PROBLEMS IN SEISMIC ZONING

by

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SYNOPSIS

The paper analyzes the problems of seismic zoning for engineering design and makes recommendations for future practice. The degree of data and judgment that are present in seismic zoning maps of different types is reviewed and the characteristics of the different forms of data are examined. A brief section is devoted to an assessment of micro-zoning and the theoretical calculation of surface motions.

It is concluded that a good seismic zoning map for engineering use should be simple, with broad zones, and should not be overly dependent on individual past earthquakes. In the writers' judgment, seismic zoning maps specifying design criteria should be drawn by knowledgeable engineers in each particular field, using more general scientific maps for data and guidance. It is concluded also that microzoning and the theoretical calculation of surface motions are not yet reliable methods for determining ground motions for design calculations; it is more appropriate to determine such motions by direct extrapolation from comparable recorded accelerograms.

INTRODUCTION

A seismic zoning map for engineering use is a map that specifies the levels of forces or motions for earthquake-resistant design, and thus it differs from a seismicity map that provides information only about the occurrence of earthquakes. Seismic zoning maps are practical tools in earthquake-resistant design because they provide useful guidance when it is not feasible to make thorough studies of the earthquake hazard at particular locations. Such studies can, in general, only be justified for large projects such as major dams, nuclear power plants, etc. It must be realized, however, that the forces specified by a seismic zoning map are only a part of the overall earthquake-resistant design procedure; to assess the true level of earthquake resistance implied by a design technique it is necessary to know the allowable stresses, strains, deflections, damping, ductility, etc., used in the design process.

The construction of seismic zoning maps is made difficult by the lack of adequate data, by the conflict between the needs for safety and economy, and by a lack of knowledge of the occurrence of earthquakes and the detailed character of potentially damaging earthquake motions. This lack of

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important knowledge is, of course, one of the major reasons for having seismic zoning maps, as it is unreasonable under these conditions to expect engineers specializing in design to make judgments about the earthquake hazards of a particular site. It is better for experts to apply the required judgment by making zoning maps. A map representing the compilation of the best available data and judgment of knowledgeable geologists, seismologists, earthquake engineers and design engineers is a practical necessity.

The undertaking of individual assessments of earthquake hazards at particular sites is an alternative to the use of a zoning map which is logically attractive and which has been used, for example, in California for determining recommended design forces for school buildings. Such investigations are not as thorough as those required for a nuclear power plant or a major dam and the results tend to be markedly inconsistent because of the combination of lack of basic data and different viewpoints and backgrounds of those making the assessments. A seismic zoning map that is based on all available information and which considers consistently the various features for a particular application would be better for the public as well as the design engineer.

The first seismic zoning map used in the United States was compiled by the U. S. Coast and Geodetic Survey in 1948 (1), revised in 1949 (2), (reflecting the 1949 earthquake near Olympia, Washington, and downgrading the region near Charleston, South Carolina from Zone 3 to Zone 2), and officially withdrawn in 1952 (3). The 1949 map, shown in Figure 1, was adopted, however, into the Uniform Building Code in 1949 and was retained there until 1970 (4), when it was replaced by the revised "Seismic Risk Map" developed by ESSA/Coast and Geodetic Survey in 1969 (5), shown in Figure 2. The maps now used by the Uniform Building Code (UBC) of the United States and the National Building Code of Canada are shown together in Figure 3. The maps are for the same purpose, but have been prepared by different groups. The maps are thought to be fair examples of the state of seismic zoning. Although the maps match at their common boundary in broad features, it is clear that seismic zoning, particularly in areas of moderate to low seismicity, is not yet a precise science.

The methods used to prepare both of the maps in Figure 3 are explained in papers published in the Proceedings of the 4WCEE. They are constructed on different principles, for example, the frequency of occurrence of earthquakes was not included as a factor in preparing the map adopted by the UBC, even though this is a very important factor for engineering purposes.

TYPES OF SEISMIC ZONING MAPS

A wide variety of seismicity maps, seismic zoning maps, etc., have been prepared, depending on whether the purpose of the map is to present basic data, to present data augmented by judgment, or to specify criteria for design; and it is important to distinguish among these different maps.

Within the last category there can be major differences depending on the application for which a map was prepared, as well as on the relative emphasis given to economy and safety. These maps can be categorized by the extent to which they portray a mixture of data and judgment.

