SELECTION OF DESIGN EARTHQUAKES FOR NUCLEAR POWER PLANTS

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SYNOPSIS

The philosophy of design for major structures, especially nuclear power plants, requires that initial units be designed to resist possible earthquake-induced ground motions. This paper is devoted to a discussion of the development of seismic criteria considering both the elastic design of structures for no loss of function and the elasto-plastic design of structures for safe and orderly shutdown (under the maximum potential earthquake conditions) Procedures for the prediction of earthquake ground motions, with emphasis on the relationship of tectonic history and seismic history, are discussed. Specific design examples are presented.

INTRODUCTION

This paper is devoted to a discussion of the development of aseismic design criteria for major structures with special emphasis on nuclear power plants. The fundamental problem involves the prediction of earthquake-induced ground motions for which critical structures need be designed. There are several considerations which must be taken into account in evaluating the potential earthquake hazard when designing a nuclear power facility. The first of these would be the economic consideration.

From an economic standpoint, the costs involved in shutdown of a facility resulting in, for example, loss of system power from a nuclear plant or hydro-electric dam, and the problem of repairing or replacing structural components which might be damaged during an earthquake must be evaluated. Most engineered structures have a fixed useful life. A study can be made of the relative cost of designing against earthquake ground motion which might be expected to occur during this economic life as compared to replacement or repair of damaged components and other consequent costs. That is, a comparison of risk versus the cost of protection against risks can be made.

It is usually possible to incorporate resistance to anticipated minor ground motions into the structure in the initial design without materially increasing the cost of the planned construction. For larger, but statistically more remote, ground motions, it might prove to be more economical to provide for future repairs to components which might be damaged during the anticipated earthquake than to design the structures to resist these ground motions.

Another consideration in selecting appropriate aseismic design criteria would be safety. Since failure of a nuclear power plant (or other major structure) would probably result in loss of life and great destruction of property, the engineer must design the power plant to resist earthquake ground motions to which the structure might conceivably be subjected.

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For nuclear plants, the engineer must do this for several reasons. He must first consider his moral and ethical responsibility. On a more practical basis, he must consider that it is possible that local opposition to construction will emphasize the earthquake hazard, and he must indicate to the local authorities that he has carefully considered and designed for this possible earthquake hazard. Furthermore, the Federal Government, in an attempt to safeguard the rights and well-being of the populace, demands that nuclear power facilities be designed to resist any potential earthquake ground motions.

CONCEPT OF TWO DESIGN EARTHQUAKES

Design philosophy for major structures should require the selection of aseismic design criteria of two types:

> Design Earthquake: The ground motion which might realistically be experienced by the structure during its economic life. The design earthquake is that level of ground motion which might, on an engineering basis, be considered possible during the life of the facility. Generally, the structure should be designed to respond with no loss of function to this level of ground motion. Stresses in structural components should remain in the elastic range, and the facility should continue to operate at full efficiency during and after the design earthquake. Up to recent times this "expected" earthquake concept has been applied, albiet conservatively, to nuclear plant design in the United States. At the present time the "design or no loss of function" earthquake is arbitrarily established at one-half the maximum potential earthquake subsequently described. As a further conservatism in the design, the maximum credible accident (with a safety factor) is also postulated to occur at the same time as the "design" earthquake.

> Maximum Potential Earthquake: The maximum level of ground motion which might be conceived as occurring at the site at any time in the future is referred to as the maximum potential earthquake. To compare this with other engineering concepts we might consider design floods. Following this analogy, the maximum potential earthquake might be considered the one in 10,000 or more year shock. The structure must be designed for a safe and orderly shutdown during the occurrence of the maximum potential earthquake. Stresses in structural components of a nuclear power plant would be permitted to enter the plastic range. Although partial or total collapse of the structure might be permitted to occur, maximum precaution against loss of life or contamination of the environment due to the release of radioactive pollutants must be provided. For nuclear plants the maximum credible accident is postulated as occurring (with no

safety factor) in conjunction with the maximum potential shock. The present terminology for this shock is "Design Basis Earthquake".

