SEISMIC RISK STUDIES IN THE UNITED STATES

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Synopsis

A new Seismic Risk Map of the United States is presented, together with strain release and maximum Modified Mercalli intensity maps of the country. Frequency of occurrence of damaging earthquakes was not considered in assigning ratings to the various zones on the risk map, but studies of earthquake frequency are included as an aid in using the risk map. The Seismic Risk Map is suggested as a revision of the Seismic Probability Map prepared by the Coast and Geodetic Survey in 1947 and withdrawn in 1952.

Introduction

The zoning of the United States for seismic risk has not received the attention in the earthquake engineering literature that the subject has enjoyed in other parts of the world, notably in countries such as Japan, the U.S.S.R. and New Zealand. Risk studies in the United States have been limited by the relatively short historical record of seismicity available for the country as compared with such countries as Japan, the difficulty in correlating known seismicity with geological evidence of tectonic activity in many areas and the general scarcity of pertinent geodetic data that might bear on the problem.

Materials Used

The historical record of earthquakes in the conterminous United States consists of data on approximately 28,000 shocks. Within the past two years the Coast and Geodetic Survey has catalogued all of the pertinent seismicity information on punched cards and magnetic tape. All earthquakes have been assigned a reference number and origin times and hypocenters have been recorded if available from instrumental data. Hypocenters

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are estimated from accounts of the shock and isoseismal data if no instrumental data are available. Magnitudes and reported intensities are also keypunched into each card. Sources of the information, availability of strong motion records, and other related data are also catalogued. A more complete description of the format of the data stored on punched cards and magnetic tape has been given by Algermissen (1). It is possible to prepare quite a number of different statistical presentations and maps of the various parameters of seismicity using the basic data retained on magnetic tape and punched cards. Two types of maps were prepared which, it is believed, are particularly useful in estimating seismic risk. These two maps show the distribution of maximum Modified Mercalli (M.M.) intensities and strain release in the United States.

Maximum Modified Mercalli Intensity

The maximum M.M. intensities reported throughout the United States from the first recorded earthquake in 1534 through 1965 are shown in Figure 1. Isoseismal maps were prepared for significant earthquakes not previously mapped by using whatever data were available. Figure 1 shows clearly that high M.M. intensities have been reported throughout a large portion of the country, even though the frequency of occurrence of high intensities in many areas may be quite low.

Strain Release

The cumulative strain release resulting from earthquakes in the time span 1900-1965 is plotted in Figure 2. Using the concept developed by Benioff (2), the strain release of an earthquake is taken to be proportional to the square root of its energy release. The energy, E, was related to earthquake magnitude, M, using the formula $\log E = 11.8 + 1.5 M$ (3). The magnitudes of earthquakes below six are known only for shocks occurring during approximately the past five years. Earthquakes whose magnitudes are six and above are known from about 1900. When magnitude values were not available, they were estimated from maximum M.M. intensity using the relation $M = 1 + 2/3\, I$, where I is M.M. intensity (4). The above empirical relationship between magnitude and intensity is only an approximation and possibly subject to considerable error. The error, however, is not large in this calculation of strain release since it was necessary to use this conversion from maximum intensity to magnitude only for small shocks for which the strain release is small. The entire United States was divided into squares of 10,000 square kilometers and the strain release associated with earthquakes within each square was summed. The strain was represented as the equivalent number of magnitude four earthquakes in each block. The equivalent number of magnitude four earthquakes is then obtained by dividing the sum of the strain release associated with earthquakes in a particular block by the strain release associated with a magnitude four earthquake.

The strain release map is useful in that it shows the current relative rate of tectonic activity in various parts of the United States. Areas of the country with a continuing, but a low level of seismic activity are revealed. These areas do not normally show up on a maximum intensity map. The exact shape and pattern of the areas shown in Figure 2 are not significant since the size of the block over which the strain energy is summed is somewhat arbitrary. A comparison of the relative strain release throughout the United States is, however, interesting and informative, as it is an index of current tectonic activity. Inspection of Figure 2 shows that the United States may be divided roughly into four areas that have different rates of strain release during the 66 year period considered. The four areas are:

Pacific West	- west of 114° W. longitude
Rocky Mountains	- 106° - 114° W. longitude
Central Plains	- 92° - 106° W. longitude
Eastern U. S.	- east of 92° W. longitude

Dividing the total equivalent number of magnitude four earthquakes in each area by the total area we obtain the following rates:

