APPROACH TO PROBABILITY EVALUATION OF DESIGN EARTHQUAKES FOR NUCLEAR PLANTS

by

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SYNOPSIS

Two theoretical earthquakes provide a basis for seismic design of nuclear power plants: a safe shutdown earthquake (SSE), and an operating basis earthquake (OBE) (1, 2). The two approaches commonly utilized to define the characteristics of these earthquakes--the capable fault approach and the tectonic province approach--are based on predominantly deterministic procedures involving uncertainties in the selection of parameters and relationships. These uncertainties can result in significant variations in the probabilities of occurrence of each characteristic. This paper identifies the areas of uncertainty and suggests a procedure for assessing the probability of two primary characteristics of design earthquakes: magnitude or intensity, and peak accelerations.

INTRODUCTION

A basic step in the seismic design of nuclear power plants is the definition of two earthquakes: a safe shutdown earthquake (SSE) and an operating basis earthquake (OBE). Each earthquake is defined by four characteristics determined somewhat sequentially: maximum magnitude or maximum source intensity, peak acceleration, response spectra, and duration. The first characteristic is defined based on the source conditions, while the remaining three are defined based on source conditions, geometry, and the properties of the materials in the source-to-site path and at the site. Although the procedures are primarily deterministic in nature, uncertainties are associated with the basic assumptions and analytical models utilized for determining these characteristics. Therefore, any specific value of a characteristic will represent a range of probabilities of occurrence.

The evaluation of probabilities of design earthquake characteristics is relevant because these characteristics form the bases for the seismic design of the power plant structures and equipment and, therefore, influence their safety analysis. Secondly, probability evaluation of design earthquakes provides a useful comparison with the probability of other safety-related design bases (such as probable maximum flood) for ensuring consistency in approach.

Because the design earthquakes are defined by more than one characteristic and because each characteristic may have a different significance

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to the nuclear plant structures, it is difficult to define a single "probability of a design earthquake". Instead, it is convenient to assess the probabilities of individual characteristics, taking into account appropriate interrelationships. This assessment can be carried out in two steps: Step 1 - assess the probabilities of earthquake magnitude and peak acceleration; Step 2 - assess the probabilities of response spectra and duration. This paper addresses the first step.

SAFE SHUTDOWN EARTHQUAKE (SSE)

Figure 1 illustrates the two most commonly utilized approaches: (a) the tectonic province approach and (b) the capable fault approach. Figure 2 shows the prominent steps, interrelations, and associated probabilities for each approach. Current procedures require that certain parameters be assigned a specific value (for example, significant distance $d = d_{min}$) (see Figure 2). Such a stipulation would represent a probability of 1.

Tectonic Province Approach: In the tectonic province approach, a relationship between frequency and earthquake intensity (magnitude) is developed if historical data are available for each province or subprovince (Figure 3). If sufficient data are not available, equations similar to the one shown in Figure 3 are selected from those proposed for larger areas of the world within which the site region lies. The maximum SSE intensity is chosen to exceed the maximum historical intensity in the province and/or at the site by applying a certain conservatism. It is difficult to estimate the degree of conservatism in terms of probabilities because the selected value generally represents an extrapolation beyond available data, and extension of the curve N = a - bM in Figure 3 often yields high probabilities for intensities MM VIII - X. Obviously, the relationship undergoes a change near the upper limit, although it is difficult to define a realistic shape of the curve based on physical conditions at the site or in the province except by subjective judgment.

The peak acceleration associated with the selected maximum intensity is estimated from intensity-acceleration correlations. For example, Trifunac and Brady (3) propose an average curve:

$$\log a_H = 0.014 + 0.30\, I_{MM} \quad , \quad IV \le I_{MM} \le X$$

For MM VII, the calculated mean value of peak acceleration is 0.13 g; and for hard rock sites, the standard deviation is 0.06 g. Assuming normal distribution, the probability of exceeding the above acceleration is p = 0.35.

