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IAEA SAFETY GUIDES IN THE LIGHT OF RECENT DEVELOPMENTS IN EARTHQUAKE ENGINEERING

A. Gürpinar, IAEA

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IAEA Expert

INTRODUCTION

The IAEA safety guides 50-SG-S1 and 50-SG-S2 are concerned with the derivation of design basis earthquake ground motion and earthquake resistant design considerations for nuclear power plants, respectively. Since the time of the development of the ideas incorporated in these safety guides, about a decade has elapsed and a review of some of these concepts is necessary, taking into account the information collected and new methods developed within this duration.

In this perspective, several issues emerge as dominant subjects of discussion. Within the scope of 50-SG-S1, collection of more and more strong motion data has permitted tentative results in development of attenuation relationships for various epicentral distances, geological conditions and earthquake magnitude. In particular, near field effects have been studied more closely and carefully. The same data base also enabled several attempts in reconstructing response spectral ordinates (instead of only peak acceleration values) using magnitude (or epicentral intensity), distance, geological conditions, etc. for specified levels of confidence. This is a step towards generation of site specific response spectra as opposed to a standard response spectrum anchored to a prescribed peak acceleration.

Also within the scope of 50-SG-S1, several European countries have launched programs of compilation and cataloging of historical seismicity. This has been considered as a viable alternative to the assessment of maximum earthquake potential based on 'fault dimensions' particularly in countries where surface faulting is very rare. Instead, a comprehensive earthquake data base with spatial and temporal homogeneity and extending back about 500 years, is considerered to give a sufficiently reliable indication of the maximum potential problem.

Surpassing historical seismicity in time, are the topics of seismicity documented by archeological evidence and paleo-seismicity. Even though the research in these are still rudimentary, through such research, the gap between the information on seismicity and tectonics as two separate entities is certainly narrowing.

Concerning the safety guide 50-SG-S2, three major subjects can be cited; (i) loading combinations which include seismic loads, (ii) two vs one level of design earthquake, (iii) PSA including earthquake effects. The first two are related and there is a current tendency, particularly in Western Europe, to adopt criteria incompatible with the recommendations of 50-SG-S2. Recently, the PSA studies are being considered as very useful in checking up various designs and pinpointing critical areas. Some studies have shown that, in fact, external loads and especially seismic effects may be very important as a PSA input.

The next two sections of this article will be devoted to the discussion of topics within the scopes of the IAEA Safety Guides 50-SG-S1 and 50-SG-S2 respectively. In particular, the results of some recent research which may have a bearing on the nuclear industry are highlighted. Conclusions and recommendations are presented in the final section.

DEVELOPMENTS RELATED TO ASSESSMENT OF GROUND MOTION

Estimation of Maximum Earthquake Potential

The IAEA Safety Guide 50-SG-S1 requires that, within the scope of the seismotectonic approach the maximum magnitude (or maximum intensity) associated with seismotectonic provinces or tectonic structures is estimated. This is done in order to have an appreciation for the maximum earthquake potential of the site. Therefore it is important to estimate the maximum earthquake potential of each of the seismotectonic provinces and the active faults within the region under consideration.

Estimates related to maximum magnitudes (or intensities) may be based either on the observed seismicity related to the seismotectonic provinces or active faults [illegible] phy[illegible] parameters of these structures such as the length of the fault, area of the fault plane, etc. The Safety Guide refers to papers by Bonilla, 1970, Mark and Bonilla, 1977, and Slemmons and McKinney, 1977, which support the latter approach.

It should be pointed out that the problem of estimating the maximum magnitude is still controversial due to the lack of data either in historical seismicity or physical fault parameters which can be associated with earthquake magnitude, depending on the region of the world. In California, for example, fault rupture - magnitude relationships yield fairly consistent results, and earthquakes in this area are generally caused by dominant and well established seismogenic tectonic structures. In contrast, historical seismicity data in all of the Americas is constrained only to very recent times. The need, therefore, arises to establish maximum magnitude based on recent seismicity and properties of the faults.