PROBABILITY OF EARTHQUAKE OCCURRENCE

Under these definitions, the ground rules for the investigation have been established.

Review of Seismic History - The first step in estimating the level of ground motion which might be experienced at a site during either the design earthquake or the maximum potential earthquake would be a review of the seismic history of the region in which the site is located. On the basis of this seismicity study, it then would be possible to statistically evaluate the possibility of similar activity in the future. A typical plot of the seismic history of an area is shown in Figure 1.

The record of seismic activity even in the most seismically active areas of the world is only a few hundred years in length. Therefore, the statistical approach to estimating the probability of earthquake occurrence is at best only a rough approximation. The accuracy of the approximation is directly proportional to the amount of seismic activity which has been recorded in an area. In seismically active areas, such as California and western Nevada, both the size and number of shocks can be estimated with a fair degree of accuracy. However, even statistical studies based upon world "averages" do not always give a satisfactory result. For example, statistically the world experiences one great earthquake (Magnitude greater than 8) per year. Yet as of this date (May, 1968) no great shock has occurred since March, 1964 (the Alaskan Good Friday earthquake)

In regions which are seismically "quiet", statistically no earthquake should occur in the future. However, no area of the earth can be considered completely immune from earthquake activity, and consideration must be given to some activity taking place even in these statistically inactive areas.

No matter what its limitation, comparison of the seismic history of various regions does, however, provide the engineer with an "index property" to assist in evaluating the earthquake hazard at a particular site.

Review of Tectonic History - In conjunction with a review of the seismic history of a region, a study of the characteristics of both regional and local structural geology should be made. Such a study would consider both regional and local faulting and structure, including size, location and history of recent tectonic activity.

Particular attention must be given to faulting (Figures 2 and 3) for several reasons. First, obviously, a fault indicates previous tectonic activity (whether during recorded history or prior to man). Continual crustal adjustment along a fault or structural belt indicates continuing regional earthquake activity. The geologic history and seismic history of an area generally correlate quite well (Figure 4). Secondly, fault displacement of any magnitude is very difficult to design against. In fact, as a result of the costs and the engineering problems involved in building across a fault, no one has yet designed a major structure to withstand fault displacement.

On the basis of the seismic history and tectonic history of a region, an attempt can then be made to relate known earthquakes to specific tectonic features. A review of theories of earthquake mechanism in the area, including such modern theories as seasonal river load, glacial rebound, etc., would be made. Where it is not possible to associate a particular shock to a known tectonic feature and a specific triggering mechanism, background knowledge of regional tectonics and the mechanism of earthquake occurrence in the region can be used to theorize on causes of local earthquakes. Thus, knowledge of the tectonics of an area truly aids one in selecting appropriate earthquakes for design.

The procedures described are applicable to any major structure. The selection of the appropriate earthquakes for structural design then is based upon the importance of the structure, economic comparisons, the degree of conservatism in the design, and the need for an appropriate degree of safety.

SELECTION OF DESIGN AND MAXIMUM POTENTIAL EARTHQUAKES

Having accumulated a thorough record of the seismic history in an area, and having related these earthquakes to known or suspected tectonic features or otherwise postulated the causes of these earthquakes, it is now possible to select the design and maximum potential earthquakes.