Capable Fault Approach: In the capable fault approach, earthquakes are associated with capable faults. The magnitude-frequency relationships, such as the one shown in Figure 3, may be considered to be a combination of earthquake distributions on the various capable faults within a tectonic province. Since the distribution of earthquake magnitudes on individual faults will vary and the maximum size of earthquakes on each fault will depend on its type and size (length), the number of faults and their contribution to various segments of the relationships in Figure 3 will vary. The maximum earthquake on each fault will vary depending upon a number of factors such as material properties, strain rate, rupture length, size of rupture surface, and stress drop. Within a tectonic province, the earthquake magnitude can be related to the rupture length (L_R) using a relationship of the type shown in Figure 4 ($M = \log L_R + C$) (4). The distribution of rupture lengths, and hence the distribution of magnitudes on a fault, is observed to vary considerably; typical examples are shown in Figure 5. The maximum rupture lengths and earthquakes associated with each fault can be established by either of the following methods:

1. Through a knowledge of material properties, strain rates, and stress conditions in the source region;
2. Through an extremal value analysis such as the Gumbel Type I analysis and selecting the value corresponding to a given probability (for example, x 10^{-6});
3. Through a compilation and analysis of historical data on length of surface rupture, length of aftershock zones supplemented by interpretations of the Quaternary geologic record (5);
4. Through subjective assignment of probabilities of rupture lengths and refining them periodically as additional geologic and seismologic data on new earthquakes on the same fault or similar faults become available by using Bayesian approach.

The next step consists of calculating the peak acceleration and assessing the probability of its exceedence. This is accomplished by utilizing a deterministic relationship of the type:

$$a = \alpha(\log L_R + C)^m \times d^n$$

L_R is assumed to be L_{Rmax} and d is assumed to be d_{min}; i.e., the minimum significant distance (6). The probability of the peak acceleration a_p is given by:

$$P(a \geq a_p) = P\left[(L_R = L_{Rmax})/(\text{event } d_{min})\right]$$

This probability should be compared with the desired probability. Figure 6 summarizes the relationships discussed above. The rupture length selected is the rupture length corresponding to the desired probability level and hence may vary for each fault depending upon the distributions sketched in Figure 5. The SSE acceleration is the highest acceleration obtained from the plot.

OPERATING BASIS EARTHQUAKE (OBE)

Current United States practice suggests that the OBE be selected to represent the peak acceleration that the structure may experience during its lifetime but no smaller than 50 percent of SSE peak acceleration. An isoacceleration curve corresponding to 50 percent SSE acceleration is sketched on Figure 6. Obviously, such accelerations can be experienced at the site due to numerous combinations of rupture lengths and significant distances. The expected probability of OBE peak acceleration is given by:

$$P(a \geqq a_{OBE}) = \sum_{F=1}^{n} P\left[(L_{Ri})/P(\mathrm{event})_{di}\right]$$

$$L_{Rmin} < L_{Ri} < L_{R} \text{ , } d_{min} < d_{i} < d$$

This probability can be compared with the effective life of the structure. In case of a tectonic province approach, procedures such as those discussed by Vanmarcke and others (7) can be utilized.

CONCLUSIONS

1. Probability of design earthquakes comprises interrelationships between different characteristics.
2. The estimation of maximum earthquake magnitudes or intensities from deterministic data is often difficult. Instead, it is preferable to estimate the earthquake corresponding to a given level of probability for each structure or tectonic province. Such a procedure also facilitates estimation of OBE.
3. The range of probabilities determined by the capable fault method is likely to be narrower than the corresponding range determined by the tectonic province approach, which can often yield unrealistic probabilities. This factor together with other physical considerations indicate that, wherever possible, the capable fault approach should be preferred and the tectonic province approach be used only on a fall-back basis.
4. A procedure is suggested for establishing maximum magnitudes and peak acceleration for SSE and OBE based on selected levels of probability.

SELECTED REFERENCES

(1) Code of Federal Regulations, 1973, Reactor site criteria: Title 10, Part 100, Appendix A, U. S. Atomic Energy Commission.

(2) U. S. Nuclear Regulatory Commission, 1975, Standard Review Plans: Sec. 2.5.

(3) Trifunac, M., and Brady, A., 1975, On the correlation of seismic intensity scales with the peaks of recorded strong ground motion: Bulletin of the Seismological Society of America, v. 65, no. 1, p. 139-162.

(4) Patwardhan, A. S., Tocher, D., and Savage, E. D., 1975, Relationship between earthquake magnitude and length of rupture surface based on aftershock zones: Geological Society of America, Abstracts with Programs, v. 7, no. 3, p. 419-420.

