \tag{2}$$

This equation was manipulated into the form of a typical regression equation for computer input

$$Z = 2.97 + 0.312 I_e - \ln \Delta \tag{3}$$

where $Z > 0$ indicates that an earthquake with intensity I_e was felt at epicentral distance Δ, and $Z < 0$ indicates that it was not felt. As discussed above, no dispersion in the attenuation equation was assumed.

The use of a point-source model and circular felt areas was assumed because of the circular or irregular shape of felt areas on many maps in the catalog. Several large shocks were exceptions and yielded elliptical felt areas. For these, the expected number of cities in a circular felt area representation is, on the average, the same as the observed number of cities within the elliptical felt area. Hence, no bias results in the comparison between calculated probabilities and observed occurrences of felt shaking results.

Cities. Sixty-two cities in the five provinces were chosen for hazard analysis.

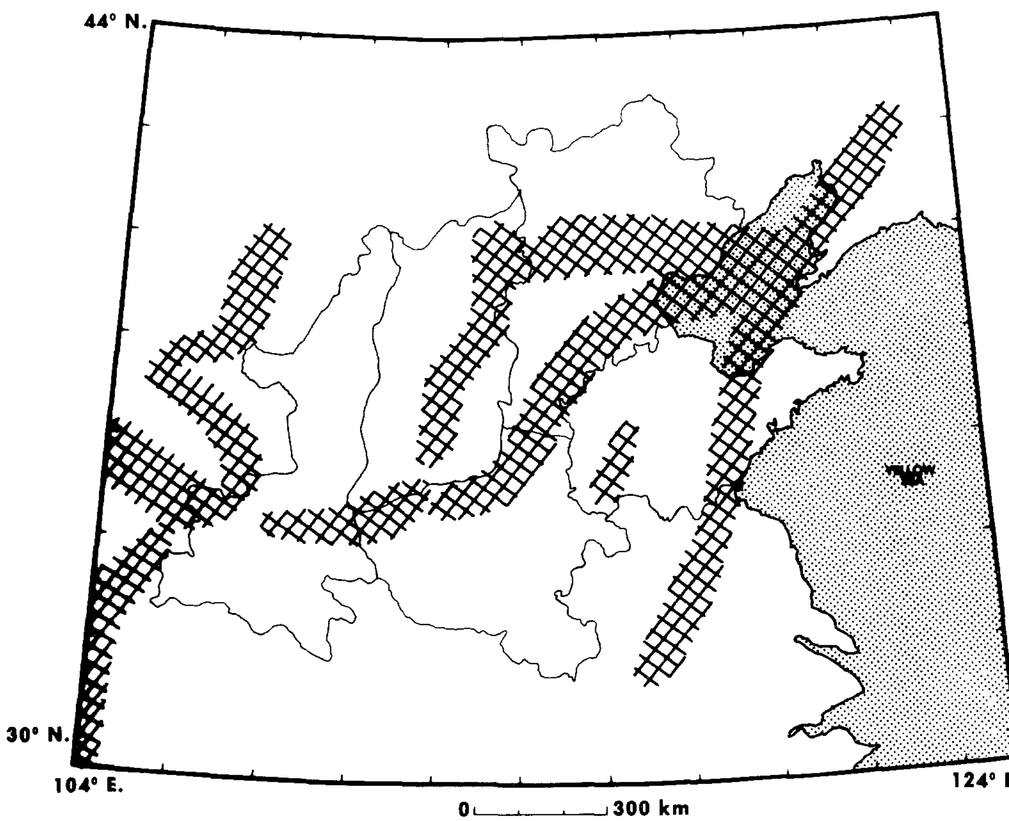

FIG. 8. Earthquake zones (after Shih *et al.*, 1974).

These cities are shown in Figure 10. Cities were used, instead of a grid system, because the epicentral locations of earthquakes in the catalog before the year 1900 are undoubtedly biased by the location of damage or felt reports. It is implicitly assumed that the locations of major cities in this region of China have not changed greatly.