Design Earthquake: The design earthquake is generally a recurrence of some close historical event at or near the original epicenter. It is sometimes wise to postulate a recurrence of the design shock at the closest approach of any earthquake activity along its related geologic structure. Often several possible earthquake occurrences must be investigated and the design earthquake chosen as that which results in the highest level of ground motion at the site. Where the design earthquake selected on this basis results in very small ground motions at the site, it is usually economically prudent to incorporate a minimum seismic factor into the design of the critical components of a structure. This minimum seismic factor is usually taken as a horizontal ground acceleration equal to five percent of gravity for important structures founded in competent materials

Maximum Potential Earthquake: The maximum potential earthquake is generally a shock similar to the largest historical shock in the region at the closest credible approach to the site, consistent with geologic structure. In many cases, the possibility of unidentified faulting near the site, related in some way to the original shock, requires that the maximum potential earthquake be considered nearer to the site than the closest approach of known geologic structure. In other words, the less we know little about earthquake sources and geologic structures, the more conservative must be our assumptions.

The possibility of occurrence of the maximum potential earthquake is generally quite remote; however, the analysis of this design condition should be based on sound engineering judgment considering an event that is, in fact, credible and should not become merely the selection of arbitrary and perhaps ultra-conservative seismic design factors.

ESTIMATED GROUND MOTION

After the selection of the design and maximum potential earthquakes, various procedures and data are used to evaluate the expected ground motions at the site. These are as follows:

1) the site geology is carefully evaluated since ground motion at the site is very much a function of local geologic conditions (Figure 5);

2) location, size, depth of expected shock, as well as possible length of strong shaking are chosen;

3) observational and instrumental data from similar shocks at sites with similar foundation materials are used to predict ground motions (using information asprovided by Housner(1), Hershberger(2), Gutenberg and Richter(3), Cloud(4), and others); and

4) an analytical approach (using recent formulae of Kanai(5) is also used to evaluate the expected particle motion in basement rock at the site. This particle motion is a function of earthquake magnitude (either measured or estimated), depth of focus and epicentral distance. For sites on rock, design criteria can be developed directly in this manner. For sites on soil, particle motions in the waves generated by the earthquake are amplified by the overburden soils. This amplification of particle motion can be estimated be means of amplification spectra. Theoretically developed amplification spectra (as discussed at length by Donovan and Matthiesen(6) and Seed and Idriss(7)) indicate to what degree particle motion in the basement rock is amplified for incoming earthquake waves of various periods. The amplification spectrum is developed theoretically by various methods and is basically a function of site geology and size of earthquake (strain level).

METHODS OF PRESENTING DATA

Seismic design criteria for both the design and maximum credible earthquake conditions can be presented in several different manners to meet specific requirements on the part of the design engineers. In its simplest form, the criteria for aseismic design can be presented as a horizontal ground acceleration or "seismic factor". This seismic factor, when multiplied by the total imposed vertical load, will indicate a lateral thrust for which the structure need be designed. This method is really only applicable to rigid structures (low natural periods) which will move as part of the foundation materials during an earthquake. However, a seismic factor can be related to building code design parameters.

Design recommendations can be presented in the form of response spectra which indicate the estimated response of the structure subjected to earthquake ground motion. The spectra are presented over a range of frequencies corresponding to the natural frequencies of the various structural elements. The spectra represent the maximum amplitude of motion in the various elements of the structure for typical degrees of damping (Figure 6).

For structures founded on rock, a response spectrum can be developed using instrumental data which are available for response of structures on rock during certain earthquakes. These data would be normalized or scaled to the specific design acceleration recommended for the site.

For structures supported on what may be considered "average" soils, response spectra to be used in design can be the average spectra developed by Housner(8). These spectra are based on available instrumental data for response of soil-supported structures from four California earthquakes.

/Response spectra can be developed for a specific site which consider the amplification characteristics of the overburden soils. The procedure would be to select typical response spectra for structures on rock, and to use these spectra in conjunction with the amplification spectrum for the particular site. The response spectrum for structures on soil is developed by multiplying the response motion of a structure on rock at a given period by the soil amplification corresponding to that same period. The resulting curve plotted over a range of periods would provide a response spectrum tailored to specific site conditions. In all cases, recorded earthquake sizes and epicentral distances should be somewhat similar to the design cases./