Seismicity Maps. The simplest seismicity map is a plot of magnitude-rated epicenters of historical earthquakes and judgment enters only to the extent of interpreting the pre-instrumental history of the region, if included. Epicentral locations alone can be quite misleading, for they do not give information on the areal extent of strong shaking for large earthquakes. Because of this, seismicity maps are sometimes drawn on the basis of the Modified Mercalli Intensity Scale, or similar scales. Although such maps give a better indication of the areal effects of strong shaking, the interpretation of the intensity scales is highly judgmental, and maps based on intensities contain a much higher ratio of judgment to data than maps of epicenters. For regions in which the recorded seismic data is scanty, the Modified Mercalli "epicentral intensity" is often used in place of magnitude to rate epicenters plotted on a map, and such maps reflect the imprecision associated with the epicentral intensities, which may be very great.

If data were available adequate to define the frequency of occurrence vs. magnitude of earthquakes over a region, an earthquake probability map could be constructed. In most parts of the world, data is insufficient for this purpose, and much estimation must be employed.

An alternate method of presenting seismicity data that is sometimes used is to plot the distribution of strain energy density associated with historical earthquakes, resulting, for example, in a contour map of cumulative strain-energy density. The disadvantage of maps of this type from an engineering viewpoint, is that individual earthquakes are not identified, and the smooth variation of the contour plots may be misleading as to future ground shaking to be expected.

Fault Maps, Seismotectonic Maps and Seismic Probability Maps. Seismic fault maps are intended to show all faults on which movement has taken place within certain specified periods of time, e.g., in historic times or in the last 10,000 years. An example of a map of this type is shown for southern California in Figure 4(6). A great deal of judgment is involved in the preparation of such a map, even for historic earthquakes in readily accessible locations. Differences of professional opinion arise over the length of fault rupture, the differentiation of faulting from effects of slides, and over the inferred characteristics of subsurface faults. The difficulties are similar in the assessment of faults that have moved within recent geologic time, but the differences of professional judgment can arise over more major features and may revolve, for example, over whether a certain fault is active in the prescribed sense. Even if the fault is judged to be active, the probability of earthquakes of various magnitudes occurring on the fault can only be estimated imprecisely, so that the use of a fault map must be based on a very large measure of judgment.

We use the name "seismotectonic map" to describe a map which is essentially a fault map augmented by other geologic information, such as inferred tectonic processes, local geology, etc. There is a considerable

variety in the information that can be included in such maps and there is clearly a major component of judgment in the selection and presentation of the material.

A seismic probability map is sometimes constructed from a fault map by assigning probabilities of occurrence of earthquakes of different magnitudes to each active fault, and assigning areal distributions of intensity to earthquakes of different magnitudes. By this procedure a map is constructed that shows a probability of intensity of shaking. Large component of judgment and estimation are required to construct such a map.

Engineering Maps. The previously discussed maps present basic data combined with professional seismological and geological judgment, and are generally not directly useful to the engineers, whose need is for quantitative guidance regarding seismic loads to be resisted within certain allowable stresses, strains, etc. Maps prepared for engineering use can vary significantly depending both upon the intended applications and the interests of the individuals constructing the map. For example, a seismic zoning map for high-rise buildings might differ from one appropriate for short-period structures; a seismic zoning map for nuclear power plants might differ from one for single-family dwellings; and a map for use in southern California might logically differ in character from a map for use in India. Also, the need for some equipment to be portable or the requirements of manufacture may dictate a different type of seismic zoning map for special applications. An example might be equipment for elevators, for which uniformity of manufacture would suggest a single seismic zone for the entire western United States. An example of an engineering zoning map intended for electrical equipment in southern California is shown in Figure 5 (6). The different zones in the map are keyed to different levels of response spectra and scaled accelerograms.

Dissimilarities in engineering zoning maps arising from differing interests of the individuals preparing them are usually the result of compromises between the requirements of economy and public safety. A map made solely from the viewpoint of public safety would be based on the strongest credible shaking, and the frequency of occurrence of the shaking would not be a factor. On the other hand, a map zoned on the economics of providing earthquake resistance vs. the cost of repair would be based on the probability of strong shaking, and no special design for earthquakes would be required in zones where the return period of potentially damaging shaking was significantly longer than the average life of structures, regardless of the hazard to public safety should such shaking occur. It is easily recognized that most existing maps, including the U. S. map in Figure 3 and its predecessors, are compromises between these two extremes. In effect, a seismic zoning map is usually a reflection of the fact that economic considerations prevent the provision of the more complete protection otherwise desirable.

