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THE EARTHQUAKE PROBLEM IN ENGINEERING DESIGN GENERATING EARTHQUAKE DESIGN BASIS INFORMATION

by

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Seismology Section

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ABSTRACT

Designing earthquake resistant structures requires certain design inputs specific to the seismotectonic status of the region, in which a critical facility is to be located. Generating these inputs requires collection of earthquake related information using present day techniques in seismology and geology, and processing the collected information to integrate it to arrive at a consolidated picture of the seismotectonics of the region. The earthquake problem in engineering design has been outlined in the context of aseismic design of nuclear power plants vis a vis current state of the art techniques. The extent to which the accepted procedures of assessing seismic risk in the region and generating the design inputs have been adherred to determines to a great extent the safety of the structures against future earthquakes. The document is a step towards developing an approach for generating these inputs, which form the earthquake design basis.

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THE EARTHQUAKE PROBLEM IN ENGINEERING DESIGN: GENERATING EARTHQUAKE DESIGN BASIS INFORMATION

(R.D.Sharma, Seismology Section)

1. INTRODUCTION

State of the art techniques in engineering design today allow mitigation of impending earthquake hazard, provided one knows:

- Where will the future earthquakes occur?
- What will be the frequencies of these occurrences?
- What will be the extent of energy release ?
- What will be their impact at a construction site?

The first three of the above questions are similar to those encountered in a long term earthquake prediction programme. The fourth one requires knowledge of the physics and geology of the earthquake source and the site regions, and of the medium through which the earthquake signals travel to reach the site. Further, one should know the nature of the impending earthquake vibrations at the site and response of the engineering structures to these vibrations. These questions do not have definite answers, and the issue can only be treated in a probabilistic manner. Estimating the probability of a site being affected by a destructive earthquake and minimizing the resulting damage through engineering design requires knowledge of:

(a) Earthquake sources in the region,

(b) Earthquake history of the region,

(c) Local site conditions including site geology,

(d) Elastic properties of the source to site transmission path of earthquake vibrations,

(e) Response of the engineering structures to elastic disturbances at different frequencies and damping conditions.

A serious difficulty faced in dealing with seismic risk problems arises from the inadequacy of the data available for assessing the damage which may be caused at a site by an impending earthquake, either from vibratory ground motions or from inelastic phenomena like surface faulting, slope instability, liquefaction and seismically induced flooding. In the absence of adequate data an approach of conservatism has to be adopted, which does not necessarily lead to safe, economic and most efficient designs. Calculations of ground motion parameters (displacement, velocity and acceleration, which are used to characterize the earthquake effects at the construction site) are always accompanied by an element of uncertainty depending on the reliability of the data, e.g. the frequencies of earthquakes of different magnitudes, the earthquake source parameters such as dimensions, type and orientation of the causative fault, nature of fault movement and source mechanism etc., as well as local site conditions. The effects of the uncertainty in the estimated design basis ground motion parameters may be translated into increase in costs of construction (see Figure 1).

Seismic risk in a region is dependent on the earthquake potential of the region. Assessment of the earthquake potential of a region is normally carried out through an examination of the earthquake history of the region. The assessment based on the historical earthquake data can be accurate only if these data are of a sufficiently long duration so as to represent the earthquake history of the region reasonably well. Except in some regions of China, where the earthquake history is as long as 3000 years, such historical earthquake data are not available. Ample evidence exists to suggest that during the times, for which historical records are available, all regions of the globe have not experienced the strongest possible earthquake. It is, therefore, beyond wisdom to depend solely on the historical records. One can recall that contrary to the ever believed stability of the Deccan shield the Koyna region was struck by a 6.5 magnitude earthquake on December 10,1967. Investigations in the region have subsequently revealed that the causative fault of this earthquake could have been recognized had adequate geological and seismological studies been carried out in the region with the objective of locating this fault. A major fault system has since then been discovered in this region (see Kaila et al.,1981) . There are several examples in the world by now where causative faults were confirmed (or discovered) after the region was struck by an earthquake. It is for this reason that there is a need to continuously update the seismotectonic and geologic data base.

Tectonic earthquakes are likely to occur only in regions where tectonic structures exist to allow accumulation of strain energy.

The size (i.e. magnitude or intensity) of an earthquake which could occur in a region depends on the capability of the tectonic structures to accumulate strain energy. If adequate investigations using modern field techniques are carried out to locate such tectonic structures, and estimate the rates of movement responsible for strain accumulation and energy release, earthquake risk in the area can be estimated more accurately, and corrective measures can be taken in design. If detailed investigations fail to reveal the presence of any significantly potent structures, and the region has been free from historical earthquakes during historical times, the probability of the region being struck by a strong earthquake in the near future may be considered fairly low.

A brief review of the earthquake aspects of siting and designing critical facilities in relation to the existing state of the art in engineering design and geophysical investigations is given here. This will help in formulating a procedure for collecting relevant geological and seismological information for selecting a seismically safe site and to arrive at a seismically safe design.

2. EARTHQUAKE PROBLEM IN ENGINEERING DESIGN

For a critical facility the problem of aseismic design encompasses three distinctly different areas, namely:

(a) seismotectonic evaluation of the construction site,

(b) application of the results of this evaluation in design to mitigate earthquake hazards, and

(c) to demonstrate the adequacy of the design, within the limits of acceptable risk.

Seismotectonic evaluation of the site aims at delineating tectonic structures, estimating the maximum earthquake potential associated with each tectonic structure and assessing the probable effects of the likely earthquakes. Acceptability of the site depends on the probability of occurrence of damaging earthquakes. Modern design procedures permit mitigation of earthquake risk through engineering design using the results of the seismotectonic evaluation, and demonstrate through analysis the adequacy of the design within the limits of acceptable risk. In case this cannot be successfully done the site has to be rejected. A site, and design, is considered acceptable only when consequences of each event at the site do not exceed the acceptable limits.