Area	No. of Equivalent Magnitude 4 earthquakes/1000 km^2/66 years
Pacific West	12
Rocky Mountains	2.0
Central Plains	.14
Eastern U. S.	.74

Another calculation of the relative strain release in the four areas was made considering only those portions of each area in which more than 0.25 equivalent magnitude four earthquakes occurred. The strain release per unit area was computed considering only the shaded portions of Figure 2. The results are:

Area	No. of Equivalent Magnitude 4 earthquakes/1000 km^2/66 years
Pacific West	13
Rocky Mountains	2.6
Central Plains	.38
Eastern U. S.	1.1

Using the first set of data on the preceding page, the strain release during the past 66 years in the Pacific West has been approximately six times greater than in the Rocky Mountain area, 86 times greater than in the Central Plains and 16 times greater than in the Eastern United States. Using the second set of data on the preceding page, the strain release in the Pacific West has been, respectively, five, 34 and 12 times greater than the other areas.

Earthquake Frequency

The difficulties encountered in any analysis of the recurrence rates of damaging earthquakes are very great. It has been stated repeatedly in the literature that the historical record of seismicity in the United States is inadequate to estimate recurrence rates. It is believed, however, that the historical record of seismicity in the United States does provide some guidelines to the relative seismicity of various areas of the country.

One approach to the problem to determining the relative seismicity of various regions is to plot earthquake magnitude versus frequency of occurrence for the areas considered. The magnitudes of earthquakes are known for shocks of magnitude six and greater since about 1900 but for small shocks the records are far less complete. In contrast, M.M. intensities have been assigned by the Coast and Geodetic Survey and other investigators to nearly all significant earthquakes known to have occurred within the United States. In order to make use of the complete historical earthquake record, maximum M.M. intensity was plotted versus earthquake frequency. A number of assumptions are necessary when the maximum intensity is used in a study of earthquake frequency. The principal assumptions are that all of the earthquakes in the area considered occurred at approximately ~~the~~ same focal depth and that the maximum intensity for each earthquake has been, in fact, reported. Earthquakes in the United States are nearly all of normal focal depth, although California and Nevada shocks are somewhat shallower (averaging about 10-15 km) than in the remainder of the country (about 30-60 km). It is possible to select geographic areas for study such that the earthquakes within each area are of approximately the same depth. The adequacy of earthquake reporting is also a significant variable and this point will be discussed in greater detail.

In 1860, all states in the western portion of the country, with the exception of California, had an average population density of less than one person per square mile. All states had population densities greater than one per square mile by 1910 with the exception of Nevada. It is clear that the low population density in the western United States prior to 1900 adversely affects the completeness of intensity data in that area, particularly for intensities less than VI or VII.

Reasonably complete records of great earthquakes will obviously be available for a longer span of years than for earthquakes of small or moderate maximum intensity. Accordingly, the intensity data were examined and an estimate was made of the total span of years for which maximum intensity data at each level of the intensity scale are nearly complete. To illustrate the technique further, Figure 3 shows the number of maximum intensity VI earthquakes reported for a north-south trending zone of seismicity through western Montana, eastern Idaho, central Utah and Arizona (region 4 of Figure 5). The data seem relatively complete from 1900 to present. To obtain the frequency of intensity VI earthquakes in this particular zone, the number of intensity VI shocks was simply divided by the time span, 1900-1967, or 68 years. Similarly, for all areas considered, the average number of earthquakes at each intensity level was determined and plotted against intensity.

The recurrence relationship for all intensity data in the United States is shown in Figure 4. It was assumed, in plotting the data, that a relationship of the form log N (per year) = a+b I exists, where N is the number of earthquakes of intensity I. Two conclusions can be drawn for this plot: 1. maximum intensities of V and below in general have not been completely reported for United States earthquakes and 2. the occurrence of great earthquakes (M.M. intensity XI and XII) is erratic over the time span considered. The recurrence curve for all United States earthquakes obviously combines data from areas of different geologic structure and tectonic activity. Accordingly, the country was divided into nine areas (Figure 5) in an attempt to obtain recurrence curves for areas that seem to be related to more or less definite trends or regions of seismic activity and are somewhat geologically similar throughout.