The situation in Europe, on the other hand, is very different. Generally, it is not easy to establish a definitive relationship between earthquakes and tectonic structures even for many events in southern Europe where the seismicity is high. This is mainly due to the lack of observation of surface faulting associated with earthquakes. However, for many parts of Europe there is generally a well documented history of earthquakes.

It is for this reason that a great effort is under way in Europe as well as in Japan and China, to prepare earthquake catalogues extending as far back as possible. An IAEA Technical Cooperation project entitled Seismic Data for Nuclear Power Plant Siting represents an international cooperation in this area for the countries in the Mediterranean basin. It is expected that this project will help the countries in their future activities related to nuclear power plant siting.

Recently, the research on historical seismicity has also extended to areas involving the compilation of archeological evidence regarding catastrophic natural events. A recent conference held in Antibes provided the occasion for the compilation of considerable information on the subject (APDCA, 1984).

There is also the interesting area of collecting and processing old seismograms which may yield additional information or different interpretation. This effort is particularly important for events which were recorded by a few instruments at the turn of the century. The proceedings of a recent conference held in Japan and sponsored by IASPEI/UNESCO contains valuable contributions regarding this topic (IASPEI/1984).

Finally, paleoseismicity has been used more and more frequently in recent years to estimate the age and frequency of prehistoric seismic events or earthquakes which were not otherwise documented. There have been some practical applications of paleoseismic techniques, particularly in the post earthquake microzonation studies of Ech-Cheliff (El Asnam) in Algeria (CTC/UNESCO, 1986).

[illegible] related to extreme value statistics which pr[illegible] [illegible] in the past decade. The ever increasing number of recorded earthquakes due to better coverage by seismic instrumentation also helps in increasing the reliability of statistical methods in general, (see for example, SECED, 1985).

Coming back to the recommendations of the Safety Guide 50-SG-S1, the major problem area is the difficulty in applying the empirical relations between fault parameters and earthquake magnitude when an obvious earthquake generating tectonic structure is not present. In a recent paper, Bonilla et al, 1984, investigate statistical relationships among earthquake magnitude, surface rupture length and surface fault displacement using a data base of 58 events. The faults are classified into five types; normal slip, reverse slip, normal oblique slip, reverse oblique slip and strike slip. The geographical distribution of the 58 events are as follows:

Turkey and Iran: 17
North and Central America: 17
China and Mongolia: 10
Japan: 6
Australia and New Zealand: 3
Greece and Bulgaria: 3
Africa: 2

It is interesting to note that, with the notable exception of the Balkans, there is no data from Europe and the only data coming from the Arab

States (i.e. Middle East and North Africa) belongs to the recent (1980) earthquake in El Asnam, Algeria.

Low Seismicity

The IAEA Safety Guide 50-SG-S1 makes an exception in its scope for nuclear power plants to be constructed in areas of low seismicity. Exactly this problem has been given a great deal of attention in the past decade. Countries in Northwestern Europe have tried to model both the occurrence of earthquakes and the strong ground motion due to earthquakes to be used in their siting and design of nuclear power plants.

In France, the United Kingdom and the Federal Republic of Germany, the nuclear industry have tried to adopt criteria compatible with the seismotoectonic setting of these countries. The fact that there are very few strong motion data available for such events makes this task particularly difficult. It was unfortunate, for example, that a significant earthquake which occurred in 1983 in Liège was not recorded by strong motion accelerographs. This event did attract, however, the attention of the nuclear industry in Northwestern Europe. Two conferences were convened, one in Liège and the other in Brussels, to discuss the effects and significance of this event (Min. Travaux Pub., 1985, Melchior, 1985).

Again, regarding the problem of low seismicity areas two other meetings may be mentioned. A NATO sponsored advanced research workshop was held in Utrecht on the Seismicity and Seismic Risk in the North Sea Basin (Ritsema and Gürpinar, 1983). More recently a conference took place in East Anglia on Earthquakes and Earthquake Engineering in Britain in 1985, (SECED, 1985). The problem of low seismicity is closely tied with other issues such as site specific near field response and one level design earthquake. These will be further discussed in subsequent sections.