The construction of a map for engineering use clearly requires major input of judgment beyond that already embodied in the seismological and geological maps upon which they are based. We also note that factors other than technical matters have a legitimate place in the construction of seismic zoning maps for engineering purposes. Jurisdictional boundaries which

affect the administration of the zoning map may suggest convenient locations of borders of zones that are ill-defined by technical information. In fact, the oddly shaped boundaries of the seismic zones in the map in Figure 1 were employed to emphasize the lack of precision in the data on which the map was based.

RELIABILITY OF THE BASIC DATA

The most important basic data for earthquake-resistant design are the strong-motion accelerograms recorded at many sites throughout the world. An eventual goal for seismic zoning would be a map keyed to collections of strong-motion records sufficient to define the seismic loading in each zone. Unfortunately, the data do not yet permit this, and this goal will not be reached for many years. The present collection of data is sufficient to produce samples of strong shaking from major earthquakes recorded under a variety of conditions, and is adequate for defining probabilities of occurrence for large areas such as California and Japan. There is not, however, enough data to define with precision the motion expected at a site or the frequency of occurrence of earthquakes in a small area, nor has the strong shaking been recorded in a great, Magnitude 8+ earthquake.

The data represented by historic accounts of earthquake damage and by seismological measurements are one step removed from the problem because it is necessary, lacking strong-motion data, to infer the strength and character of the shaking. In the case of seismological measurements it is necessary to use some relation between a seismological measure of the earthquake, such as Richter Magnitude, and engineering measures of the strength of shaking, such as spectrum intensity.

Although Intensity Scales, such as Modified Mercalli, are intended to measure the severity of shaking, they are not defined to do this effectively. The most serious weakness is a failure to separate effects on engineered structures from general effects on people, objects and nonengineered construction. The higher ratings of these scales are also well known to be overly sensitive to effects exhibited by soils which can occur under a wide range of severity of shaking. In the light of current information it appears that a given MM Intensity rating can be produced by shaking of various strengths and durations, and the Intensity ratings of a given earthquake cannot be accepted as indicative of the severity of shaking in an engineering sense without further examination.

Empirical relations between Richter Magnitude and the level of strong shaking are more reliable, but the most common of these, which relate Magnitude and epicentral distance to maximum acceleration, are known from comparisons with data to be very approximate. For example, it was observed in the San Fernando earthquake that the peak accelerations at locations equally distant varied by a factor of two(7). Furthermore, by definition, the Magnitude is the maximum response in the long-period range, measured at distances of a 100 km. or more, whereas the peak acceleration is in the short-period range and is measured at distances as short as a few kilometers. It is not surprising then, that these quantities cannot be precisely related by an empirical equation.

Use of evidence of faulting in geologically recent but prehistoric times, and other tectonic information, is another step further removed from the problem. Judgment is required to estimate the possible occurrence of earthquakes from such data and also to infer the Magnitude of potential earthquakes. These judgments are often stated as additions to the historic record in terms of Magnitudes or Intensities, thus reducing the engineering problem to that discussed above.

MICROZONING AND CALCULATIONS OF SURFACE MOTIONS

Several methods have recently been proposed to calculate surface motions in earthquakes, given the occurrence of an earthquake of specified Magnitude on a specific fault. As shown in Figure 6, the main features from the point of view of calculating surface motions are the nature of the source mechanism, the effect of the travel path geology upon the seismic waves, and the effects of local site conditions on the surface motion. Some techniques begin at the source, while others begin at the base of the local site, with bedrock motion adjusted for the distance from the fault. When combined with a probabilistic estimate of the occurrence of earthquakes on the given fault, this becomes a form of seismic zoning, and such analyses have been used to estimate earthquake motions for the design of important facilities. If this approach is carried to its logical conclusion by identifying all sources of motion over a large area, such as the State of California, and attaching probabilistic estimates to each source in a consistent manner, the results could be compared with the historic record to assess the accuracy of the process. This has not yet been done, and it is our feeling that most studies of this type would, if done for a large area, result in probabilistic estimates for strong shaking that are significantly higher than can be substantiated by historic seismicity.

Efforts to calculate surface motions by beginning somewhere in the source—travel path—site effects chain are useful scientific studies that have as their goal the explanation of the nature of earthquake motions. Only the surface motions have been measured in strong earthquakes, however, and therefore it is not yet possible to distinguish the effects of assumptions about the different portions of the chain. The assumptions required are quite severe and, in our opinion, can involve errors exceeding those attendant on directly estimating the surface motion from extrapolation of recorded motions. Furthermore, strong-motions records obtained at El Centro (8) indicate that for firm soils, local site effects are less important than effects of different source mechanisms and travel paths. Similarly, the motions measured in Pasadena during the San Fernando earthquake showed behavior inconsistent with the usual results of calculation techniques (9). Such results, and the present lack of measured bedrock and source motions indicate that these methods are over-simplified, and are not at this time capable of reliably calculating the surface motion in most practical cases.