Figure 6 shows the recurrence intensities for California, based on approximately 16,000 earthquakes. The slope of the least squares line, log N = a+b I, is 0.54 and corresponds to a value of b of 0.83 in the equation log N = a+b M where M is the magnitude and the conversion M = 1 + 2/3 I is used. For the equation log N = a+b (8-M), Gutenberg and Richter (5) obtained a value of 0.88 for Southern California and Allen, _et al_. (3) obtained a value of 0.86. Both of these slopes are in close agreement with the value obtained from the data in Figure 6. The curve for Nevada shows a similar slope.

Area 8 (Figure 5) includes the southeast Missouri area where great earthquakes occurred during 1811-12 together with the St. Lawrence Valley region. The recurrence relationship is shown in Figure 7. The 1811-12 New Madrid earthquakes (maximum intensity = XII) were not used in computing the least squares line. There is considerable question as to the validity of considering these two active seismic regions as one area for statistical purposes.

Recurrence curves were constructed for the regions separately, but there were only slight differences in the slopes of the lines.

A summary of recurrence relationships are shown in Table I. The areas are arranged in order of decreasing VII M.M. activity. The seismic risk zones associated approximately with the areas used in the frequency studies are also indicated. Table II shows the frequency of occurrence of earthquakes of various maximum intensity levels per 100 years per 100,000 km^2. The frequencies in Table I have been divided by the area of each region. Assuming that the recurrence relationship has some validity, these tables are measures of the relative seismicity of each area and could be used on a broad scale for planning purposes. The results shown must be used with many qualifications and reservations. The numbers in parentheses are recurrence rates based on the least squares lines only, that is, earthquakes with the indicated maximum intensity are not known to have occurred in that particular area. It should be stated again that the above results depend upon the assumption that a relationship of the type $\log N = a+b\,I$ is valid for these data and that the decisions made regarding the completeness of the data sample were reasonably correct.

Seismic Risk Map

A Seismic Probability Map of the United States was prepared in 1948 by F. P. Ulrich with the advice of seismologists throughout the United States (6) and was issued by the Coast and Geodetic Survey in 1948. In 1949, the Seismic Probability Map was revised such that the Charleston, South Carolina area was changed from Zone 3 to Zone 2 and a Zone 3 was set up for the Puget Sound region of Washington which had formerly been included in Zone 2 (7). The revised map was adopted by the Pacific Coast Building Officials Conference for inclusion in the 1952 edition of the Uniform Building Code. Subsequent editions of the Uniform Building Code have included this map with no changes (8).

The map was withdrawn by the Coast and Geodetic Survey in 1952 as "subject to misinterpretation and too general to satisfy the requirements of many users." The annual publication United States Earthquakes has included a map showing locations of destructive and near destructive earthquakes throughout the United States, but the Coast and Geodetic Survey has offered no other probability map.

The Seismic Probability Map has been most useful as part of the criteria in the establishment of lateral force requirements for buildings but it does, however, have several obvious limitations.

As pointed out by Richter (9), the circular spot numbered 3 in Montana corresponds to damaging earthquakes in 1935, but the map ignores other earthquakes and known active structures in the same geological province. Along many zone boundaries, Zone 3 borders Zone 1 and Zone 2 borders Zone 0. If a major earthquake is considered possible in Zone 3, the normal distribution of intensities would suggest that an area of Zone 2 should surround it, the same reasoning being true for the peripheries of Zone 2 areas. The original Seismic Probability Map describes Zones 0 through 3 only in terms of "no damage, minor damage, moderate damage and major damage" respectively. No attempt was made to correlate the zones with intensity.

The map presented in Figure 8, which will be termed a "Seismic Risk Map," is meant to be an interim revision of the original Coast and Geodetic Survey Seismic Probability Map. The map in Figure 8 is actually more than a revision of the old map in that the factors used in constructing the new risk map are somewhat different from those considered in the original map.

The Seismic Risk Map presented here is based on the following factors:

1. the distribution of M.M. intensities associated with the known seismic history of the United States,

2. strain release in the United States since 1900, and

3. the association of strain release patterns with large scale geologic features believed to be related to recent seismic activity.

Where seismic activity has occurred intermittently along a recognizable geologic trend, it has been, in general, assumed that seismic activity could occur with equal likelihood anywhere along that trend or structure. In areas where the relations between seismicity and geologic structure are not clear or where only limited geologic information is available, the risk zones are based on the distribution of M.M. intensities and strain release. In all cases, the size and shape of the zones have been heavily influenced by the historical distribution of intensities (Figure 1). It is realized that it would be desirable to relate risk to a measurable quantity less subjective than M.M. intensity, but the available strong motion and other data appear to be insufficient to attempt this at present. No special corrections are presented for types of surficial geology and soils that may increase or decrease the intensity of shaking. It should be remarked, however, that the M.M. intensities reported for an earthquake are usually the maximum effects observed on the worst ground.