Results of Analyses

The first analysis was made using 100 years of data to estimate the activity rate and maximum possible intensity, I_{max} of each seismic source. These estimates for the rate and I_{max} were used as input to the hazard analysis, and the probability of at least one occurrence of felt shaking [that is, the probability that $Z > 0$ in equation

(3)] during the succeeding 50 years was calculated for each city studied. This analysis is thus comparable to hazard analysis in certain parts of the United States, where 100 years of earthquake history are available and the design lifetime of the structure of interest is 50 years. The calculated probabilities were compared to the observed fraction of cities which actually experienced shaking in the corresponding 50 years. (As explained above, the determination of which cities experienced shaking was made using the mean felt radius as determined from felt area maps.) Earthquake data from the years 50 B.C. through 49 A.D. were used to calculate probabilities of shaking from 50 A.D. through 99 A.D. and were compared to observations of shaking during that period; this was repeated 37 times, at 50-year intervals, the last comparison interval being 1900 through 1949. Thus, 2,356 hazard analyses were done in all (62 cities times 38 time periods). The calculated probabilities of a city

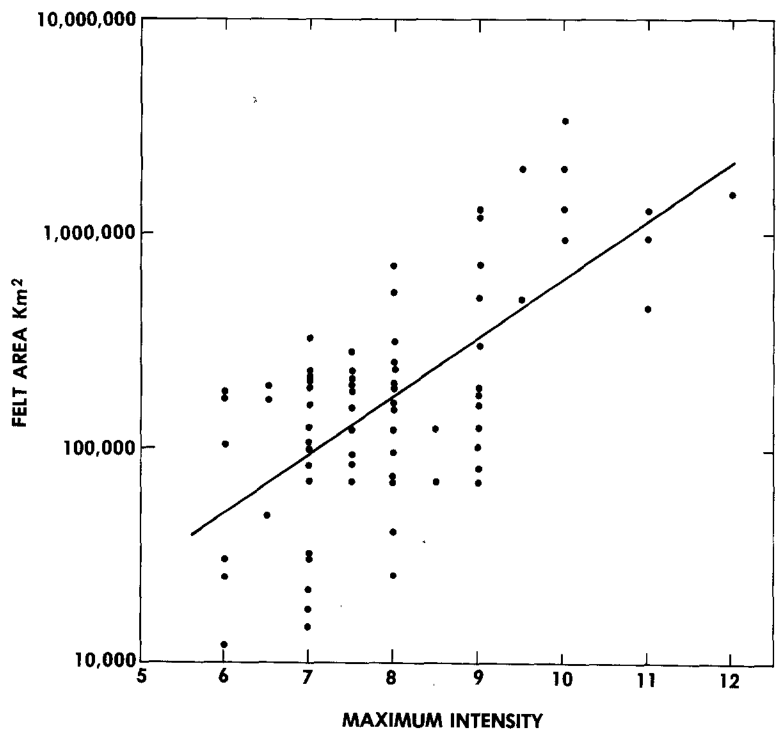

FIG. 9. Maximum intensity versus felt area.

experiencing shaking ranged from 0.01 to 0.99; these probabilities were divided into ten groups (0 to 0.09, 0.1 to 0.19, and so forth) and were compared to the fraction of cities which actually experienced shaking one or more times. Table 1 summarizes the results.

The results obtained for different cities are correlated because one large event will cause felt shaking in many cities. Thus, the results obtained here do not constitute independent observations, and the usual statistical techniques cannot be applied to the results in Table 1 to determine how well the data fit the estimated probabilities. Exact calculation of the correlation of felt shaking between cities, to allow a quantitative evaluation of the accuracy of the hazard analysis, is a formidable task. Instead, what is relied on in this study is a graphical comparison of calculated probabilities and observed fractions of cities that experienced felt shaking.

Such a comparison is shown in Figure 11, where the data presented in Table 1 are plotted. Figure 11 indicates (as Table 1 does) that the observed fraction of occurrences of felt shaking in the cities studied agrees in general with the calculated probabilities. The high fraction of observed shaking relative to the calculated probability at 0.05 results from active 50-year intervals (for example, the one shown at the year 1300 on Figure 2) with large events, preceded by relative quiescence or only small events. The low fractions of observed shaking relative to the calculated probabilities at 0.85 and 0.95 can be attributed to large bursts of seismic activity (for example, that shown during the years 1600 to 1699 on Figure 2) followed by lesser activity.