Response Spectra

The response spectrum recommended in the IAEA Safety Guide 50-SG-S1 has been widely used in the aseismic design of nuclear power plants worldwide. This is a standardized response spectrum based on the horizontal components of eight earthquakes (sixteen records) where the smoothed ordinates correspond to the median plus one standard deviation, i.e. 84 percentile, of the response spectra of these points. This spectrum is anchored to the peak ground acceleration value at 33 hz. which is determined for each site. Once this value is chosen, however, the response spectrum is fixed at all other points, implying that specific site conditions as well as the travel path do not make significant difference such that the envelope response spectrum requires any modification. This spectrum was originally derived for the USNRC by Newmark et al, 1973. At the time of the derivation of this response spectrum, the number of strong motion recordings was only about 10% of the number which today exists in data banks.

Several authors have attempted a site specific statistical approach using this data base, i.e. deriving empirical relationships between spectral ordinates defined at a number of frequencies and magnitude, distance, soil conditions, etc. as a function of the confidence level. Among these, the works of Trifunac, 1980, Donovan, 1983, Campbell, 1985, may be cited. Recently Petrovski, 1986, analyzed some 150 records from Italian and Yugoslavian earthquakes (Fruili, 1976; Montenegro, 1979 and Irpinia, 1980) in a similar manner.

Studies also exist to correlate intensities and response spectrum ordinates (Trifunac, 1980). In particular, the French nuclear power plant siting program uses site specific response spectra based on intensities, magnitudes and hypocentral distance.

On the one hand, the amount of strong motion data collected after 1973 as well as the information regarding site geological conditions make it very reasonable to use site specific response spectra for nuclear power plant design. On the other hand, however, only a handful of major nuclear power plant suppliers exist in the world and designing, verifying and even checking of every item for a different set of site conditions, i.e. design response spectra is not a practical proposition. Consequently, recent trends have emerged in some Western European countries, who are also nuclear power plant exporters, where standardized response spectra of USNRC R.G. 1.60 have been replaced with design response spectra of narrower band with more emphasis on the higher frequency components. The purpose of this is to simulate the near field earthquake effects which generally control the design in Western European countries. This is a reasonably solution as long as the time history (especially the duration) is also adequately simulated. The spectral matching should be carried out not only for response spectral ordinates but also the power spectral density function, i.e. the frequency partitioning of the mean square value.

The problem arises when these nuclear power plants are exported to countries where the seismotectonic setting differs appreciably from that of Western Europe. The Horasan record obtained at a distance of 20 km in Eastern Turkey, for example, manifests unusually high spectral ordinates in the range 0.2 - 0.4 hz. This particular component significantly exceeds the USNRC R.G. 1.60 response spectrum for lower frequencies.

In Figures 1-5, response spectra of five recent earthquakes are presented. Superimposed on each figure is the standardized response spectrum of Newmark et al, 1973, scaled to the corresponding peak acceleration value.

DEVELOPMENTS RELATED TO EARTHQUAKE RESISTANT DESIGN

One Level vs Two Level Earthquake Design

As an extension of the issues of low seismicity and near field site specific response spectra the problem of one level vs two level of design basis earthquake is also a current topic of discussion.

The USNRC definitely requires a two level earthquake, SSE and OBE with the specific condition that the OBE peak ground acceleration is at least one half of that associated with the SSE. The IAEA 50-SG-S1 also recommends two levels, S2 and S1 where the latter may be based on probabilistic analysis but the former should be the result of seismotectonic considerations.

The recent tendency in Western Europe to adopt a one level earthquake is consistent with the seismotectonics of these countries and the low frequency of earthquakes of any damage potential. However, for countries with different seismotectonic conditions, the following points should be considered (Gürpinar, 1984):

- What are the safety margins (i.e. the allowable stresses) associated with the design of items against the S2 earthquake?

- What is the expected performance of the Category I items during a moderate (less severe than S2) but more probable earthquake affecting the nuclear power plant?