Information on earthquakes, which occurred earlier than the 20th century is available only for those regions of the globe where major earthquakes have occurred. In the post instrumental period (1960 onwards),the quality of earthquake data improved significantly on a global scale, but only for some regions which are well covered by sensitive seismograph. The detection capability of the existing worlwide standardized seismograph network (WWSSN) is much too limited (magnitude 4.5 and above) to allow collection of data on the more frequent earthquakes, which are smaller in magnitude, preventing a meaningful statistical analysis of the earthquake data. Further, a tectonic map of a region shows a large number of lineaments distributed over the area in a rather complex manner. Not all of the observed lineaments are the surface expressions of capable faults [A capable fault is one which has a significant potential for a relative displacement at or near the ground surface (IAEA,1979a)]. Again, among the capable faults all are not equally hazardous. For example, in a highly tectonic environment, a fault with a slip rate of 5 cm/year and a slip potential of as much as 10 meters during a single event may give rise to a large earthquake (M>7) every 200 years. In a less active environment, a fault with a slip rate of 0.0005 cm/year and a maximum slip potential of only 25 cms in one single event the recurrence intervals will be of the order of 50,000 years, and the maximum event will be of much smaller magnitude. The two faults, therefore, cannot be considered equally hazardous. The impact of geological conditions is also dependent on the age and degree of the most recent tectonic (or volcanic activity). For example, if the site topography was affected by faulting (or volcanism) during the late cenozoic times, the site may be considered unsuitable, whereas a similar topography in an older environment will be of much less concern.

A typical seismotectonic evaluation programme for a site may be illustrated through a set of questions which may be answered in yes/no (see APPENDIX A),though answering each question requires a large data base. Use of this questionnaire may lead to the development of an Expert System for Evaluating a site, and the site evaluation process itself (Shah et al.,1987). The efficacy of evaluation will naturally depend on the quality and quantity of the information available to support each answer.

2.1. EARTHQUAKE RELATED INFORMATION

The earthquake related information required for siting and designing a critical facility includes:

(i) vibratory ground motion (displacement, velocity and acceleration) likely to be produced at the site by an earthquake different frequencies and under different damping conditions,

(ii) geological hazards due to ground failure phenomena, e.g. surface faulting, liquefaction, slope instability, subsidence and collapse,

(iii) potential seismically induced flooding, and

(iv) foundation properties.

Engineering solutions are generally possible to mitigate, through design, the potential vibratory effects of earthquakes, and demonstrate the adequacy of the design measures but that is not so for effects arising from the ground failure phenomena. If it is not possible to demonstrate that engineering solutions existed to mitigate the effects arising from earthquakes, the site is to be rejected.

2.1.1. CHARACTERIZATION OF DESIGN BASIS VIBRATORY GROUND MOTION

Design basis vibratory ground motions, which are used as inputs to aseismic design, are generally defined as a set of displacement, velocity and acceleration response spectra (plots of the responses of single degree of freedom oscillators to the corresponding ground motion plotted as a function of natural frequency or period of the oscillator, see Figure 2) at various damping coefficients. Two levels of ground motions have been prescribed for a site of a nuclear power plant. These have been called the S2 and S1 levels in the IAEA terminology and the SSE (safe shut down earthquake) and the OBE (operating basis earthquake) in the USNRC terminology (IAEA,1979a ; USNRC,1980). The S2 level, which is close to the SSE level, determines the ultimate safety of the structures. It is that level of the ground motion which has a very low probability of being exceeded at the site during the operating life time of the nuclear power plant. The S1 level corresponds to the OBE, and is that value of the ground motion which can be reasonably expected to occur at the site once during this period. Inspection of the structures has been recommended after the occurrence of an S1 level event. Depending on their respective roles during operation different parts, components and systems of a nuclear power plant, are required to be designed for S2 or S1, or for both, levels (see IAEA,1979b). Whereas evaluation of these parameters is dependent on the knowledge of the seismotectonic status of the region around the site and site geology, uncertainties in the basic information will result in additional conservatism in aseismic design. Depending upon the state of this knowledge deterministic, probabilistic or empirical approaches may be adopted for the evaluation. IAEA (1979a) has suggested that S1 may be evaluated on the basis of a purely probabilistic or a combined probabilistic and seismotectonic approach while the S2 level should be estimated using a seismotectonic approach, taking into account the earthquake history of the region. Though knowledge of all the components of ground motion (acceleration, velocity and displacement) is necessary to fix the design basis, peak ground acceleration is normally used because of its familiarity and wide acceptance as a measure of lateral forces on high frequency structures (natural frequency higher than, say, 25 Hz). For intermediate (say, 1-10 Hz) and low frequency (less than 1 Hz) systems ground velocity and ground displacement data are more important. Ground velocity and displacement are generally better predictable than ground acceleration. The amplitudes of ground displacement are propagated more coherently than amplitudes of ground velocity or acceleration because their low frequency spectral composition is less sensitive to scattering by small geological inhomogeneities, and are therefore useful in wave propagation studies. Displacement time histories are also useful for determining seismic moments, stress drop and source dimensions.

The design basis ground motions are characterized by:

(a) Response spectra for various damping coefficients.

(b) Time histories of the earthquake signals.

Response spectra are the basic instruments used for transmitting the seismological parameters to engineering structures through design. In principle they should be generated from actual ground motion time histories, which could represent as closely as possible the earthquake ground motion resulting from the design basis earthquake. There are obvious difficulties in predicting the ground motion time history of the design basis earthquake. However, statistical procedures allow determination of spectral shapes with specified probabilities of exceedance (see Blume et al., 1973). Time history of actual ground motion is believed to be capable of providing an improvement in analysis over the response spectrum (which generally leads to over conservatism in design), provided the time history can be specified accurately. One way of arriving at the time history is to suitably modify the accelerogram from a past earthquake by adjusting the amplitudes and frequencies to the levels attributed to the design basis earthquake. In an alternative approach a synthetic time history compatible with the specified response spectrum is generated with predefined constraints from peak ground acceleration, total duration and envelope of the response spectra (Tsai,1972; Rizo et al.,1973; Shaw et al.,1973; Gasaparini and Vanmarcke,1976; Iyengar and Rao,1979; Ghosh and Muralidharan,1985).

Determination of the spectral shape of the ground motion requires a knowledge of relative influences of several parameters, namely:

(a) source spectral characteristics of earthquakes,

(b) attenuation characteristics of geological materials which transmit the seismic waves from the earthquake source to the site.

(c) ground motion modification characteristics of the site geology.