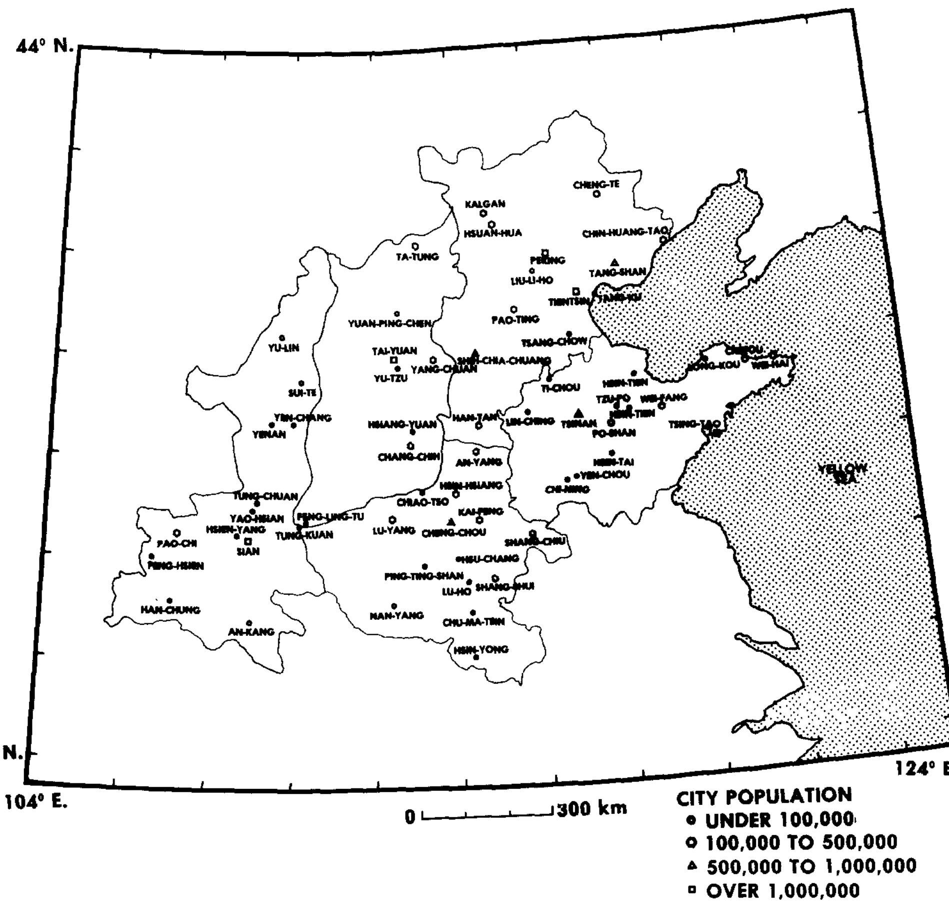

FIG. 10. Cities in five provinces used for hazard analysis.

Another analysis was done assuming that 200 years of history were available to determine activity rates and maximum possible intensities for calculating probabilities of felt shaking during the succeeding 50 years. In this analysis, 36 time intervals of 200 years were used, beginning with the interval 50 B.C. to 149 A.D. which was compared to felt events during the period 150 A.D. to 199 A.D. The results are shown in Figure 12. Surprisingly, 200 years of history (used as input to the hazard analysis) lead to worse estimates of probabilities of felt shaking than do 100 years of history. In fact, it can be stated that, for probabilities above 0.5, the observed fraction of cities experiencing shaking has virtually no dependence on the calculated probability of that shaking. This can be understood by close examination of the periodicities between 1300 and 1950 in the catalog shown in Figure 2. (This time period accounts for most of the calculated probabilities and observed fractions above 0.5 in Figure 12). These periodicities have a cycle of about 300 years; using 200 years of history means that, if a high rate has been observed, resulting in large calculated probabilities (>0.8), fewer felt events will be observed than expected because the succeeding 50 years corresponds to a low point in the periodicity. Conversely, if a

TABLE 1

SUMMARY OF RESULTS FOR 100-YEAR INPUT TO HAZARD ANALYSIS FOR THE YEARS 50 B.C. TO 1949 A.D.