A recently developed analysis procedure consists of determining the response of structures to earthquake loading by subjecting a mathematical analog of the structure to a digitized earthquake accelerogram. In this case, aseismic design criteria would consist of recommendations for suitable earthquake accelerograms to be used as input into the analysis, and appropriate scaling or normalizing factors for the design and maximum potential earthquakes. This earthquake accelerogram can be the original strong motion record of a shock with a similar time history to the design and/or maximum potential earthquakes. The strong motion record should have been recorded at a site with similar subsurface conditons to the subject site and similar magnitude and epicentral distance characteristics. In addition, the statistical problems inherent in using just one earthquake record must be recognized. Where it is anticipated that the design and/or maximum credible earthquakes would have a different time history than those shocks for which strong motion records are available, these strong motion records may be modified to suit the specific design conditions. These modifications included altering spectral content, repeating portions of the record as well as normalizing to appropriate ground motion levels.

DESIGN EXAMPLE

An example of how this approach to selecting aseismic design criteria has been used in practice is presented herein. An engineering seismology study was performed for a nuclear power station in upstate New York. The plant site is located in west-central New York State near the town of Oswego on the south shore of Lake Ontario. The foundations of all significant units will be placed upon the competent sandstone-shale bedrock of the area, the Oswego sandstone. The study was performed in the following manner:

Review of Seismic History: A comprehensive study was made of the seismic history of the northeastern United States and southeastern Canada, including the seismically active St. Lawrence Valley region. Particular emphasis was given to the seismicity of west-central New York State. All available publications of both the United States and Canadian Governments as well as other agencies which catalog earthquake activity in this area were studied. In addition, university professors and prominent local individuals having information regarding local earthquake activity were interviewed.

The length of record was quite good, extending as far back as 1534. One point noted in this study was that a number of the earlier shocks may have been over-rated. The result of this review of seismic history indicated that, although the number of earthquakes occurring in the northeastern United States and eastern Canada is fairly high and several major shocks have occurred in the St. Lawrence River Valley, the locale which the site is located is seismically inactive.

Study of Tectonic History: In reviewing the geologic history of the region, it was apparent that very little tectonic activity has taken place in western New York State. There is no evidence of major faulting or structure in the bedrock region. This review of all available geologic literature was supplemented by field reconnaissance and interviews with knowledgeable local individuals to confirm this fact.

Most of the minor earthquake activity in west-central New York State appears to be related to readjustments along zones of weakness in the bedrock. The readjustment is most likely caused by differential rebound resulting from the retreat of the glaciers and subsequent release in pressure on the basement rock. The shocks are generally of fairly low magnitude and are rather infrequent in occurrence.

However, there is a considerable degree of seismic activity in the St. Lawrence River Valley northeast of the site. Many of these earthquakes have been of major proportion. These earthquakes are related to well-documented geologic structure referred to by some authors as the St. Lawrence Rift System. This block faulted structural system (as well as the corresponding trend of seismic activity) follows the St. Lawrence River southwest to the confluence with the Ottawa River and then trends to the northwest. This structural system is completely unrelated to the tectonics of western New York State, including the site area. The Canadian Shield, a stable platform, projects into the United States in the vicinity of the site. The faulting related to the Appalachians to the east of the site does not approach within about 50 miles of Oswego. Lowville, New York, marks the western extremity of known faulting. These areas are shown in Figure 7.

Selection of Design Earthquakes: On the basis of the review of seismicity and tectonic history of the region and site area, two possible earthquakes were considered in evaluating the design conditions:

1) an Intensity VI earthquake at a distance of about 50 miles (corresponding to the 1853 shock near Lowville, New York; and
2) an Intensity VIII (probably somewhat overrated) shock at a distance of about 110 miles (corresponding to the 1929 shock near Attica, New York).

The intensity of ground motion at the site due to the occurrence of either of these possible earthquakes would be barely perceptible.