The use of microtremors and microseisms for seismic zoning is also a valid topic for scientific research, but does not yet appear to be a reliable method of seismic zoning for purposes of engineering. The principal difficulties are the observed nonstationarity of the motions (8), the unknown character of the sources of the motions, and the lack of correlation with the measured characteristics of strong ground shaking.

CONCLUSIONS AND RECOMMENDATIONS

Characteristics of a Good Map. A major feature of a good seismic zoning map is that it should not change substantially after the occurrence of an earthquake: this means that, if possible, the map should not be overly dependent on any one past earthquake. This is the weakness of maps formally derived from a history which is too short to establish the seismicity of the region under study. In a practical sense, the users of a seismic zoning map really want to know what earthquake ground shaking their structures will experience. Thus, it is unavoidable that the quality of a seismic zoning map is to a large degree dependent on how well it predicts the future occurrence of ground shaking.

Another major characteristic of a good seismic map is that it not be overly elaborate. In our opinion, it is a mistake to try to draw highly detailed maps or to put a lot of information on the map. Such refinements are not justified in view of the state of the basic data, and their presence forms a barrier to understanding by those who would use the map. A map intending to specify criteria for earthquake engineering design must do so unambiguously so the user will not have to make further judgments that are out of his area of competence. A map giving expected MM Intensities or a map showing expected maximum ground acceleration are examples of maps in a form not directly useful to the engineers.

A good seismic map for use in engineering design should be adapted to the particular needs and design practices of the users. Thus, it is to be expected that a seismic zoning map for tall buildings might differ in important details from one to be used for electrical transmission facilities. It is not good practice, in general, to adopt a map and associated design criteria that were developed for a particular application directly into a different application.

Ground Motions for Design. It is our judgment that the most appropriate way to select earthquake motions for purposes of design is to assemble a group of strong-motion records recorded under as comparable conditions as possible, and to extrapolate from these records, by simple scaling, the required motions. The records used can be augmented by artificial earthquake records if necessary. This simple approach seems best suited to the present state of knowledge, and makes clear to potential users the nature of the judgments involved. The more elaborate approaches that introduce additional approximations and estimations without providing any more basic data tend to obscure the distinction between information derived from reliable data and the results provided by approximate methods of calculation.

Construction of Seismic Zoning Maps. In agreement with other authors, it is our conclusion that a number of maps should be drawn with each group of workers preparing the type of map that is within its area of competence. For example, government agencies are the logical groups to prepare large-scale maps of seismicity, faulting, and other pertinent geologic features. Such maps would form the basic data for seismic zoning maps to be used to specify forces for design. It is important that maps specifying criteria for design be updated periodically. Such updating is required because of expected increases in the knowledge of earthquake effects, and because the earthquake protection

demanded by society changes with time, increasing directly with increasing urbanization and industrialization.

In view of the state of knowledge in the various disciplines that contribute to seismic zoning for engineering design, and the large judgmental factors involved, it appears to us that the only workable way to develop a seismic zoning map for the purpose of specifying criteria for design in a particular field is to convene a group of the most knowledgeable people in the field and have them construct the map. The group would have to review first the scientific maps and data, with advice as needed, and assess to its best judgment the degree of conservatism embodied in current design procedures. A seismic design map drawn by such a group should represent a reasonable balance of the various factors that are important to the earthquake-resistant design problems of their segment of the engineering profession.