(5) Sherard, J. L., Cluff, L. S., and Allen, C. R., 1974, Potentially active faults in dam foundations: Geotechnique, v. 24, no. 3, p. 367-428.

(6) Tocher, D., and Patwardhan, A. S., 1975, Attenuation of peak acceleration in earthquakes: Geological Society of America, Abstracts with Programs, v. 7, no. 3, p. 426-427.

(7) Vanmarcke, E. H., Cornell, C. A., Whitman, R. V., Reed, J. V., 1973, Methodology for optimum seismic design: Fifth World Conference on Earthquake Engineering, Rome, Italy, v. 3, p. 2521-2530.

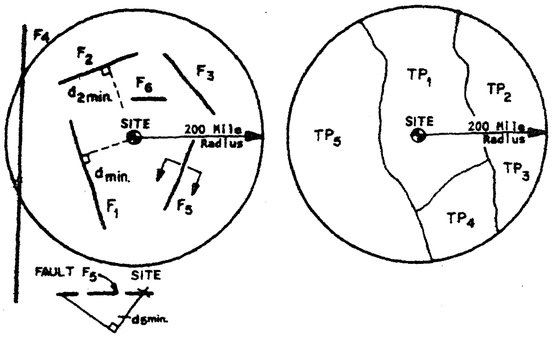


Figure 1. TECTONIC PROVINCE AND CAPABLE FAULT APPROACH

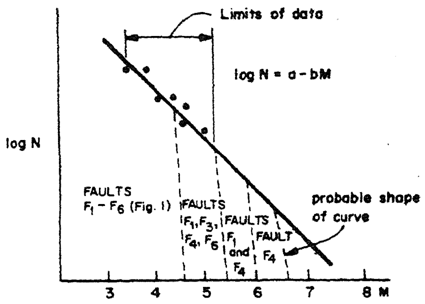
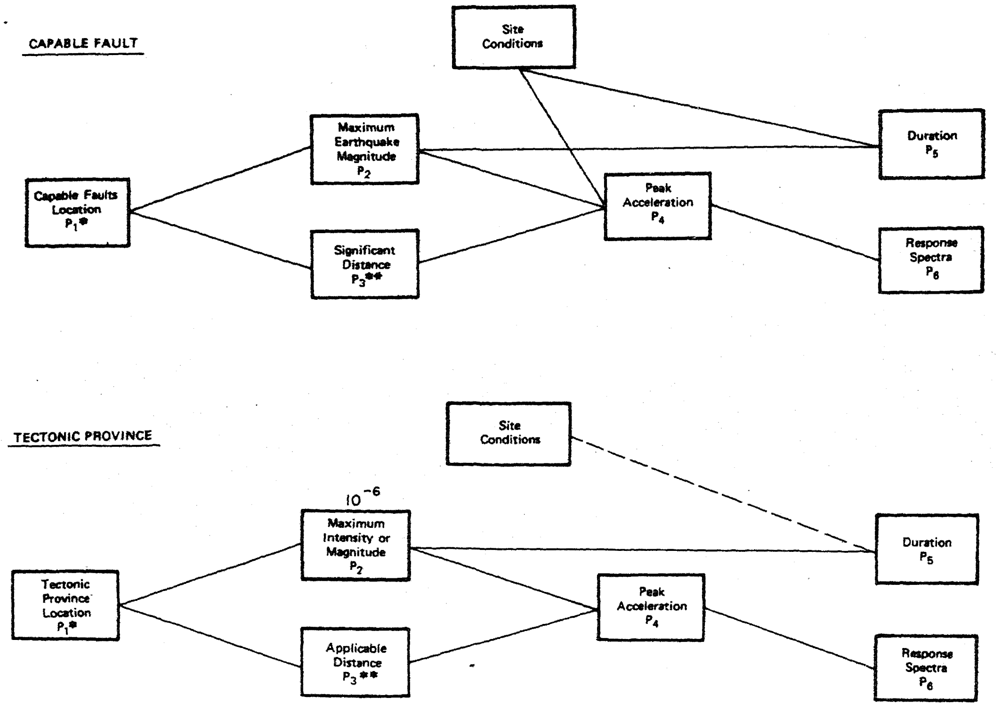


