PROBABILISTIC EVALUATION OF THE SSE DESIGN SPECTRUM FOR A NUCLEAR POWER PLANT SITE: A CASE STUDY

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This study examines the probability of exceeding the design response spectrum associated with the Safe Shutdown Earthquake (SSE) for a nuclear power plant site in California. The study was carried out for a single fault which was considered capable according to U.S. Nuclear Regulatory Commission (NRC) criteria and which proved to be a controlling fault using a deterministic procedure. The purpose of the probability study was to evaluate the conservatism of the SSE design spectrum resulting from the deterministic procedure and, by implication, the conservatism of the NRC criteria for establishing fault capability.

The probabilistic model developed for this study incorporates the major factors that influence seismic risk at a given site; i.e., the size and frequency of earthquakes, their location relative to the site, the attenuation of generated ground motions, and the frequency distribution of energy arriving at the site. Significant features of the model are the probabilistic treatment of much of the important input data and the use of geologic displacements rather than historic seismicity records to establish the frequency of earthquakes along the fault.

The results of this study demonstrate that, for the fault considered, the SSE design spectrum recommended by the regulatory agencies is associated with an average return period in excess of 10^7 years (i.e., an annual probability of being exceeded of less than 10^{-7}). The dominant factor in these results is the extremely low earthquake recurrence rate for this fault as determined from the geologic displacement history. These findings indicate that the current regulatory criteria for determining fault capability can result in extremely conservative requirements for seismic design spectra for nuclear power plant projects.

1. Introduction

In the United States, at present, the design response spectrum for the SSE is established through a deterministic procedure whereby:

a. The maximum earthquake for the site is established according to the criteria of 10 CFR 100, Appendix A; Reference (1),

b. The ground accelerations at the site are determined by assuming the maximum earthquake occurs at the point on the tectonic structure or tectonic province nearest the site, and

c. A response spectrum is used to define the ground accelerations determined in step b.

The above procedure was developed, and was intended to be applied, in a conservative manner. The degree of conservatism actually achieved can not be established, however, from the deterministic approach. This study developes a probabilistic methodology for evaluating the conservatism of the SSE design spectrum for a case involving a capable fault in the vicinity of a nuclear power plant site. The methodology is sufficiently general, however, to be applied to other sites where potential earthquakes are associated with a known fault zone.

2. Analytical Model

The probabilistic model developed for this study is based upon a modification and extension of the procedure described by Cornell, Reference (2).

The available body of recorded ground motions suggests that the amplitude of motion at a site is primarily influenced by the magnitude of the earthquake, M, and the source-site distance, R. The scatter in observed amplitudes about the mean value can be reasonably approximated by a lognormal distribution function. Given the above, the conditional probability density function for the amplitude of ground motion at a site may be written:

$$P_{Y|M,R}(y) = \frac{1}{y\sigma_{\ln y}\sqrt{2\pi}} \exp\left[\frac{-1}{2\sigma^2_{\ln y}} \left(\ln \frac{y}{\breve{y}}\right)^2\right] \tag{1}$$

where $\sigma_{\ln y}$ is the standard deviation of the lognormal distribution and $\breve{y}$ is the median amplitude of ground motion for an earthquake of magnitude, M, and distance, R.

If the magnitude and distance of a future earthquake are treated as independent variables, with probability density functions of $P_M(m)$ and $P_R(r)$, respectively, the probability density function for ground motion amplitude, given the occurrence of an earthquake, E, is given by:

$$P_{Y|E}(y) = \int_{r_o}^{r_c} \int_{m_o}^{m_c} P_{Y|M,R}(y)\, P_m(m)\, P_R(r)\, dm dr \tag{2}$$

where m_o is the smallest earthquake of engineering significance, m_c is the largest credible earthquake, r_o is the shortest possible distance and r_c is the greatest distance of concern.

The probability that an earthquake will produce a site response equal to or exceeding any specified value, y_i, is then determined as:

$$P[i|E] = P[y \geq y_i | E] = \int_{y_i}^{\infty} p_{Y|E}(y)\,dy \qquad (3)$$

If the annual probability that an earthquake of interest (i.e., $m_o \leq M \leq m_c$ and $r_o \leq R \leq r_c$) will occur is defined as $P[E]$, the annual probability of equaling or exceeding y_i is expressed:

$$P[i] = P[y \geq y_i] = P[i|E]\;P[E] \qquad (4)$$

The average return period for the amplitude y_i is determined by assuming that earthquake occurrences follow a Poisson arrival process. For $P[i] \ll 1$, the average return period, T_i, is approximated very closely by:

$$T_i = 1/P[i] \qquad (5)$$

The average return period may be calculated for any given level of site response or, conversely, the level of response may be determined for any specified return period. The latter procedure is adopted in this study.