The risk zones in the northeast portion of the United States are not greatly changed from the original risk map. The St. Lawrence Valley continues to be Zone 3 because of the great earthquakes in 1663 and 1925 and lesser shocks near Attica, N.Y. in 1929 and near Massena, N.Y. in 1944. The Boston, Massachusetts area was zoned 3 in consequence of the earthquake east of Cape Ann in 1755 and many other lesser earthquakes in the area. The Zone 3 rating in the Charleston, South Carolina area is a consequence of the 1886 earthquake. Zone 2 has been extended to include the main structures of the Appalachian area from Pennsylvania to Alabama which are associated with numerous moderate earthquakes. Zone 3 and Zone 2 in the Mississippi Valley have been very much enlarged over those zones on the old Seismic Probability Map. The new zone more nearly reflects the probable distribution of intensities in any repetition of the 1811-12 series near New Madrid, Missouri. Zone 2 has been extended northeast across a zone of relatively minor seismicity in Indiana to southwestern Ohio. Although earthquakes with maximum M.M. intensities of VII are known in western Ohio (10), connection of Zone 2 in Ohio with the Zone 2 surrounding the New Madrid, Missouri area is a matter of interpretation. This zone is based on the apparent alignment of epicenters from the St. Lawrence Valley to southeast Missouri. There is no conclusive geologic evidence at present for the alignment, and other interpretations are possible (10).

A Zone 2 area has been drawn along the Nemaha Ridge structure in Nebraska, Kansas and Oklahoma which includes the 1952 earthquake near El Reno, Oklahoma and numerous other shocks along the Nemaha Ridge. The north-central plains states have been, for the most part, rated in Zone 1 because of the lack of data relating seismicity with geologic structure and because of the rather widespread and erratic distribution of moderate earthquake activity. North Dakota is a good example. No earthquakes (11) are known to have occurred in the state until July 8, 1968 when a magnitude 4.4 earthquake shook the Bismarck area (12). The Zone 3 area restricted to southeastern Montana on the old map has been extended southward through Idaho and Utah. The large earthquake near Hebgen Lake, Montana in 1959, the Kosmo, Utah shock of 1934, the series of shocks in 1920 and 1921 near Elsinore, in southern Utah and the related north-south trending faults amply justify the zoning.

Only minor changes have been made from the original map in the states bordering the Pacific. The original Zone 1 rating in Oregon has been slightly changed. Other minor changes have been made in the shape of the Zone 3 area in Washington at the south end of Zone 2 in the Great Valley of California.

Discussion and Summary

The Seismic Risk Map presented is offered as a revision of the Seismic Probability Map originally prepared by the Coast and Geodetic Survey in 1947. The new map is only an interim one and does not represent the final form of a risk map for the United States. It does not consider the frequency of occurrence of the seismic events in each zone. An estimate of the relative rates of occurrence of earthquakes of various maximum M.M. intensity in different zones has been made in this paper using strain release and earthquake recurrence data.

It is suggested that eventually it may be possible to estimate seismic risk in the United States using three separate maps: one map would be geological in nature, showing all geological structure thought to be related to seismic activity, with assignment of relative risk to each of the structures; a second map would estimate the frequency of occurrence of earthquakes of various magnitudes or maximum intensities throughout the United States; and a third map would show the distribution of maximum M.M. intensity in the United States such as is shown in Figure 1 of this paper. If proper coefficients are assigned to each area or feature of each of the three maps, it would be possible to obtain both the long term (risk over a very long time) and short term (risk over 25-50 years) risks in the following manner: The short term risk at a particular site could be obtained by a weighted consideration of coefficients from maps 1, 2 and 3. Long term risk could be obtained from a similar integration of data from maps 1 and 3. Much additional work remains to be done, particularly with regard to the relationship between geologic structure and earthquake occurrence. It is hoped that the data and maps presented will be useful in developing future seismic risk maps for the United States.