Depth of the earthquake source is an important parameter in design because, firstly, it determines the transmission path of the seismic signals from the earthquake source to the site and, secondly, it influences the partition of energy between surface waves and body waves, thereby affecting the response spectrum. However, the application of depth as a design parameter is limited because of the absence of adequate understanding of its role in a quantitative manner.

For elastic vibrations the earth acts as a filter, particularly for the high frequencies, so that the high frequency content of the seismic disturbance decreases as the recording station moves away from the source. It is possible to derive frequency dependent distance scaling laws, which govern the frequency filtering effects of the earth, provided adequate ground motion time histories from strong earthquakes have been recorded in the region (King and Hays,1977).

Attenuation characteristics of the medium play a very important role in the evaluation of ground motion parameters. The most suitable procedure for defining the seismic attenuation of an area is to use a set of strong motion records with adequate allowance for site geology (Schnable and Seed,1973, Schnable et al..1972). Isoseismal maps from past earthquakes prove helpful in specifying the attenuation law when accelerograms are not available (Howell and Schultz, 1975; Trifunac and Brady,1975; Murphy and O'Brien, 1977; Kaila and Sarkar, 1977).

Physical properties beneath the site modify the amplitude level and spectral composition of the ground motion significantly. Structures founded on unconsolidated material are frequently damaged by ground shaking. Buildings having a certain natural period suffer more damage from ground shaking when located on geological materials having similar characteristic periods because of the resonance phenomenon, where local geological material amplifies the ground motion in a period range that close to the natural period of the structure. When the unconsolidated material underlying a site modifies the seismic input, the amplitude of the surface ground motion increases in a narrow frequency band and decreases for the other frequencies. The amplitude of the amplified ground motion depends on a number of factors, e.g. shear velocity, density, damping, thickness of the layer, water content and geometry of the boundaries of the unconsolidated deposits. For the long duration high strain ground motions non linear effects also become important. The general effects of nonlinear behaviour are to decrease amplification level (relative to what would have occurred during a linear behaviour) and to lengthen the characteristic period. At low strain levels unconsolidated materials respond in a manner close to that predicted by the theory of elastic wave propagation. In strata above the base rock the seismic waves in the free field are amplified or attenuated depending on the frequency transfer characteristics of the strata and the the strain level of the vibration. Thus the response spectra of accelerograms obtained at the surface and base rock at the same site have different frequency characteristics.

One of the two alternative approaches described below is adopted for arriving at the response spectra for aseismic design.

2.1.2. SITE-DEPENDENT RESPONSE SPECTRA

Site-dependent response spectra are developed from strong motion time histories recorded at the site, or areas of similar seismic, geological and soil conditions by giving due consideration to site area absorption characteristics and the source mechanisms of the earthquakes affecting the site. Usually, actual earthquake records are obtained from ground motions of intensities lower than those defined for the S2 level event (and sometimes even for S1). This calls for certain modification in the spectra of the available time histories to account for the change in frequency characteristics associated with a higher strain level of ground motion before they can be adopted in design.

2.1.3. STANDARD RESPONSE SPECTRA

Generalized response spectral shapes with relatively smooth characteristics have been defined for application in regions where it is not possible to derive site-dependent response spectra. These spectra have been obtained by combining a set of response spectra derived from recorded earthquakes. These spectral shapes are used with appropriate scaling of the corresponding ground motion parameter (acceleration, velocity or displacement). Housner (1959) had produced a standard response spectral shape based on the ground acceleration values of four major and well recorded earthquakes, namely: the 1934 and 1940 imperial valley earthquakes (magnitudes 6.5 and 7.0 respectively), the 1949 Puget Sound earthquake (magnitude 7.1) and the 1952 Kern county earthquake (magnitude 7.7). A larger ensemble of accelerograms was later on used by Blume et al.(1973) to arrive at standard response spectra. These spectra became popular as WASH-1254 (or USAEC) response spectra. The earthquakes used in the derivation of these spectra had been recorded in the distance range 8 to 56 kms under varying site conditions (soil, rock etc.). In another technique Newmark and Hall(1969) related the response spectrum for a specified damping value to the peak values of the ground motion parameters through certain amplification factors. These factors were determined statistically from the response spectra of the 1940 Imperial valley earthquake. The standard response spectra of the Regulatory guide 1.60 (USAEC,1973) are based on this approach.

2.1.4. VERTICAL AND HORIZONTAL MOTIONS

It has been observed that vertical peak ground acceleration is approximately equivalent to the horizontal peak ground acceleration when fault movement has a large vertical component. On the average vertical peak ground acceleration is about two thirds of the peak horizontal ground acceleration, when fault movement is primarily horizontal. Same procedures are valid for evaluating the design response spectra for the horizontal and vertical directions, provided the corresponding time histories are used in computations. If specific information on the components of peak ground is not available, a ratio of the peak acceleration in the vertical direction to that in the horizontal direction in the range 1/2 to 2/3 has been suggested by the IAEA (1979a). It should, however, be noted that the scatter in the ratio of the two components is fairly large. For a set of eighteen earthquake records obtained from several earthquakes on rock sites, the ratio (A_v/A_h), where A_v and A_h represent the vertical and the horizontal peak ground accelerations respectively, has shown a ratio of 0.5 with a standard deviation of 0.22 (Ghosh et al.,1986). A direct implication of this observation is that the vertical peak ground acceleration cannot form the basis of arriving at the horizontal peak ground acceleration on the basis of this factor.

3. EVALUATING DESIGN BASIS VIBRATORY GROUND MOTIONS

Evaluation of the design basis vibratory ground motions requires arriving at response spectra and time histories of earthquakes against which the structures are required to be aseismically designed. Depending on the available data base two different approaches of evaluation are in vogue today. One is based on purely probabilistic methods while the other combines the probabilistic methods with seismotectonic considerations related to the known (and unknown) geological structures on the one hand and and the earthquake history of the region on the other. In both cases the aim is to estimate the level of ground motion that has an acceptably low probability of being exceeded at the site during the useful life of the structures.