In general, Y may be any ground motion parameter of interest. If Y represents the pseudo-velocity spectral ordinate at any given frequency and, if each ordinate is determined independently for any single return period, a response spectrum can be generated which represents a uniform level of seismic risk (i.e., the probability of exceeding the spectrum will be constant at all frequencies).

3. Application

3.1 Site Conditions

The site and capable fault (Pond-Poso Creek fault) considered in this study are located in Southern California and are shown in Figure 1; the historic earthquakes in the vicinity of this fault are also shown. Considering the location accuracy for these earthquakes, it is possible that one or more may be associated with the Pond-Poso Creek fault. Geologic investigations have determined the displacements across this fault zone for several datable geologic horizons. The youngest such horizon (the Etch-Horizon) indicates a cumulative displacement of approximately 160 meters in roughly 4.75 million years (this displacement is shown as the "Base Case" in Figure 2). The average annual displacement of 3.3×10^{-5} meters/year is the largest for any of the horizons for which reliable data could be obtained.

Despite the lack of positive historic seismicity and the small geologic displacements, the Pond-Poso Creek fault was considered capable according to NRC criteria listed in Reference (1), and was assigned a maximum credible earthquake of magnitude 7.0 and a source-site distance of 18 km. For these conditions, the site ground motions were defined by Regulatory Guide 1.60 Design Response Spectra, Reference (3), normalized to 0.45g.

From a deterministic viewpoint, each step leading to the 0.45g design spectra is defensible and it might even be argued that additional conservatism is required given the importance of the structures. The following sections examine the overall conservatism in the 0.45g design spectra for this site.

3.2 Earthquake Magnitude and Frequency

The seismicity of a fault or region is commonly defined by Richter's magnitude/recurrence interval relationship, Reference (4):

$$\log_{10} n_m = \alpha - \beta m \tag{6}$$

where n_m is the number of earthquakes greater than magnitude m in a given time interval and α and β are constants.

The constants α and β are normally determined from the historic seismicity of a region. For seismically active regions in Southern California, the value of β is approximately 0.9 ($\pm$ 0.1), Reference (5); this range of values was assumed to apply to the Pond-Poso Creek fault. The historic seismicity associated with this fault is too low to reliably determine the constant α and no general range of values can be reasonably assumed. In order to overcome this lack of data, an alternative method is developed for establishing the value of α based upon the geologic displacement record for the fault. Figure 2 shows the cumulative displacement profile for the Etch-Horizon (a most probable "Base Case" is shown along with "Variations" reflecting the bounds on measurement uncertainties). If it is conservatively assumed that the entire observed displacement is the result of seismic activity, the average total number of earthquakes required to produce this displacement profile may be determined as follows:

$$n_t = A / \int_{m_o}^{m_c} P_M(m)\, A(m)\, dm \tag{7}$$

where n_t is the average total number of earthquakes in the magnitude interval m_o to m_c, A is the total area under the cumulative displacement profile and A (m) is the displacement area contributed by an earthquake of magnitude m.

The displacement area A (m) is determined as the product of an average rupture length, L (m), and an average fault displacement, D (m):

$$A(m) = L(m)\, D(m) \tag{8}$$

Rupture length and displacement may be expressed as empirical relationships of the following form, References (6) and (7), respectively:

$$\log_{10} L = \alpha_1 + \beta_1 m \qquad \pm \sigma_L \tag{9}$$

$$\log_{10} D = \alpha_2 + \beta_2 m \qquad \pm \sigma_D \tag{10}$$

where α and β are constants and σ designates the standard deviation for the assumed log-normal distributions of L and D.

The probability density function for earthquake magnitude follows directly from equation (6). Defining $\beta' = \beta \log_e 10$, then:

$$P_M(m) = \frac{\beta' e^{-\beta' m}}{e^{\beta' m_o} - e^{-\beta' m_c}} \tag{11}$$

Combining equations (7) through (11), the average total number of earthquakes is obtained as:

$$n_t = A \left[\frac{\beta' e^{(\alpha'_1 + \alpha'_2)}}{e^{-\beta' m_o} - e^{-\beta' m_c}} \right]^{-1} \left[\frac{e^{(-\beta' + \beta'_1 + \beta'_2)m_c} - e^{(-\beta' + \beta'_1 + \beta'_2)m_o}}{-\beta' + \beta'_1 + \beta'_2} \right]^{-1} \tag{12}$$

where a prime denotes the change of base: $x' = x \log_e 10$.

Given n_t and the age of the geologic horizon, T, the value of α for a specified time period of one year is determined as:

$$\alpha = \log_{10}\left(\frac{n_t}{T}\right) - \log_{10}\left(10^{-\beta m_o} - 10^{-\beta m_c}\right) \qquad \pm \sigma_\alpha \tag{13}$$

For the specific geologic horizon considered, a cumulative displacement area of approximately 8.3 km^2 has occurred in roughly 4.75 million years. Given a value of $m_c = 7.0$ and assuming $m_o = 4.0$ represents the smallest earthquake of interest, the mean value of α for the Pond-Poso Creek fault is determined to be approximately 1.12. Based upon this value, the average annual probability of a magnitude 7 earthquake occurring anywhere along the fault is 6.6×10^{-6}.