- What are the criteria for inspection after the occurrence of a moderate but more probable earthquake affecting the nuclear power plant?

It may be noted that the USNRC is in the process of reconsidering some aspects of the two level earthquake and in particular the condition that the OBE peak ground acceleration should be one half of that of SSE.

Loading Combinations and Environmental Conditions

The IAEA Safety Guide 50-SG-S2 recommends that the plant process loading conditions L1 (normal conditions), L2 (anticipated operational occurrences) and L3 (accident conditions) are combined with the design basis earthquake loads S1 and S2. One of the combinations suggested in 50-SG-S2 is as follows:

> "Consideration should be given to the need of taking into account appropriate combinations of the S1 and S2 ground motions with L2 and L3 conditions initiated by the failure or loss of function of items made to withstand the ground motions."

The recommendation involves, among others, a combination of the stresses due to the S2 ground motion with those caused by a large LOCA. More specifically, it is implied that a LOCA may be caused by the S2 earthquake even if the items whose failure cause the LOCA have been designed to withstand the S2 earthquake. The way in which these two loads may be combined is not clear, however, in the Safety Guide 50-SG-S2 and substantial interpretation and discussion is required before such a recommendation can be implemented.

One such interpretation, taken from Gürpinar 1984, is given below:

- "The primary coolant pressure boundary (PCPB) shall be designed to withstand the S2 level earthquake. It is therefore recognized that the catastrophic failure of PCPB (guillotine-type break) shall be assumed as a consequence of the S2 level earthquake. It shall be assumed that this impairment leads to a total load on the containment structure consisting of full load due to S2 earthquake and one half of the maximum load due to the guillotine-type break.

- The loading due to the S2 earthquake on the PCPB and high-energy piping within the containment shall be combined with the reaction forces due to 10% break assumed in critical locations of the major piping considered below."

These specifications are in line with the defence-in-depth approach for which a quantification of safety in terms of failure probabilities of items is possible.

Environmental conditions which are assumed to exist at the time of the S1 and S2 events are mentioned in the Safety Guide 50-SG-S2 in the following way:

"Environmental conditions and other natural phenomena assumed to exist for the purpose of carrying out each evaluation in this section should be chosen on the basis of a risk evaluation."

This paragraph is one of the few places in either 50-SG-S1 or 50-SG-S2 that a risk evaluation is referred to specifically.

Again, for illustration purposes, an interpretation of this general recommendation is given below (Gürpinar, 1984):

"For environmental conditions independent of the occurrence of S1 and S2, the following combinations shall be considered:

- The conservatively established mean value of the environmental condition (in particular design level of groundwater) shall be

- assumed to occur simultaneously with S2,

- A sufficiently conservative level, i.e. at least the 84 percentile, of the environmental condition shall be assumed to occur simultaneously with S1."

In this context, the most important environmental consideration is the level of water table to be assumed during the earthquake. As nuclear power plant structures are generally embedded, the uplift due to buyoancy has an adverse effect on these when combined with vertical and horizontal components of the earthquake input.

Further discussion related to probabilistic risk concepts including seismic effects will be presented in the next section.

Incorporation of Seismic Loads in PSA and PRA Studies

Within the last decade PSA and PRA (probabilistic safety assessment and probabilistic risk analysis) studies have contributed to the basic understanding of safety priorities in nuclear power plants. As earthquake loads are major contributors to the overall risk, it is necessary to pose the question of whether or not it is possible to include these as initiating events into PRA studies. The first requirement for this is to define the earthquakes S1 and S2 on a probabilistic basis.

Regardless of the regulatory position for the basis for evaluation (deterministic vs probabilistic) of the S1 or S2 earthquake, it is possible to calculate probabilistic estimates of exceedence levels of the vibratory ground motion levels corresponding to these earthquakes using certain assumptions for the stochastic nature of earthquake occurrence. A schematic diagram of such an approach is given in Figure 6.