3.1. PROBABILISTIC APPROACH

The purely probabilistic approach has been considered more suitable for the S1 (or the OBE) level ground motion, which is normally based on an event likely to occur once during the operating life of the nuclear power plant. For the S2 level motion, which determines the ultimate safety of the structures, it is desirable that all possible earthquake sources are considered, and an event (or a combination of events) having recurrence intervals of over several thousand years is chosen. Probabilistic evaluation of earthquake ground motion is based on:

(a) Earthquake history of the region,

(b) data on intensity of ground motion from historical earthquakes experienced in the region, and

(c) an acceptable probabilistic model to describe the phenomenon of earthquake occurrence in the region.

Generally a Poisson distribution model, characterized by constancy of the occurrence rate and independence between two successive earthquakes, is used (see Lomnitz,1976). Though global earthquake frequencies can be fitted into such a model, there are difficulties in its application to regional data. Availability of regional earthquake data is usually much too limited to construct a model and test its validity over very long intervals on a regional basis. For this reason a probabilistic approach has been recommended only for estimating the S1 level motion. Probabilistic considerations may be used for estimating the S2 level motion only when combined with seismotectonic considerations. A schematic diagram for estimating design basis vibratory ground motions using a probabilistic approach is illustrated in Figure 3. The probability, P(a) of a certain specified value **a** of the ground motion parameter being exceeded during the life time of the structures at the site is computed by evaluating the integral:

$$P(a) = \int_{M=M_o}^{M=M_{max}} \int_{S=a}^{S=S_{max}} P_1(M).P_2(S,M)\ dM\ dS \ \ldots\ldots\ldots\ldots (1)$$

Here $P_1(M)$ is the probability that an earthquake of magnitude M occurs in the region during the operating life time of the power plant and $P_2(S,M)$ is the probability that the corresponding ground motion parameter exceeds the value S. M_o is the magnitude of that earthquake, which can be considered of little consequence as far as engineering structures are concerned. Evaluation of this integral assumes an accurate knowledge of the location and frequencies of earthquakes of different magnitudes affecting the site during the life time of the nuclear power plant, a mathematical relationship between earthquake magnitude and the ground motion parameter and an attenuation law to convert the ground motion (acceleration, velocity or displacement) in the epicentral region to that at the site. The exceedance probability computed from equation (1) is related to return period T of the causative event through the relation:

$$T(a) = -L/\log_e[1.0-P(a)] \ \ldots\ldots\ldots\ldots (2)$$

where L is the life time of the structure in years. (see Lomnitz, 1976). The results of such an evaluation may be presented in the form of a return period v/s peak ground acceleration at a specified site (see Figure 4).

3.2. DETERMINISTIC APPROACH

The S2-level ground motion corresponds directly to the ultimate safety of the structures at the site, because it represents the maximum level of ground motion which is used in design and is that level of ground motion which has a very low probability of being exceeded. Its estimates have, therefore, to be based on the maximum earthquake potential of the region. 10 CFR 100-Appendix A (USNRC,1980) had outlined the investigations to be carried out for estimating the SSE level ground motion (which corresponds to the S2-level ground motion), and had recommended the use of a deterministic approach for converting the maximum earthquake potential associated with the site into the corresponding ground motion parameter. In this approach mathematical relationships between several fault parameters (e.g. length, width, rate of movement etc.) are related to the magnitude of the maximum credible earthquake associated with a fault (see Chinnery ,1969). A value is then assigned to each of the ground motion parameters on the basis of the magnitude of the maximum credible earthquake. Application of this approach requires reliable data base containing records of past earthquakes, and faults should have been investigated in detail to allow estimation of the maximum earthquake potential of the region in a this manner.

3.3. THE SEISMOTECTONIC APPROACH

Inadequacy of the data set required for constructing the models describing regional earthquake occurrence do not permit estimation of design basis ground motion parameters, S2 or S1 level, very accurately. Available information on the regional geology and tectonics have, therefore, to be combined with statistical procedures to improve upon the estimates in order to provide for a reasonable degree of conservatism. For this purpose the region around the site is divided into smaller units, called tectonic provinces, which are characterized by relative similarity of geological and structural features, and maximum earthquake potential of each such unit is assessed on tectonic considerations. Implementation of the seismotectonic approach requires the use of some basic entities, namely:

3.3.1. TECTONIC STRUCTURE

A large scale dislocation or distortion within the earth's crust extending over several kilometers.

3.3.2. TECTONIC PROVINCE

A contiguous geographical region characterized by a relative consistency of geological features contained therein.

3.3.3. FAULT

A tectonic structure along which differential slippage of the adjacent earth materials has occurred parallel to the fracture plane.

3.3.4. CAPABLE FAULT

A fault which has exhibited one or more of the following properties:

(i) Movement at or near the ground surface within the past 35,000 years or movements of recurring nature within the past 500,000 years.

(ii) Macroseismicity instrumentally determined with records of sufficient precision to demonstrate a direct relationship with the fault.

(iii) A structural relationship to a capable fault according to the two characteristics given above such that movement on one could be reasonably expected to be accompanied by the movement on the other.

Evaluation of design basis ground motion parameters in a seismotectonic approach is carried out on the basis of the maximum earthquake potential associated with the tectonic province in which the site is located, and the adjoining tectonic provinces. The maximum earthquake potential inside each seismotectonic province associated with specific tectonic structures or floating earthquakes, which could not be associated with particular tectonic structures, is evaluated. For the tectonic province, in which the site lies, the maximum earthquake potential associated with each tectonic structure is moved to an appropriate location on the structure closest to the site. The maximum floating earthquake potential is assumed to occur at a certain distance from the site. This distance is determined on the basis of investigations carried out to ensure that within this distance the possibility of active tectonic structures may be ruled out. Further, maximum earthquake potential (of both the above types) of the seismotectonic provinces adjacent to that of the site is assumed to be located at the boundaries of these provinces closest to the site.