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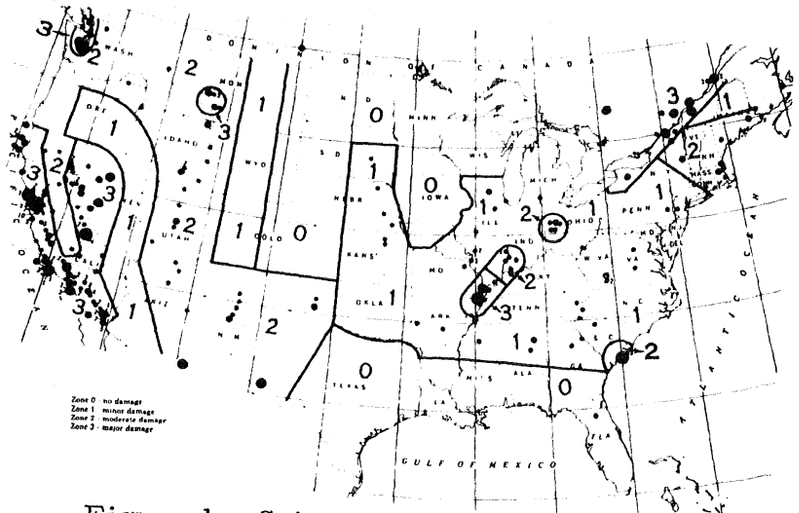

Figure 1. Seismic zoning map adopted by Uniform Building Code, 1949-1970 (2).

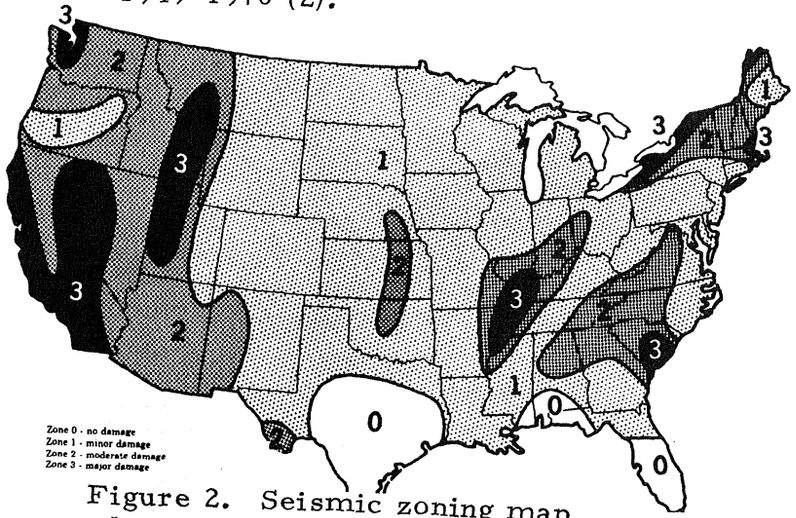

Figure 2. Seismic zoning map adopted by Uniform Building Code from 1970 to date (5).

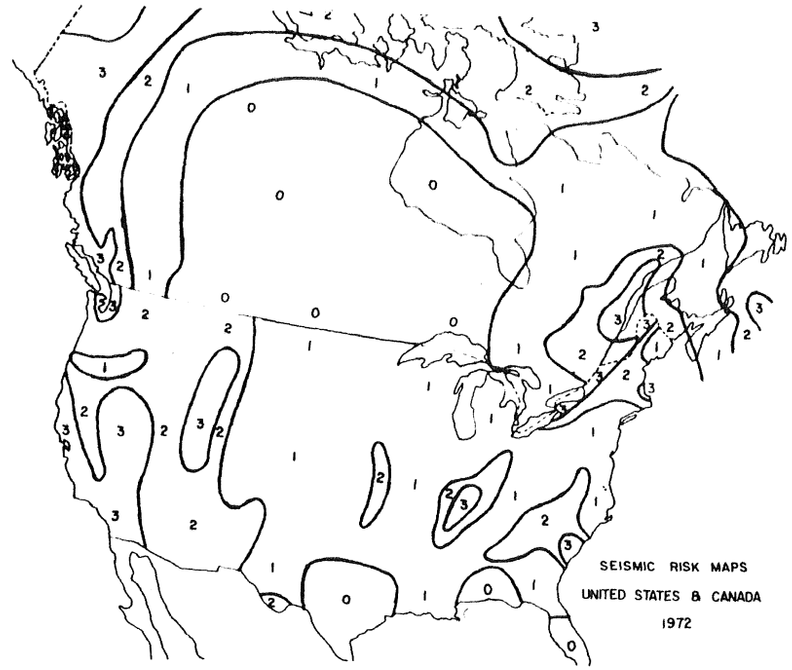

Figure 3. Comparison of seismic zoning maps now in use in building codes of Canada and U.S.