Selection of Maximum Potential Earthquake: The possibility that the site in question will experience significant earthquake ground motion is quite remote. However, the maximum potential earthquake was considered to be the largest earthquake in the region at the closest approach to the site consistent with regional geologic structure.

The largest earthquakes in the region had their epicenters in the St. Lawrence River Valley. These earthquakes are related to the major block faulting in that area, which is in no way similar to the geology of the site area. It was considered, however, that the remote possibility exists that there is some relation between faulting of this St. Lawrence system and local faulting identified near Lowville, New York (scene of a small earthquake in 1853). This is indeed a conservatism, based primarily on our lack of information. The maximum potential earthquake for the site was therefore considered to be an Intensity IX earthquake (similar to a 1925 shock in the St. Lawrence River Valley) at a distance of about 50 miles from the site (corresponding to the local faulting near Lowville).

Estimated Ground Motion: Since ground motions at the site resulting from the two earthquakes considered in selecting the design earthquake would be very small, it would today be considered appropriate that a minimum horizontal ground acceleration equal to five percent of gravity be incorporated in the design. On the subject project, however, aseismic design was based only on the maximum potential condition.

In order to estimate ground motion which would result from the occurrence of the maximum potential earthquake, observational and instrumental data from similar shocks were evaluated to provide a range of possible design values. Then the formulae of Kanai(9,10,11) (since revised) were used to evaluate the expected particle motion in basement rock at the site, considering the earthquake size and epicentral distance.

The magnitude of the 1925 St. Lawrence shock was about 7.0. It was assumed that the shock was of shallow origin (which is characteristic of earthquakes in the northeastern United States). Utilizing these data and assumptions, a maximum horizontal ground acceleration of 11 percent g was calculated. Since the structure was to be founded on rock, it was not necessary to take into account any amplification characteristics of overburden soils in developing ground accelerations.

Methods of Presenting Data: On the subject project, the seismic design criteria for both the design and maximum potential conditions were presented in the form of horizontal ground accelerations and appropriate response spectra.

CONCLUSIONS

An attempt has been made to illustrate how a practical engineering approach can be used to develop seismic design criteria for major structures. The selection of the design and maximum potential earthquake conditions for a particular site can be raised to a level above that of arbitrary conservatism. Generally, we have found there is a relationship between tectonics and earthquake occurrence, and the tectonic history of a region must be very carefully evaluated and considered when attempting to predict the possibility of future earthquake occurrence in an area.

A useful contribution to the science of engineering seismology has been made by those who have developed seismic probability maps. However, these probability maps, which are based solely on the seismic history of the area without regard to tectonics or the mechanism of earthquake occurrence, must be used with judgment especially when one is dealing with a structure of extreme importance such as a nuclear power plant. The period of record for earthquake occurrence in the United States is not of sufficient length to insure that areas which are apparently seismically inactive will experience "no damage" from future earthquakes. On the other hand, an extreme degree of conservatism is introduced when two remote areas of earthquake activity, such as the St. Lawrence River Valley and Attica, New York, are arbitrarily connected without consideration of the respective geologic features. The region between these two zones of seismic activity happens to be one of the most stable, seismically "quiet" areas in the country.

As an ever-expanding system of earthquake monitoring stations adds to the supply of strong motion records, and as investigators use these data to improve the theory of earthquake wave propagation, soil amplification, etc., we will be able to refine the selection of aseismic design criteria. However, in the meantime, we must make full use of the tools available to us: engineering seismology, statistics, geology and geophysics, etc., in evaluating the earthquake hazard for construction sites.