Figure 3. EARTHQUAKE MAGNITUDE (INTENSITY) — FREQUENCY RELATIONSHIP



* Assigned probability p = 1 through geologic and seismologic investigation

** Assigned probability p = 1, 10CFR 100AppA. USNRC

Figure 2. PROBABILITY INTERRELATIONSHIP

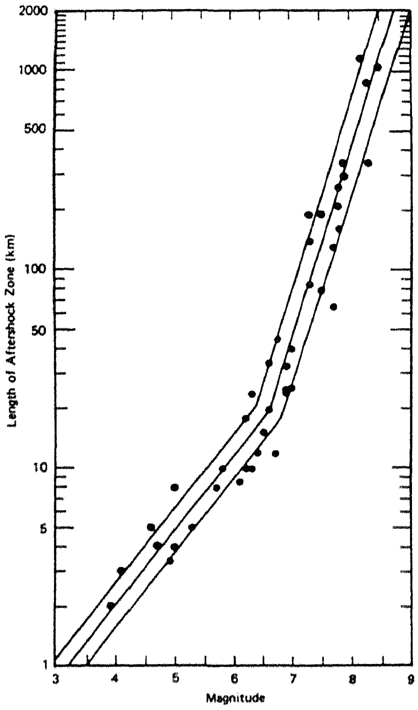


Figure 4. MAGNITUDE RUPTURE LENGTH

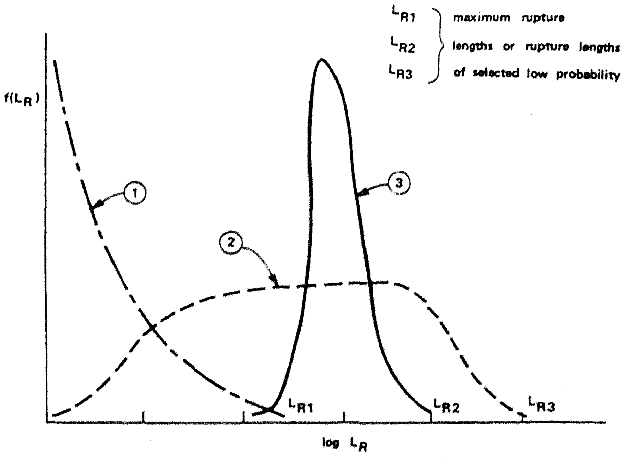


Figure 5. SCHEMATIC FREQUENCY DISTRIBUTION OF RUPTURE LENGTHS OF FAULTS

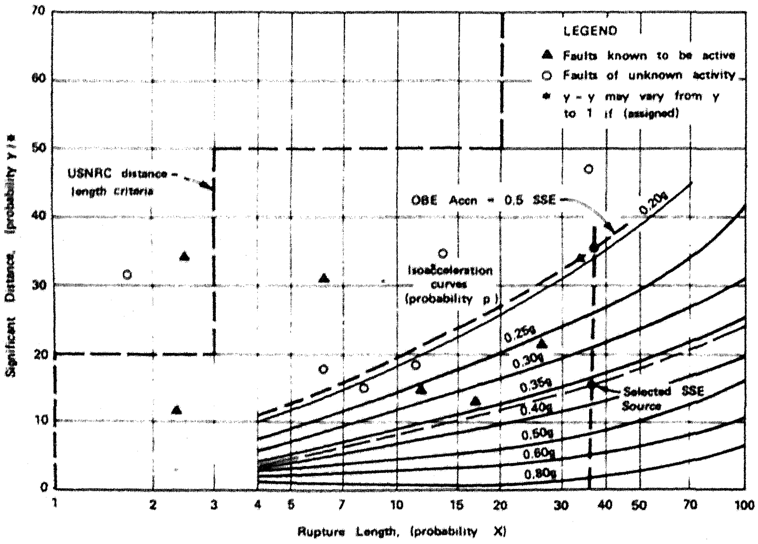


Figure 6. EVALUATION OF RELATIVE SIGNIFICANCE OF EARTHQUAKE SOURCE

DISCUSSION

I.N. Gupta (U.S.A.)

Is it possible for you to suggest some realistic values for the probability of occurrence of the safe shutdown and operating basis earthquake ? The discussor would like to know if there is consensus of opinion among various countries on these important numbers.

Author's Closure

Not received.