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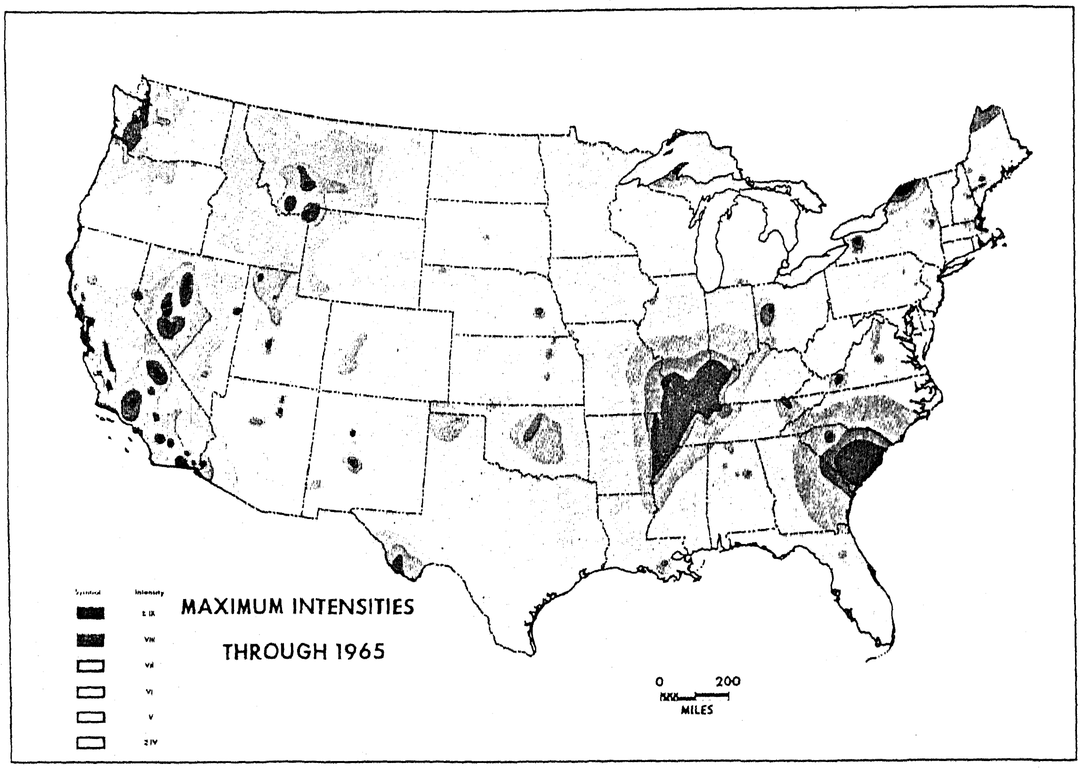

Figure 1 Maximum Modified Mercalli intensities throughout the United States - all historical data through 1965

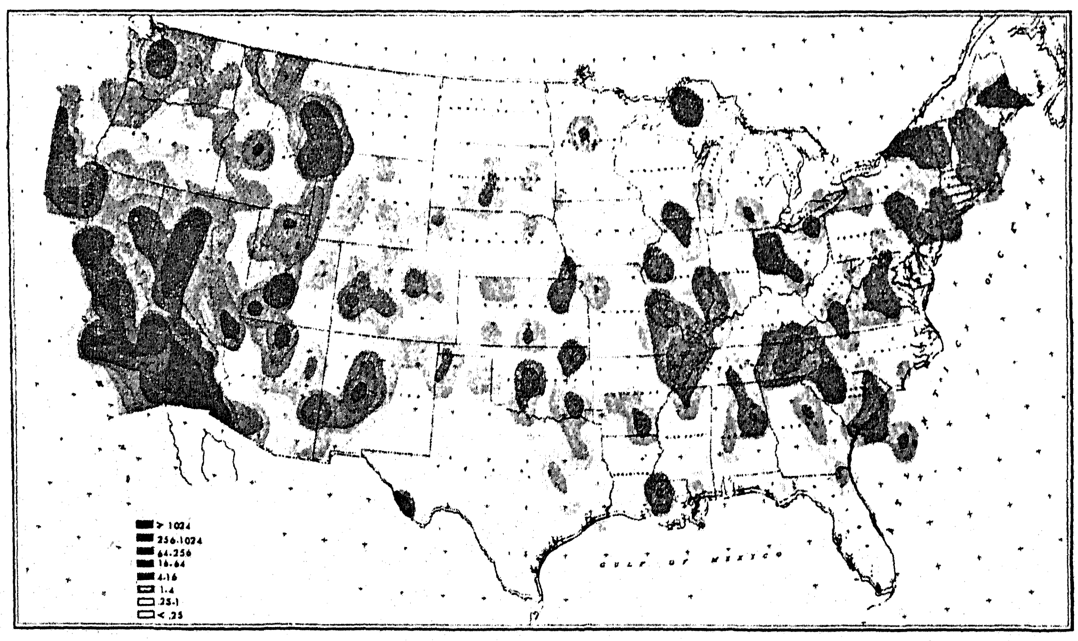

Figure 2 Strain release in the United States, 1900 to 1965, expressed as the equivalent number of magnitude four earthquakes