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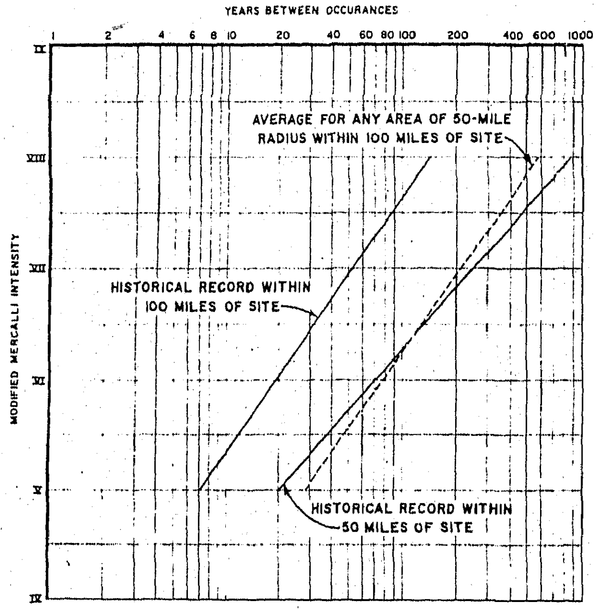

FIG. 1 PROBABILITY OF EARTHQUAKE OCCURRENCE

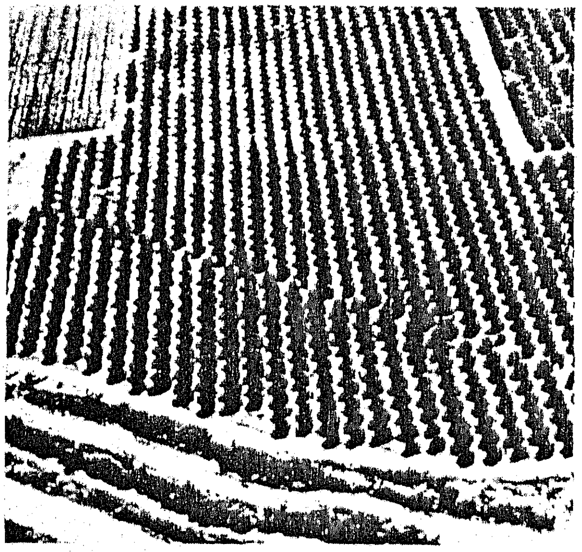

FIG. 2 AERIAL VIEW OF ORCHARD ACROSS IMPERIAL VALLEY FAULT