3.3 Hypocentral Distance

If it can be assumed that the distribution of earthquake magnitudes is independent of the location of a given earthquake, the fault displacement profile is an indication of the spatial distribution of all magnitude earthquakes (i.e., a larger observed displacement in a particular section of the fault implies an increased number of earthquakes of all magnitudes within the same section). Based upon this assumption, the probability density function for earthquake location is assumed to have the same shape as the fault displacement profile shown in Figure 2. An assumed focal depth of 16 km and a transformation of variables is then used to determine the probability density function for source-site distance, $P_R(r)$, for use in equation (2).

3.4 Attenuation of Ground Motion

For this study, the attenuation of ground motion was assumed to be of the following form; References (8) and (9):

$$y = c_1 e^{c_2 m} R^{-c_3} \qquad \pm \sigma_y \tag{14}$$

where y is the mean value of site response and c_1, c_2 and c_3 are constants determined from a regression analysis of recorded ground motion data.

The primary measure of site response used in this study is the pseudo-velocity spectral ordinate at a specified frequency. Separate regression analyses were performed for 16 different frequencies between 0.5 and 25 Hz. Uncertainty in the response was treated using equation (1). The data set consisted of 64 ground motion records obtained on soils similar to those at the site. Peak acceleration and spectrum intensity were used as alternate measures of site response.

4. Results

The probabilistic site response spectra which were established by this study are illustrated in Figure 3, along with the 0.45g Regulatory Guide 1.60 design spectrum established using the deterministic procedure. It may be observed that the 0.45g spectrum exceeds, by a very wide margin, the level of site response that is expected once in 10,000,000 years, on the average. The average annual probability of exceeding the 0.45g spectrum is thus on the order of 10^{-7} to 10^{-8}.

These results were obtained based upon the most reasonable estimates of all parameters that could not be treated in a probabilistic fashion (see Table 1, "Base Case"). A sensitivity study was then performed to consider variations of these parameters within expected limits. The variations examined and the individual effect these variations had on the results are summarized in Table 1. The simultaneous variation of all parameters (Figure 4) results in an annual probability of exceeding the 0.45g design spectrum on the order of 10^{-6} to 10^{-7}.

5. Conclusions

Based upon the results reported above, it is believed that a conservative order of magnitude estimate for the probability of exceeding the SSE design spectrum is 10^{-7} per year for the specific fault and site considered. The major factor contributing to this result is the very low probability, determined from the geologic displacement history, that large earthquakes will occur (i.e., $\sim 10^{-5}$ per year for magnitude 7 events). This low occurrence probability indicates that the current regulatory criteria for establishing fault capability may be unnecessarily conservative in certain applications. Fault capability, per se, does not imply a significant level of seismic risk for a nuclear power plant site.

References

(1) U.S. Nuclear Regulatory Commission, "Title 10 - Code of Federal Regulations - Part 100, Appendix A - Seismic and Geologic Siting Criteria for Nuclear Power Plants" (10 CFR 100, Appendix A).

(2) Cornell, C. Allin, 1968, "Engineering Seismic Risk Analysis", Bulletin of the Seismological Society of America, Volume 58, No. 5.

(3) U.S. Nuclear Regulatory Commission, "Regulatory Guide 1.60 - Design Response Spectra for Seismic Design of Nuclear Power Plants".

(4) Richter, C. F., 1958, Elementary Seismology, W. H. Freeman and Co., San Francisco, California.

(5) Hileman, J., Allen, C., Nordquist, J., 1973, "Seismicity of the Southern California Region, January 1, 1932 to December 31, 1972", Seismological Laboratory, Cal. Tech., Pasadena, California.

(6) Patwardhan, A. S., Tocher, D., and Savage, E. D., 1975, "Relationship Between Earthquake Magnitude and Length of Rupture Surface Based on Aftershock Zones", Abstracts of the 71st Annual Meeting of the Cordilleran Section of GSA, Volume 7, No. 3.

(7) Geller, R. J., 1976, "Scaling Relations for Earthquake Source Parameters and Magnitude", Bulletin of the Seismological Society of America, Volume 66, No. 5.

(8) Esteva, L., and Rosenblueth, E., 1963, "Spectra of Earthquakes at Moderate and Large Distances", Soc. Mex. de Ing. Sismica, II, No. 1, p 1-18 (Mexico).