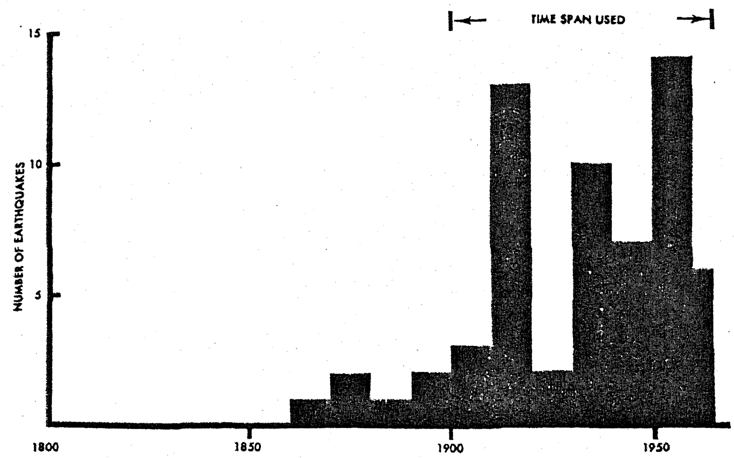

Figure 3 The number of maximum Modified Mercalli intensity VI earthquakes reported in each ten year period through 1965 (region 4 of Figure 5)

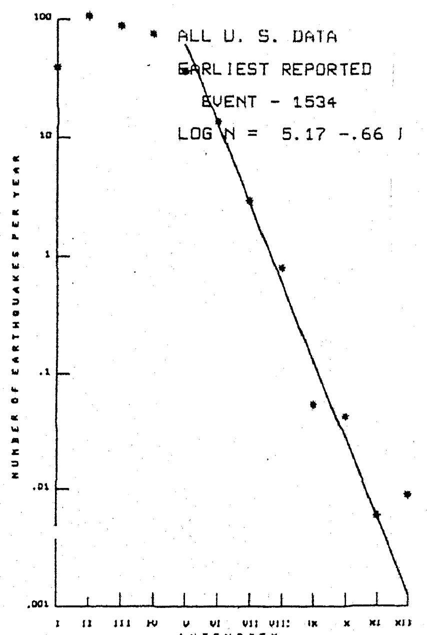

Figure 4 Frequency of earthquake occurrence (per year) vs. maximum M.M. intensity all U. S. data 1534-1965