Once these probabilities are assigned to S1 and S2, then a combination of these with other loads and accident scenarios may be accomplished to be used in PSA and PRA type studies. This requires a reliability analysis where the resistance parameters of the buildings or other systems are also expressed in terms of probabilistic functions.

More commonly these are identified using fragility curves derived from experiments or field observations.

Aside from the fact that seismic effects may be significant contributors to the overall risk, other considerations also necessitate including these effects into the framework of a PSA.

The first one is the consideration for events which may exceed the design basis earthquake (i.e. S2). This may be necessary for assessing the "what if" situation which arises in safety evaluations based on the defence in-depth concept.

Another use may arise in the specification of post-earthquake inspection programs. Typically, the S1 and S2 earthquakes have the same response spectral shape. This is a design simplification but generally is not representative of the true-state-of-nature. In some cases, it may be useful to consider, within the framework of a PSA, a typical earthquake response spectrum which may occur several times during the plant's lifetime, so that those items which may be overstressed during this "more frequent" event are identified in advance. This would be of particular importance if the response spectrum of this more frequent earthquake exceeds the design S1 spectrum in certain frequency bands.

Many PSA studies consider events up till the core melt. Seismic effects may contribute to the final risk even after this point. Some of these are listed below:

- increased probability of human error subsequent to the occurrence of a destructive earthquake,
- increased probability of leakage from the containment structure,
- significant probability of damage to lifelines and other infrastructures which may have been planned for use in the context of emergency planning and evacuation,
- increased probability of delayed response to the nuclear accident (by authorities and the public) due to the interference of another catastrophic event.

CONCLUSIONS AND RECOMMENDATIONS

In the light of the technical developments indicated above and the need of some countries to deviate from the recommendations of the IAEA Safety Guides, it is important to consider the following issues in the siting and design of nuclear power plants against earthquake loads. The IAEA could initiate and coordinate these recommended activities.

(1) The issue of maximum earthquake potential related to seismotectonic provinces or tectonic structures should be resolved taking into account adequacy of the data base both in historical seismicity and surface faulting for different geographical regions of the world. New developments in topics such as paleoseismicity should also be considered to be of importance in such studies.

(2) The exception which is made for "low seismicity" areas in the Safety Guide 50-SG-S1 should be considered and possibly a Technical Document should be developed to cover such areas.

(3) The use of standard vs site specific response spectra should be reconsidered in the light of new strong motion data. Standardized national spectra different from that recommended by the Agency should also be reviewed in this context.

(4) The question of one level vs. two level design earthquake should be considered particularly for countries of "low seismicity".

(5) Safety implications of the export of nuclear power plant design from certain countries to others having different seismotectonic conditions should be evaluated. The development of a Technical Document on this topic would be useful.

(6) Incorporation of new aseismic design provisions used in conventional structures (such as various base isolation systems) should also be discussed for nuclear power plants.

(7) Seismic effects should be included in the scope of PSA and PRA studies. A Technical Document on the subject would be very useful.

(8) Seismic effects in the siting and design of nuclear facilities other than nuclear power plants should be considered more systematically. In this context, nuclear waste disposal facilities should be considered with high priority.

(9) Several case studies of older nuclear power plants should be selected in various countries to review their seismic design characteristics in the light of current developments and aging problems. PSA would be a powerful tool for the evaluation of such cases.

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Figure Captions

Figure 1. Response Spectrum of Ancona 21 June 1972 Palombina Record E-W Component and Newmark Spectrum Scaled to Same PGA (0.24g), 2% Damping.

Figure 2. Response Spectrum of 15 October 1979 Imperial Valley Earthquake recorded at USGS Station No. 5165 and Newmark Spectrum Scaled to Same PGA (0.35g), 7% Damping (Taken from NUREG/CR-1665 Report, 1980).

Figure 3. Response Spectrum of 3 March 1985 Chile Earthquake N10E Component Recorded in Lolleo and Newmark Spectrum Scaled to Same PGA (0.67g), 5% Damping
(Taken from Celebi and Hanks, 1986).