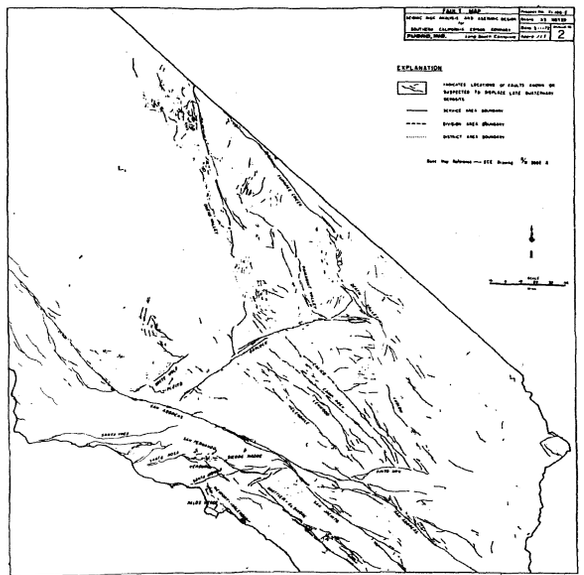

Figure 4. Fault map of southern California showing faults judged to be active within past 500,000 years (6).

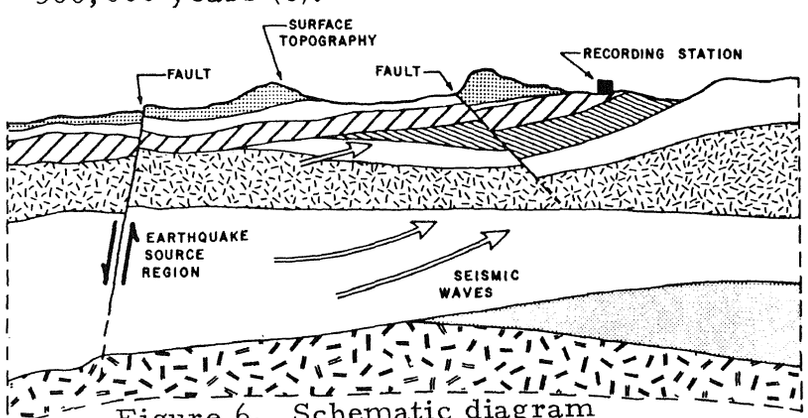

Figure 6. Schematic diagram showing relation of earthquake source, travel path, and local site conditions.

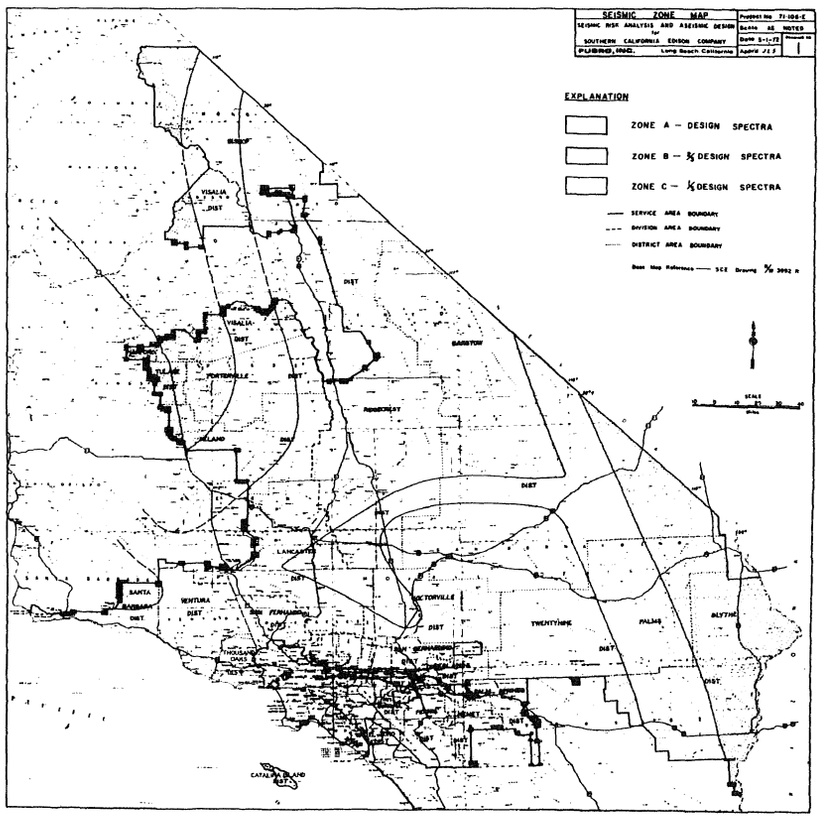

Figure 5. Seismic zoning map prepared by Fugro, Inc. for Southern California Edison Co. Intended use is for earthquake-resistant design of electrical equipment (6).