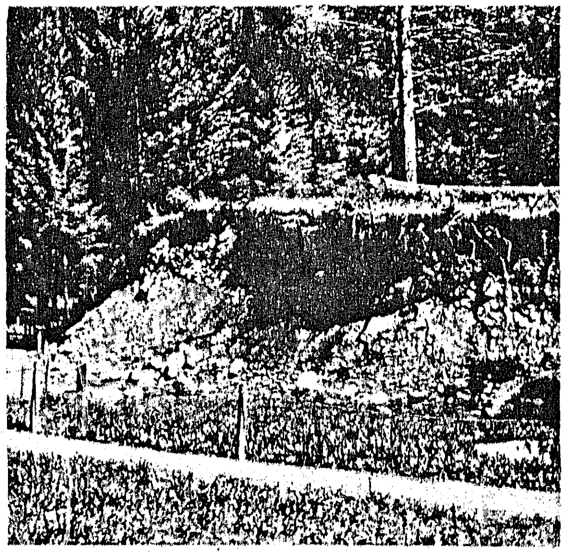

FIG. 3 VERTICAL DISPLACEMENT AT HEBGEN LAKE, MONTANA-1959

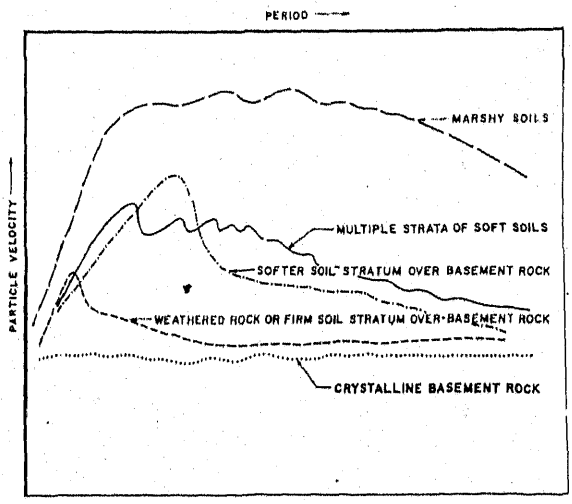

FIG. 5 TYPICAL POSSIBLE TTERNS OF GROUND MC