3.4. DEFINING DESIGN BASIS GROUND MOTIONS

For defining the design basis ground motions, a circular area of about 300 kilometres radius around the site isinvestigated. To begin with the following data are collected and examined, depending on availability:

(A) SEISMOLOGICAL DATA:

(i) Dates, origin times, magnitudes/intensities and hypocentral parameters of past earthquakes including data on microearthquakes (earthquakes of magnitude less than 3 are called microearthquakes),

(ii) seismic velocity structures (crustal velocities as a function of depth for the compressional and shear waves),

(iii) strong motion earthquake records/ isoseismal maps from the site region, and other similar areas,

(B) GEOLOGICAL DATA:

(i) Characteristics of ground in terms of the lithological units,e.g. crystalline, volcanic, sedimentary, alluvial etc.,

(ii) stratigraphic details,e.g. superposition and extent and age of various stratigraphic units,

(ii) age of sediments,

(iv) subsurface characteristics,

(v) tectonic structure details with descriptions of lineaments, faults, suspected faults etc.

(vi) evidence for (or against surface faulting) from past earthquakes (see Bonila,1975).

(C) GEOPHYSICAL DATA:

(i) Observations on horizontal and vertical ground movements,

(ii) Gravity anomalies,

(iii) Magnetic anomalies,

(iv) Hot springs and heat flow measurements.

(D) MAN INDUCED EVENTS:

(i) Reservoirs in the area,

(ii) Mineral extraction activity,

(iii) fluid injection details.

The adequacy of these data for the purpose of arriving at the earthquake design basis is then examined, taking into consideration the definitions and the roles of the design basis ground motions. The S1 level motion is estimated on the basis of historical earthquakes, which have occurred in the region. It is estimated as that level of ground motion at the site, which has a definite probability of not being exceeded (say once during the operating life of the nuclear power plant). A wholly probabilistic approach or a seismotectonic approach combined with the probabilistic approach may be used to estimate the S1 level motion. The S2 level motion is to be estimated either wholly on the seismotectonic considerations or using a combined probabilistic cum seismotectonic approach. The S1 and S2 level estimates form the basis of specifying the design response spectra and ground motion time histories. The statistical nature of the estimation process allows the determination of exceedance probability levels, which can be associated with specified values of S1 and S2 and the ordinates of the corresponding response spectra. Depending on the seismic risk associated with a particular site, the uncertainties in the data base and the importance of the structures to be erected, the design basis may be fixed. For example, the mean value may be used for a site in a region of moderate seismicity risk conditions whereas $M+\sigma$ value (σ being the standard deviation) may be used for sites in regions of higher seismicity (see Blume et al.,1973). More than one earthquake may have to be postulated for determining design basis, and these may produce maximum vibratory ground motion at the site at different frequencies. In such cases the design basis is to be specified as a combination (an envelope, Mean or $M+\sigma$) of the response spectra for various damping coefficients. In that case each earthquake has to be described in terms of maximum intensity scale value or magnitude and distance from source to the site area. The evaluation procedure consists, broadly, of the following steps:

(1) A magnitude frequency relation and a maximum magnitude cut off is assumed for each tectonic unit (causative fault or a tectonic province).

(2) A seismic source model (point, line, area or volume source) is selected for each tectonic unit.

(3) An attenuation law for ground motions for paths between each tectonic unit and the site is assumed.

(4) Probability of exceeding the specified value of a particular ground motion parameter is estimated for each site source combination.

(5) The probabilities of exceedance from all tectonic units are combined to arrive at final figures of the ground motion parameters.

Ground motion parameters (displacement, velocity or acceleration) at the site are estimated (at a predetermined confidence level) by incorporating the influences of all potential earthquake sources and site area characteristics. Analysis of these data should enable one to classify a site broadly into a low, moderate or high seismic risk site. Such a classification, then, can be used in the final specification of the design parameters.

4. UPGRADING THE DATA BASE

Construction sites for nuclear power plants are, generally, chosen in areas which are not apparently seismically active. This is mostly due to the fact that recorded earthquake data from the region are sparse. By now it has become reasonably evident that no region on the globe can be taken as aseismic unless it has been proved so. The reason of absence of earthquake records could well be that there are no good seismographs in the area capable of recording commonly occurring earthquakes, and strong earthquakes may occur in the region, but at great time intervals. It is, therefore, desirable that as soon as a site is approved as reasonably acceptable the process of collecting data related with earthquake occurrence begins. The steps to acquire these data include:

4.1. A MICROEARTHQUAKE NETWORK

The very first question which needs to be answered in a site evaluation programme is whether earthquakes were currently occurring in the site region. It is for this reason that a seismograph network to record microearthquakes occurring within a twenty five kilometers radius, and locate them accurately (preferably within ±1 kilometer) is installed as early as possible. Data for a period of two to three years should become available before making a final decision (see IAEA,1985).

4.2. INTERPRETATION OF REMOTE SENSING DATA

Interpretation of landsat imageries (1:250,000 scale) to pick up all significant lineaments should be carried out independently. Areal photographs (1:25,000 scale) of two or three diffrent dates should be examined to see any possible changes that might have occurred due to fault movement in the area. Information from landsat imageries and areal photographs should be combined with geological maps to arrive at a coherent picture of the tectonic status of the region (McEldowney and Pascucci, 1979 ; Zall and Michael,1980).

4.3. GROUND TRUTH VERIFICATION

The tectonic features, which are suspected to be related with capable faults, must be verified on the basis of field checks by geologists. The evidence in favour of, or against, fault capabilty should be analysed in the light of the information collected from the field.

5. LIMITATIONS OF DATA USED IN ASEISMIC DESIGN

It must be noted that aseismic design is based on the information contained in the data base and certain procedures, judgments and inferences are used to translate this information into design parameters. The assumptions underlying this translation, and limitations of the data must be kept in view while vital safety related decisions are made. In connection with a review of a Californian site Jerry Eton, a USGS seismologist, once stated:

" It is hoped that this review will illustrate the tenuous nature of the scientific judgments that must be made, these judgments then serving as the body of 'fact' on which the engineering design of the plant will be based. The primary difficulty is that

the seismologist is called upon to make judgment that require large extrapolations beyond his professional experiences, and even beyond those of the science he serves. When such seismological judgments are shorn of qualifications and condensed to a convenient statement for engineering guidance, they take on unwarranted ring of certainty that belies their shaky foundations. The thread of responsibility is broken at this step, the seismologist believing that he has handed it over to the engineer, who reasonably feels that it remains with the seismologist" (cf. Meehan,1987).