Range of Calculated Probability	Number of Cities		Observed Fraction
	In this range	Which experienced felt shaking	
0–0.09	686	109	0.16
0.1–0.19	518	89	0.17
0.2–0.29	368	94	0.25
0.3–0.39	194	68	0.35
0.4–0.49	115	61	0.53
0.5–0.59	114	67	0.59
0.6–0.69	95	58	0.61
0.7–0.79	85	66	0.77
0.8–0.89	95	68	0.72
0.9–1.0	86	78	0.91

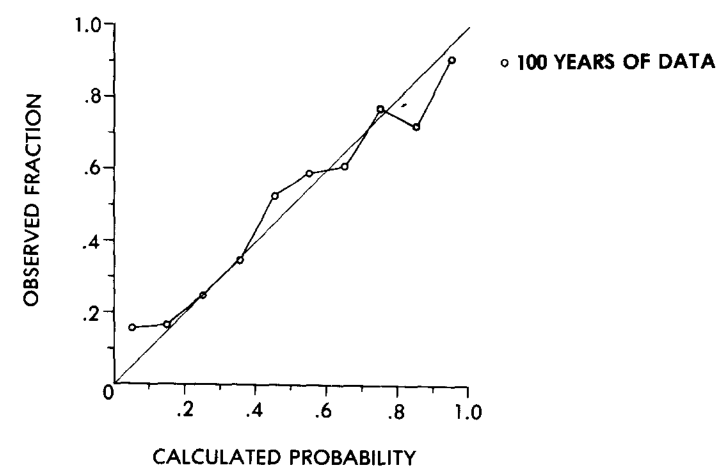

FIG. 11. Calculated probability versus observed fraction of cities experiencing felt shaking, for period 50 B.C. to 1949 A.D., using 100 years of data for hazard analysis.

low rate has been observed, the fraction of felt events is underestimated because the following 50 years correspond to a peak in the periodicity. The analysis based on 100 years is more accurate apparently because this time period contains more information about where the following 50 years will be on the periodicity cycle.

The next step was to determine if data from only a 50-year time interval can be used to accurately calculate hazard probabilities. The analysis was again repeated, using 38 intervals beginning with the period 0 to 49 A.D. and comparing calculations to observations in the succeeding 50 years. The results are shown on Figure 12.

They indicate better agreement than do the results from 200 years of data. This reinforces the conclusion that, for estimating probabilities of felt shaking, *the recent past is a good indicator of the near future.* In fact, the results from 50 years of data err slightly on the conservative side; that is, the calculated probabilities of shaking are slightly larger than the fractions obtained from observations of felt events derived from the earthquake catalog.

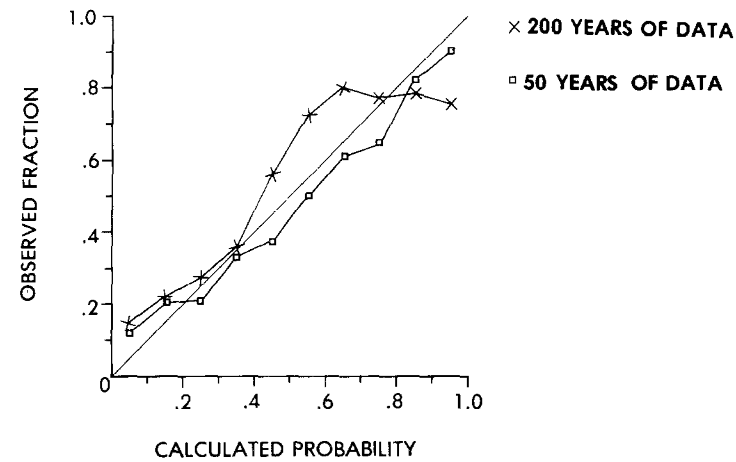

FIG. 12. Calculated probability versus observed fractions of cities experiencing felt shaking, for period 50 B.C. to 1949 A.D., using 200 years of data and 50 years of data for hazard analysis.