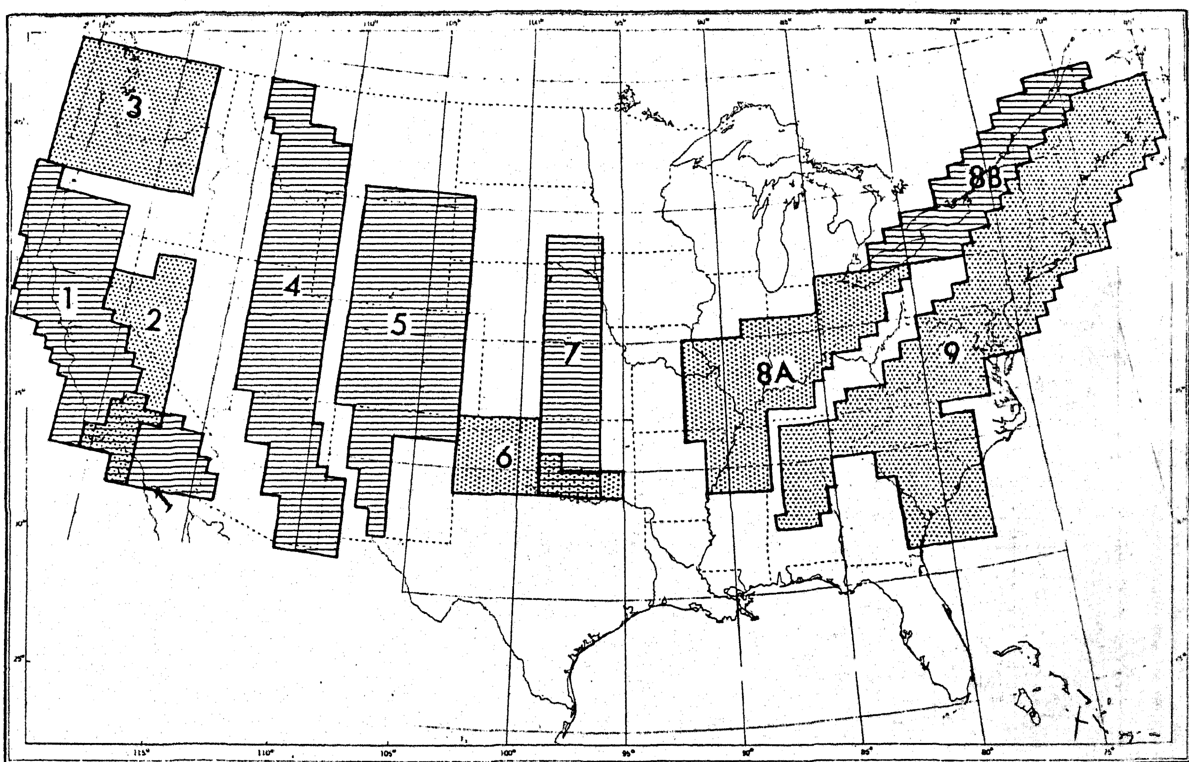

Figure 5 Location map showing the areas for which recurrence formulas were computed

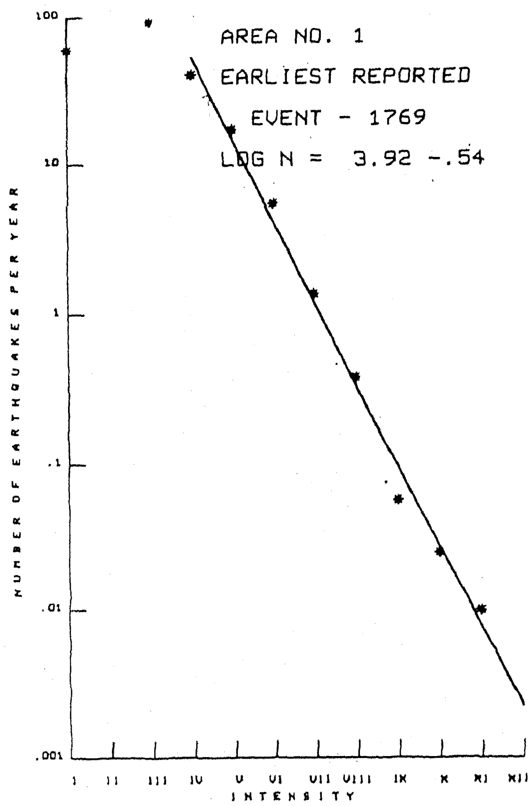

Figure 6 Frequency of earthquake occurrence (per year) vs. maximum M.M. intensity area 1, California

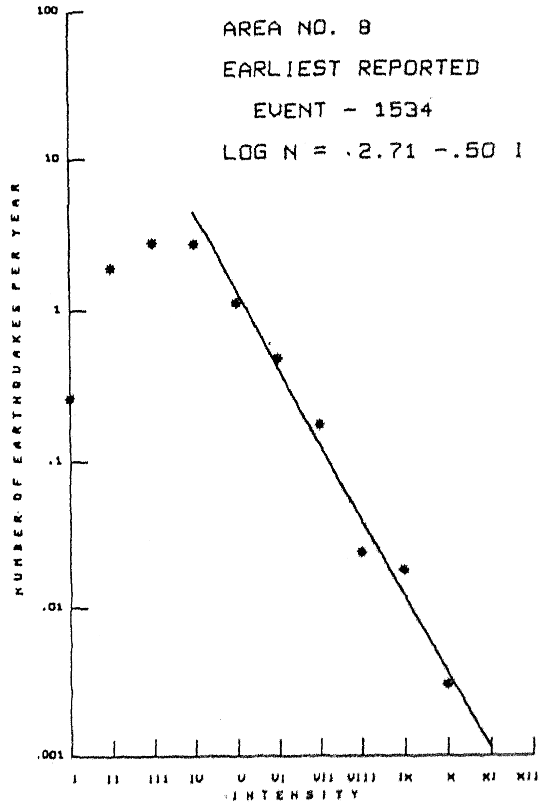

Figure 7 Frequency of earthquake occurrence (per year) vs. maximum M.M. intensity - area 8, Southeast Missouri to the St. Lawrence Valley