The need of bridging the communication gap between the seismologist and the design engineer cannot be overemphasized. Sometimes, complications arise when expert opinion from outside is required while examining the information at hand, and to select from the possible alternative interpretations. The objective is to examine the collected information for its impact on design. Posing the problem to an expert to achieve the desired result is an important part of this activity. The response from an specialist confronted with a question on fault capability or magnitude of an earthquake may lead, though inadvertently, to incorect conclusions. It is, therefore, necessary to fully understand the position of the specialist on the issue under consideration, and the very basis of the position taken by him.

6. PROBLEMS OF REVIEW

Designing earthquake resistant structures is a multidisciplinary task requiring strong interaction between geologists, seismologists, engineers, administrators and reviewers. Collection of the data required for specifying the earthquake design basis is a lengthy task. The situation gets complicated on account of the variations in the data for the same event reported from different data sources. This is particularly so for the magnitudes/intensity of the historical earthquakes. Another area, where discrepancies occur are the geological and tectonic maps. Seismotectonic maps are not readily available, at least in India, where earthquake monitoring and geological mapping come under the purview of different agencies (IMD and GSI respectively). Seismotectonic maps for any site evaluation programme are to be prepared by superimposing information from different sources, using data of varying accuracy. Technological advances in acquisition and processing of remote sensing data, field geology and monitoring techniques have made it possible to find the answers of several questions related to fault capability, but that may not be within the the reach of the site evaluation team. (It may be existing in research institutions, and it might well be possible to take advantage of the development in a specific case). The codes and guides in any discipline, which normally reflect the existing state of the art lay heavy responsibility on the authors of site evaluation reports on the one hand and on the reviewers on the other. It is, therefore, necessary that a code of practice is adopted for the entire exercise including the *review*.

Earthquake design parameters are normally derived by using a forward process where one step follows the other. The review process is slightly different. If examination of every bit of information is undertaken, then the chances of the reviewer being fully satisfied are remote even if a voluminous report is presented for the review. Moreover, during the review it would be hardly possible to muster enough time and resources to go through the review exercise that way. A different approach has, therefore, to be chosen. One would look for specific information in the report, so as to establish the adequacy of the recommendations. This will need those facts (maps, numbers, formulae etc.) which were used in the report in arriving at vital decisions. It is, therefore, necessary that all such information is placed within the report before it is placed in front of the reviewer. If this practice is not followed, the review will not produce the desired results. Before placing the report in front of an independent reviewer, it is desirable that a preliminary inhouse review is carried out. For carrying out the preliminary review, the authors may be requested to answer the questions given in APPENDIX A. This will help the independent reviewers as well as a generalist involved in decision making, and establish a sound communication channel between the different parties including the regulatory body. This approach aims at establishing the quality of both the site investigations and the review process. Safety against impending earthquake hazard can be best demonstrated by first ensuring that the laid down procedures have been followed all through, from the site evaluation to the design and operation stage, and then that implications of all the collected information have been accommodated in design.

Increased public awareness, which has resulted largely due to the chain of catastrophes (not necessarily earthquake related) the world over, has placed additional responsibility on those involved in earthquake risk assignments. This is because the issue is related with public safety.A post accident analysis of the accident in the Chernobyl reactor has indicated that the accident was caused by violation of procedures. It is therefore absolutely necessary that once procedures have been laid down to carry out any saftey related investigations, they should be strictly followed at all stages. Only then safety against the impending hazard can be ensured. Dissemination of information at different levels plays a very important role in this respect. It is necessary that a balance is struck between witholding information as confidential and making it public. In this particular area, leaked information in a guarded environment can add to the confusion instead of preventing it. This is not, by any means, to suggest release of information as soon as it is collected, or not to disclose facts in the face of misgivings and controversies.

There may be situations when difference of opinion between the reviewer and the authors of the report are not resolved satisfactorily. The very concept of review implies that more weight would be given to the opinion of the reviewer. In this particular case the one associated with higher risk will take precedence over others.

7. CONCLUSIONS

A normal building code, for example the IS-1893, is not suitable for use in aseismic design of critical facilities, such as nuclear power plants. Elaborate investigations are required to determine the design parameters for a critical facility, and such investigations should be planned sufficiently in advance. Unless investigations have been carried out to look for a particular evidence, absence of evidence alone should not be used for supporting a judgment if its applicability determines safety. Experts play a vital rore in a site evaluation programe. This role must be fully recognized. The limitations of the basic information base and inferences of the evaluation must be well understood. Finally, in the review, it is necessary that adequacy of the site evaluation process itself is scrutinized before taking up the review of the results of evaluation.

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APPENDIX A

A TYPICAL QUESTIONNAIRE FOR SITE EVALUATION

1. Has evidence been looked for historical surface faulting?..yes/no

2. Have studies been carried out to describe the potential of surface faulting?..............................yes/no

3. Are all known faults in region listed? ....yes/no

4. Are dead faults identified?......................yes/no

5. Have the remaining faults been classified as capable faults?..yes/no

6. Has information been collected to describe the degree of capability for the faults,which have been classified as capable?...yes/no

7. Do the available earthquake epicentral data reasonably reflect the earthquake history of the region ....yes/no

8. Were additional investigations undertaken and completed for improving the data base:

   (a) examination of land sat imageries.......yes/no
   (b) examination of aerial photographs.......yes/no
   (c) ground checks of suspected faults.......yes/no
   (d) microearthquake studies ....yes/no

9. Whatever investigations were considered necessary for arriving at optimum design basis have been completed..yes/no

10. Are the basis of engineering and geological judgments and their limitations described in the report?........yes/no

11. Are additional investigations likey to alter the postulated earthquake design basis ....yes/no

12. If the answer to any of these question is 'yes', then the details of the investigations, the methodology used and the conclusions arrived at have been given...........yes/no

13. If the answer to any of the questions is 'no', the implications of the answer and the basis of the judgment applied and the associated limitations have been examined.
....yes/no