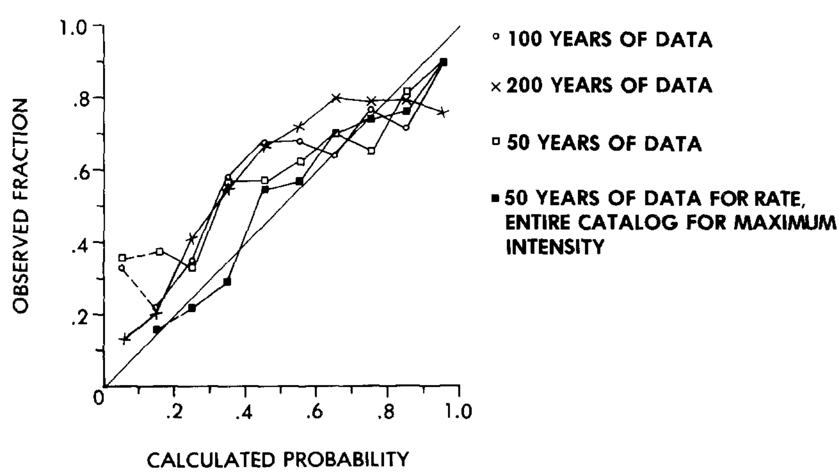

FIG. 13. Calculated probability versus observed fraction of cities experiencing felt shaking, for period 1250 A.D. to 1949 A.D., using 100 years of data, 200 years of data, and 50 years of data for hazard analysis. Dashed lines indicate comparisons determined by fewer than 20 observations.

It is likely that seismicity in the study region was incompletely reported before the year 1300; thus, the numbers of intensity VI and VII events before that year (Figure 2) may be erroneously small. For this reason, the comparisons between calculated probabilities and observed fractions were repeated using only 50-year intervals from 1350 to 1950, that is, during the time period when seismicity is most apparently periodic. The results for 100 years, 200 years, and 50 years of data are shown in Figure 13. There is less consistency between calculated probabilities and observed fractions than for the results reported above for the entire 1900 years, because of both the periodicity in activity rates and the smaller number of data (744 hazard analyses or 62 cities times 12 intervals, versus 2,356 hazard analyses previously) used in the comparisons. However, the same general observations can be made, these being (1) the indiscriminate use of 200 years of seismic data provides poor estimates of hazard generally, and useless estimates at high probability levels, and (2) the use of data from shorter time periods provides better estimates.

An additional set of results are shown on Figure 13 for an analysis in which 50 years of data were used to estimate the activity rate in each source and the entire catalog was examined to assign maximum intensities. As discussed above, this simulates the case for which only 50 years of seismic history are available in an area, but good geological or geophysical models have been developed to determine maximum earthquake sizes on faults. Those results, shown on Figure 13, indicate that very good agreement between calculated probabilities and observed occurrences can be obtained using only 50 years of seismic history. This emphasizes the importance of developing theories to estimate maximum earthquake size on faults or of accounting for the uncertainty in maximum size when these theories are not available.

Conclusions

When compared to observed occurrences during 1900 years of the Chinese earthquake catalog, a simple seismic hazard analysis, assuming a stationary earthquake process and using 100 years of earthquake history as data, yields accurate probabilities of the occurrence of felt shaking during 50-year intervals at chosen locations. A necessary condition for this success is knowledge of the Quaternary faulting of the region, at least to the extent that possible sources of large events can be identified. Uncertainty in the activity rates of seismic sources, as estimated by events during the 100 years, must be accounted for explicitly.

Two hundred years of indiscriminately used data do not provide better estimates of probabilities of felt shaking than do 100 years of data; in fact, 200 years of data yield worse estimates, particularly for calculated probabilities above 0.5. This results from the apparent periodicity of seismicity in the catalog starting in the year 1300, which has a cycle of about 300 years. Fifty years of data can be used to provide good estimates of felt-shaking hazard, indicating that the most recent past is the best indicator of seismic activity in the near future, at least for the Chinese earthquakes used in this study. These results hold for the time period 1350 to 1949, when the catalog is most apparently periodic, as well as for the entire 1900 years examined (50 A.D. to 1949 A.D.).

These results should not be construed to mean that an engineer faced with a seismic design decision is at a disadvantage when more data is available. Rather, they indicate that a large amount of data cannot be indiscriminately thrown together, for instance to calculate a mean activity rate; the old data must be tempered by the more recent evidence, with more weight given to the latter, for estimating earthquake effects in the near future. The conclusions for specific time intervals reached here are dependent on the periodicity observed in the Chinese catalog; given present knowledge of earthquake processes, this periodicity cannot be generalized to other parts of the world. The results obtained here are specifically for probabilities of felt shaking, which may occur at low intensities; these results cannot be extrapolated to higher intensities (for instance to calculate probabilities of damaging shaking), without additional investigation. However, they do indicate that the mere existence of periodicity and non-stationarity in earthquake processes does not require the abandonment of simple, stationary models as useful tools in seismic hazard analysis.

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