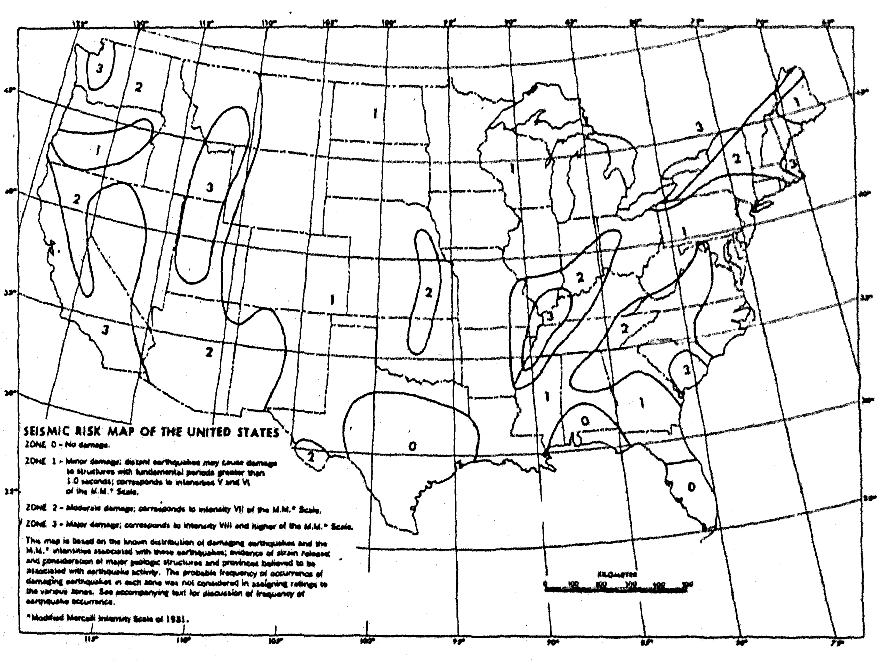

Figure 8 Seismic Risk Map of the United States :

TABLE I

SUMMARY OF EARTHQUAKE RECURRENCE FORMULAS

AREA	RISK ZONE	LOG N = a + b I (per year) a	b	EARTHQUAKES PER 100 YEARS V	VI	VII	VIII
1. 2. California, Nevada	3,2	4.11	-0.55	2290	646	182	51.3
1. California	3,2	3.92	-0.54	1660	479	138	39.8
2. Nevada	3,2	3.98	-0.56	1510	417	115	31.6
4. Montana, Idaho, Utah, Arizona	3,2	3.41	-0.56	407	112	30.9	8.5
8. Mississippi Valley, St. Lawrence Valley	3,2,1	2.71	-0.50	162	51.3	16.2	5.1
3. Puget Sound, Washington	3,2	3.45	-0.62	224	53.7	12.9	3.1
9. East Coast	3,2,1	3.02	-0.58	132	34.7	9.1	2.4
5. Wyoming, Colorado, New Mexico	3,2,1	3.66	-0.68	182	38.0	7.9	1.7
7. Nebraska, Kansas, Oklahoma	2,1	1.99	-0.49	34.7	11.2	3.6	1.2
6. Oklahoma, North Texas	2,1	2.10	-0.55	22.4	6.3	1.8	(0.5)

TABLE II

SUMMARY OF EARTHQUAKE RECURRENCE FORMULAS

AREA	RISK ZONE	EARTHQUAKES PER 100 YEARS PER 100,000 KM.^{2} V	VI	VII	VIII
1. 2. California, Nevada	3,2	300	84.6	23.8	6.72
4. Montana, Idaho, Utah, Arizona	3,2	64.4	17.7	4.89	1.35
3. Puget Sound, Washington	3,2	68.0	16.3	3.92	0.94
8. Mississippi Valley, St. Lawrence Valley	3,2,1	24.2	7.65	2.42	0.76
7. Nebraska, Kansas, Oklahoma	2,1	13.0	4.20	1.35	0.45
5. Wyoming, Colorado, New Mexico	3,2,1	32.8	6.85	1.42	0.31
6. Oklahoma, North Texas	2,1	13.3	3.73	1.07	0.30
9. East Coast	3,2,1	12.8	3.39	0.88	0.23