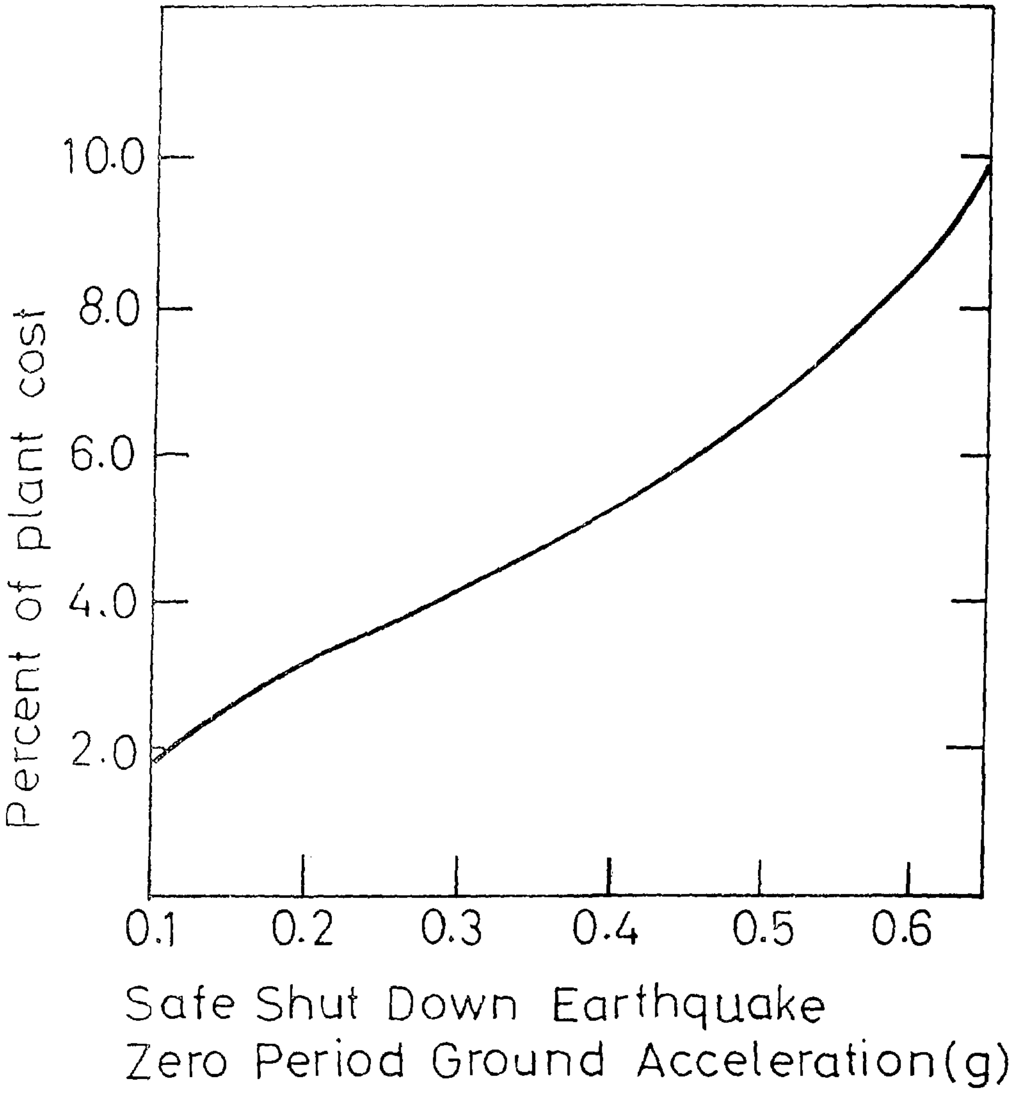
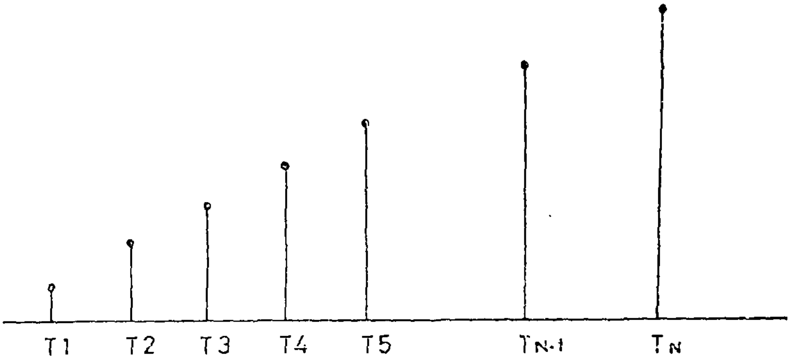


FIG. 1 Estimated cost increase in Aseismic Design of Nuclear Power Plants (USNRC - 1981)



HARMONIC OSCILLATORS OF DIFERENT NATURAL FREQUENCIES ($2\pi/T_N$)

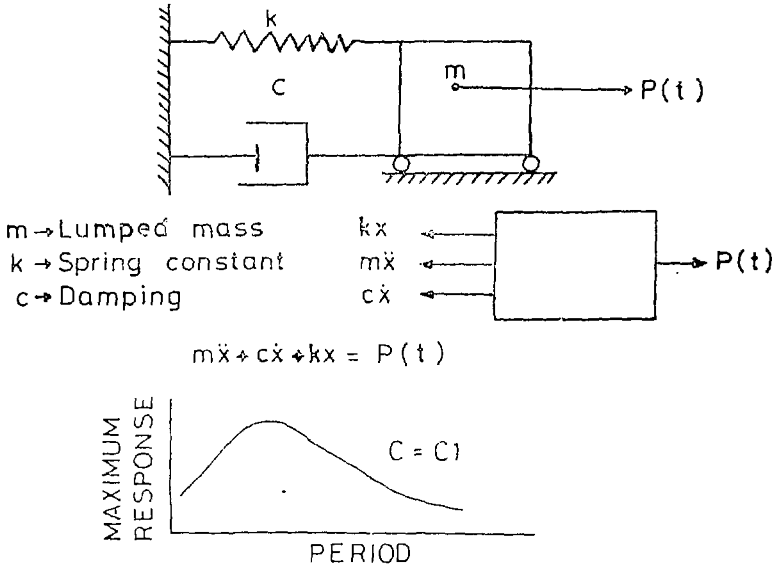


FIG. 2 RESPONSE SPECTRUM : AN ILLUSTRATION.

[A time dependent force P(t) is applied separately to single degree of freedom (SDF) systems of natural periods $T_1, T_2, .. T_N$, and the maximum response of each SDF system plotted as a function of the natural period constitutes the response spectrum.]