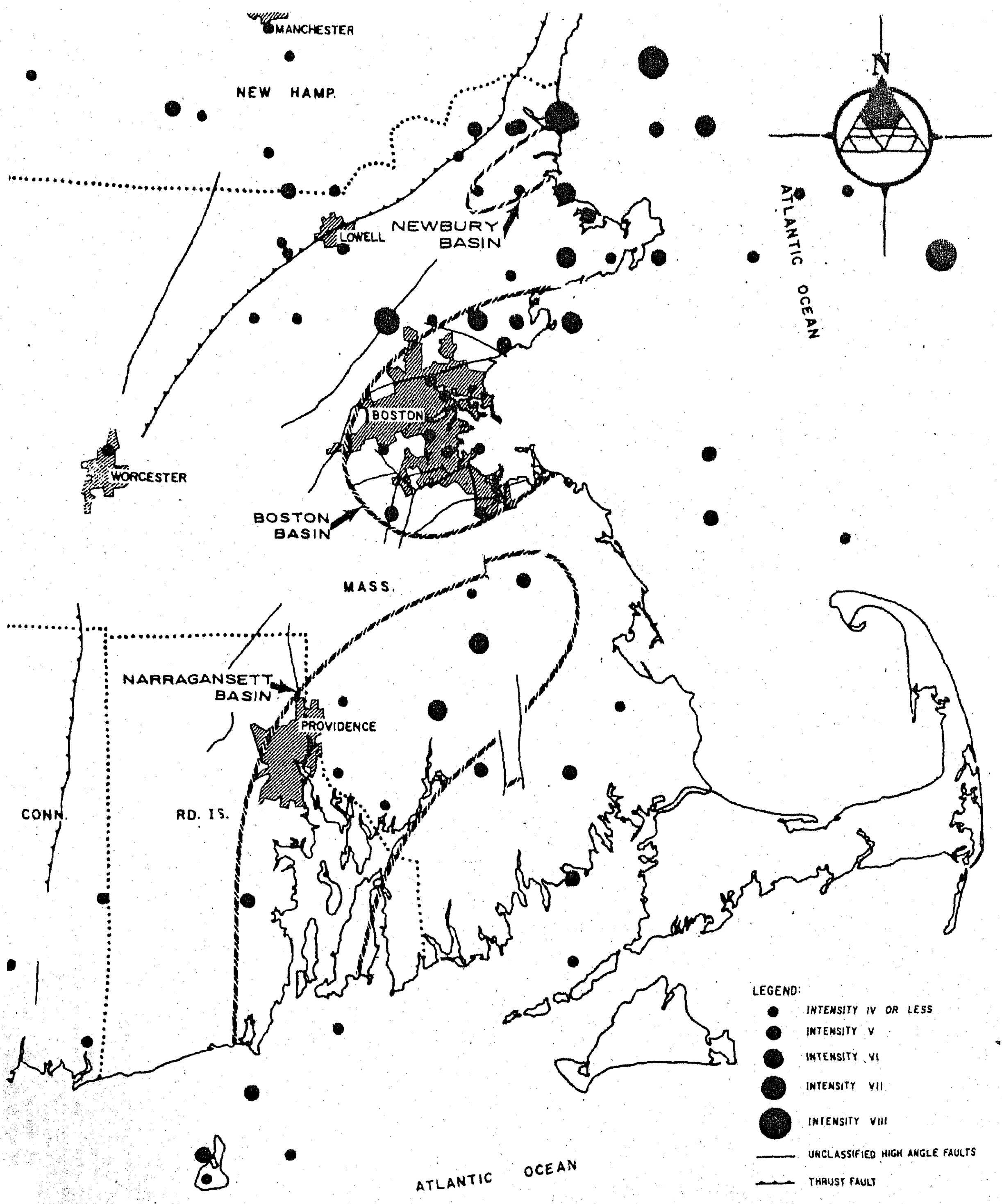

FIG. 4 STRUCTURAL MAP OF MASSACHUSETTS SHOWING EARTHQUAKE EPICENTERS

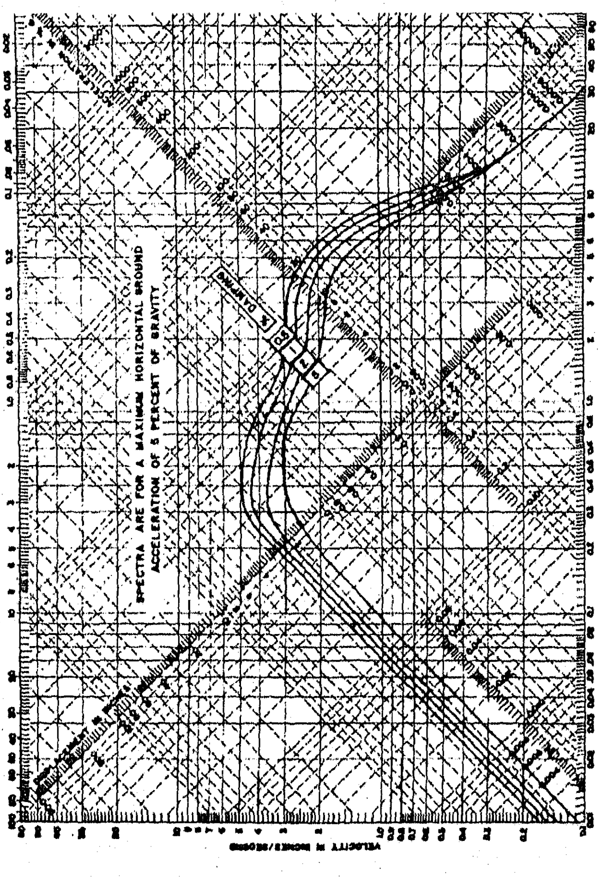

FIG. 6 RESPONSE SPECTRA

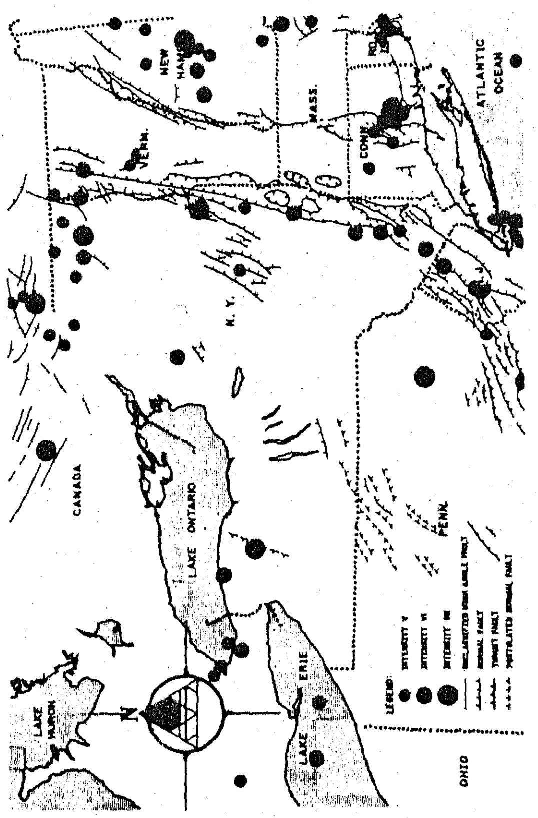

FIG. 7 REGIONAL TECTONICS