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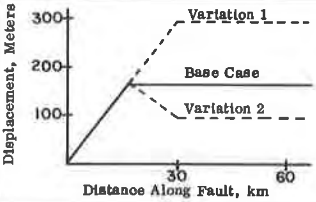
TABLE I: SUMMARY OF SENSITIVITY STUDY RESULTS

Parameter	Case	Percent Change From Base Case	
		Peak Acceleration	Spectrum Intensity
A. Total Displacement/Age of Etch-Horizon	Base Case: Approx. 160 meters in 4.75 million years Variation 1: Approx. 190 meters in 4.0 million years. Variation 2: Approx. 130 meters in 5.5 million years.	0% + 8.2% - 7.6%	0% + 8.8% - 8.2%
B. Shape of the displacement profile on the Etch-Horizon (interpretation of geophysical data)		+ 10.1% 0% - 7.9%	+ 10.8% 0% - 8.6%
C. Fault Length	Base Case: 60 kilometers Variation 1: 77 kilometers	0% 0%	0% 0%
D. Focal Depth	Base Case: 16 kilometers Variation 1: 8 kilometers Variation 2: 24 kilometers	0% + 18.5% - 16.6%	0% + 19.3% - 17.1%
E. Magnitude/Recurrence Interval Relationship	Base Case: $\log_{10} n_m = \alpha - 0.9\ m$ Variation 1: $\log_{10} n_m = \alpha - 0.8\ m$. Variation 2: $\log_{10} n_m = \alpha - 1.0\ m$	0% + 5.8% - 6.1%	0% + 7.3% - 7.8%

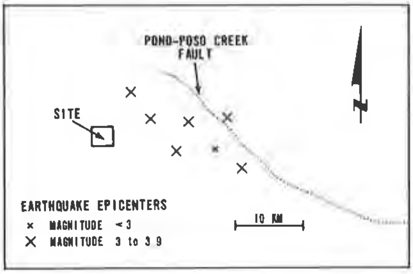


FIGURE 1 - FAULT-SITE GEOMETRY AND HISTORIC SEISMICITY

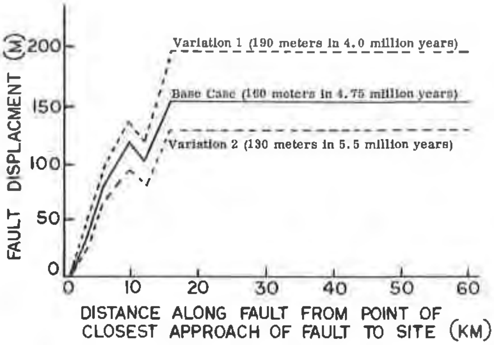


FIGURE 2 - CUMULATIVE DISPLACEMENT PROFILE FOR THE POND-POSO CREEK FAULT

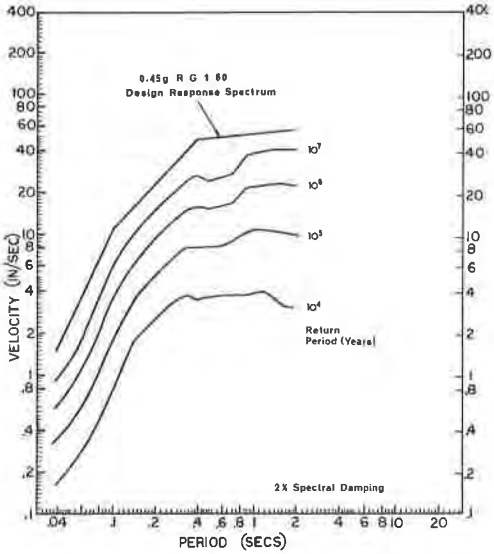


FIGURE 3 - SITE RESPONSE AS A FUNCTION OF AVERAGE RETURN PERIOD

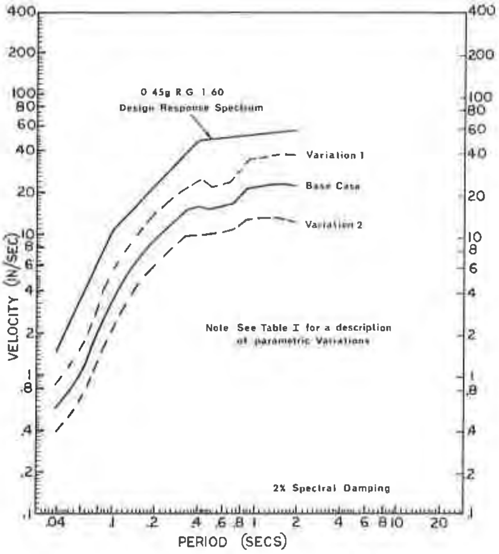


FIGURE 4 - SENSITIVITY OF SITE RESPONSE TO THE SIMULTANEOUS VARIATION OF PARAMETERS - ONE MILLION YEAR RETURN PERIOD