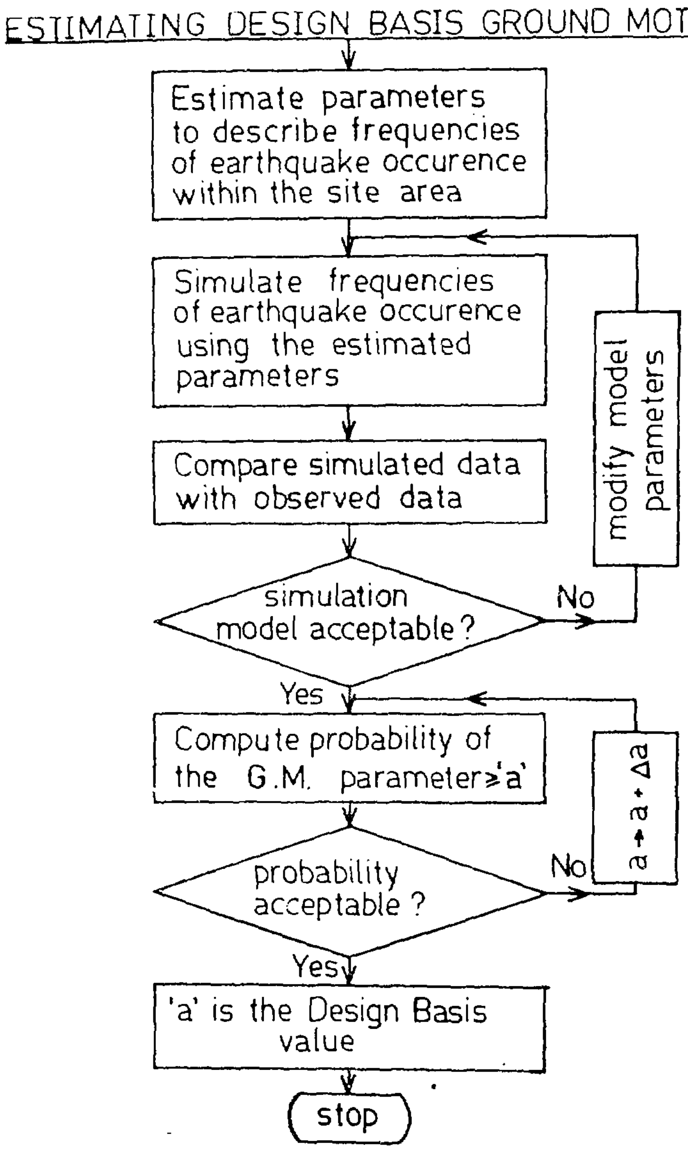


FIG. 3 FLOW CHART ILLUSTRATING THE PROBABILISTIC APPROACH OF ESTIMATING DESIGN BASIS GROUND MOTIONS.

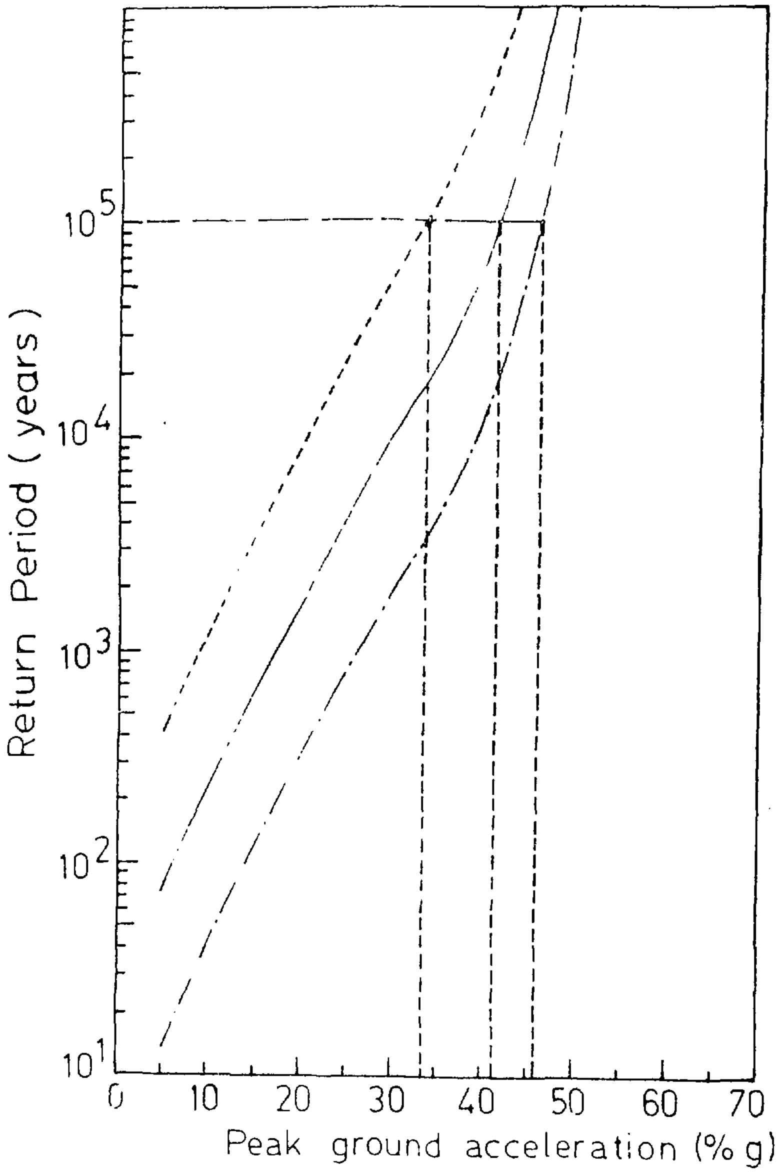


FIG. 4. RETURN PERIODS OF DIFFERENT LEVELS OF PEAK GROUND ACCELERATION ESTIMATED USING A PROBABILISTIC REGION AND SEISMIC MODELS BASED ON GLOBAL DATA. [Return periods of the causative event has been plotted as a function of the peak ground acceleration for three different models of seismic severity, the lowest curve representing severe most of the three.]

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