Figure 4. Response Spectrum of 19 September 1985 Mexico Earthquake Recorded in Mexico City Station SCT and Newmark Spectrum Scaled to Same PGA (0.19g), 5% Damping.
(Taken from Celebi and Hanks, 1986).

Figure 5. Response Spectrum of 30 October 1983 Horasan (Eastern Turkey) Earthquake N-S Component Recorded at Meteorology Building and Newmark Spectrum Scaled to Same PGA (0.18g), 2% Damping.

Figure 5. Schematic Representation of Seismic Risk Analysis Methodology.

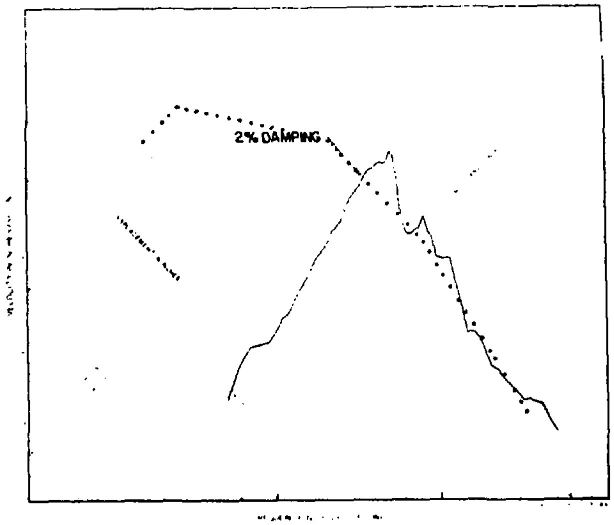
2% DAMPING

Fig. 1

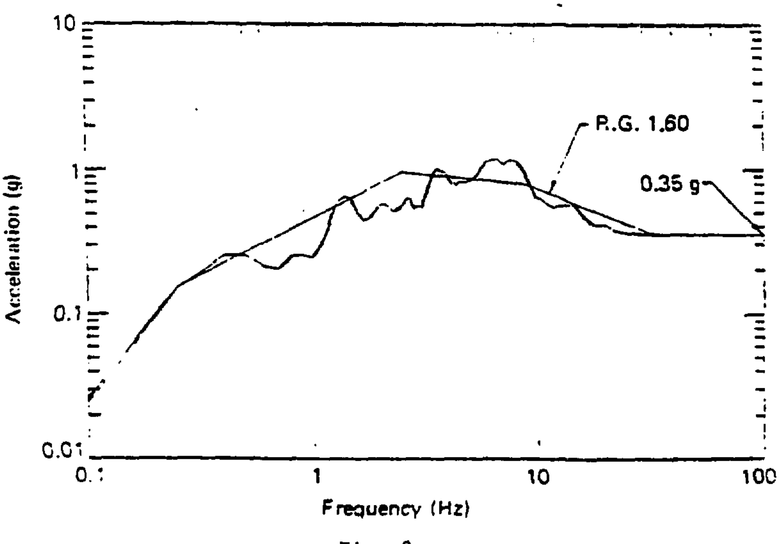
10
1
0.1
0.01
0.1
1
10
100
Acceleration (g)
Frequency (Hz)
R.G. 1.60
0.35 g

Fig. 2

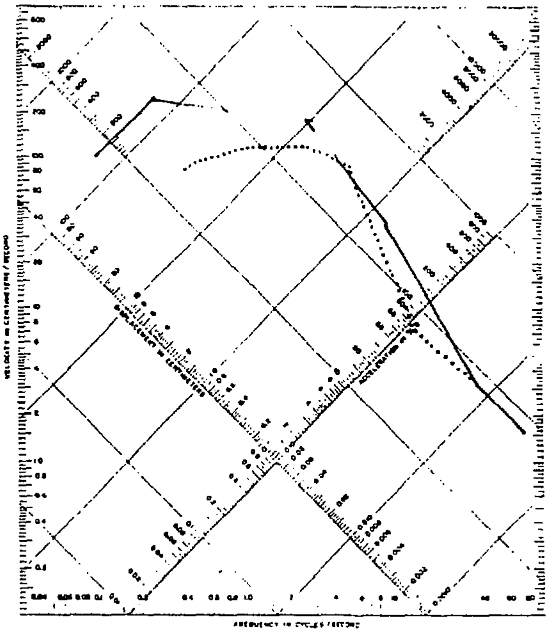
VELOCITY IN CENTIMETERS / SECOND
DISPLACEMENT IN CENTIMETERS
ACCELERATION IN G
FREQUENCY IN CYCLES / SECOND

Fig. 3

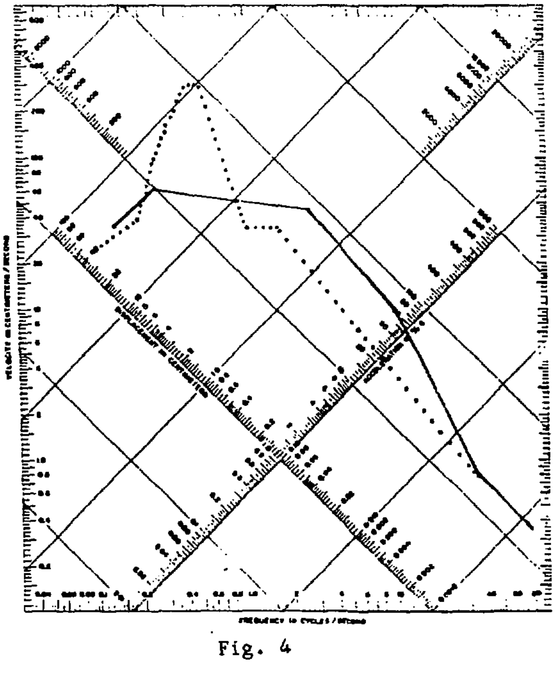
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Fig. 4

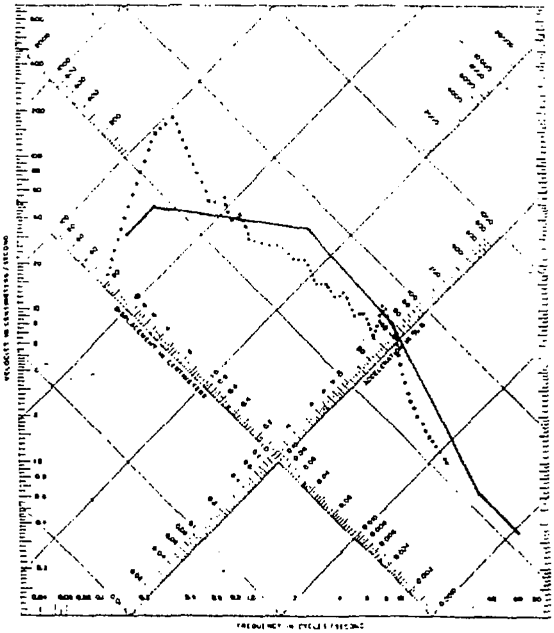
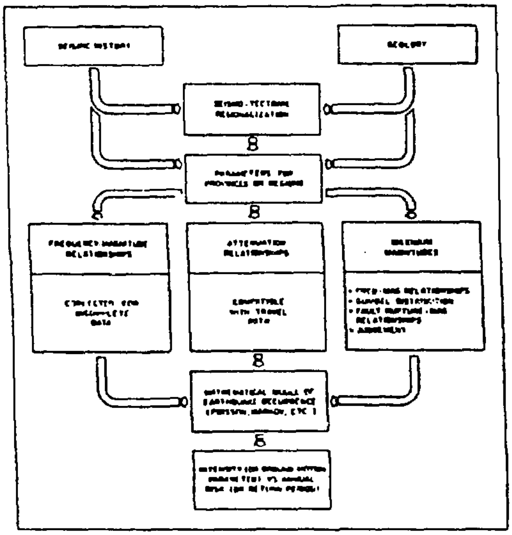


Fig. 5



Schematic representation
of seismic risk analysis methodology

Fig. 6