

SEISMIC FATIGUE CONSIDERATIONS
IN NUCLEAR POWER PLANT DESIGN

by

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ABSTRACT

An approach is presented whereby the probable number of equivalent operational basis earthquakes at a site during the lifetime of a power plant is determined. The method uses data on the frequency of occurrence of earthquakes for the region, the attenuation of earthquake intensity with distance from the epicenter and the duration of strong motion at the site. The results can be input directly into the fatigue life evaluation of the proposed nuclear power facility.

NOTATION

A,a	=	maximum ground acceleration at site
a ₀	=	maximum ground acceleration for OBE
a _x	=	maximum ground acceleration at epicenter
b	=	material constant derived from fatigue test data
β	=	seismicity factor
D _i	=	cumulative fatigue damage for seismic event i
d ₀	=	cumulative fatigue damage for OBE
E	=	expected value
f	=	probability density function
F	=	distribution function
h	=	focal depth
λ	=	mean annual number of earthquakes
ln	=	natural logarithm (base e)
log	=	common logarithm (base 10)
M,m	=	Richter magnitude
N,n	=	total number of earthquakes of interest
n ₀	=	number of equivalent OBE's
n	=	number of cycles
OBE	=	operational basis earthquake
R,r	=	focal distance
σ	=	stress
T,t	=	duration of strong motion at site
t ₀	=	duration of strong motion for OBE
x	=	radius of circular areal source
y	=	length of fault

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INTRODUCTION

Earthquakes of varying intensities are expected to occur during the service life of most nuclear power plants. At present, however, nuclear power plants are analyzed for two levels of earthquake loading --- an operational basis earthquake and a design basis earthquake or safe shutdown earthquake. The fatigue evaluation for the facility should consider the cumulative fatigue damage associated with all earthquake intensities that are expected to occur at the site.

A technique is presented herein which enables one to transform earthquakes of various intensities into equivalent operational basis earthquakes. The procedure leads to the number of equivalent operational basis earthquakes that are expected to occur during the service life of a proposed nuclear power plant. The approach uses data on the frequency of occurrence of all strong motion earthquakes for the region under consideration together with information on the attenuation of earthquake intensity with distance from the epicenter. Random variables included in the formulation are the maximum acceleration and duration of strong motion at the site, the earthquake magnitude, the focal distance, and the number of strong motion earthquakes in the region. The influence of local geology and soil conditions is also incorporated. The results can be input directly into the fatigue life evaluation of the proposed nuclear power facility. To illustrate the approach, numerical results are presented for a hypothetical site.

EQUIVALENT OPERATIONAL BASIS EARTHQUAKES

If the total number of earthquakes of interest occurring in the region surrounding the site during the service life of the facility is denoted by n , the cumulative fatigue damage can be expressed as

$$\sum_{i=1}^n D_i \quad (1)$$

where D_i equals the cumulative fatigue damage for seismic event i . The above expression assumes a linear cumulative fatigue damage law.

The number of equivalent operational basis earthquakes that are expected to occur is defined by

$$n_o = \frac{1}{d_o} \sum_{i=1}^n D_i \quad (2)$$

where d_o represents the cumulative fatigue damage associated with the operational basis earthquake specified for the site. Hence, the seismic fatigue damage accumulated in the structure during the service life of the facility is given by the product $n_o d_o$.

In general, however, the total number of earthquakes n and the cumulative fatigue damage D_i for future seismic events is unknown. Therefore, they shall be treated as random variables in the formulation. The frequency of occurrence of earthquakes in a region can be reasonably approximated using the relation (1)

$$\log \lambda = b_1 - b_2 m \quad (3)$$

where λ is the mean annual number of earthquakes that originated in a given volume of the earth's crust and whose magnitude exceeds m . The parameters, b_1 and b_2 , are empirical constants. Assuming that the occurrence of earthquakes follows a Poisson arrival process with average occurrence rate of λ per year, we may write (2)

$$P [N=n] = \frac{(\lambda t)^n \exp(-\lambda t)}{n!} \quad (4)$$

where $P [N=n]$ denotes the probability that the number of earthquakes with magnitude greater than m in a time interval t for a given region is exactly n .

If the total number of earthquakes in the region is sufficiently large, equation (2) can be rewritten in the form

$$n_o = \frac{1}{d_o} n E(D) \quad (5)$$

where the notation $E(D)$ denotes the expected value of fatigue damage for any seismic event of interest in the region. On the following pages, expressions for d_o and $E(D)$ for future earthquakes are derived using statistical information available from past earthquakes in the region.

SEISMIC FATIGUE INTENSITY

Applying the Palmgren-Miner hypothesis for fatigue damage and a linear approximation to the S - N curve, the cumulative fatigue damage D in a component is expressed as

$$D = \frac{1}{c} \sigma^b \eta \quad (6)$$

where σ equals the stress amplitude, η represents the number of cycles, and b and c are material constants. The ratio $1/b$ designates the slope of the linear approximation to the S - N curve (figure 1).

Assuming that the stress amplitude is proportional to A , the maximum ground acceleration at the site, and the number of cycles is proportional to T , the duration of strong motion at the site, the cumulative fatigue damage due to a seismic event takes the form

$$D = k A^b T \quad (7)$$

where $A > a_e$, k is an undetermined constant of proportionality and a_e is defined such that no fatigue damage occurs during earthquakes whose maximum site acceleration is less than a_e .

Thus, a_e is analogous to the endurance limit of stress exhibited by many structural materials. The cumulative fatigue damage d_o associated with the OBE is given by

$$d_o = k a_o^b t_o \quad (8)$$

where a_o and t_o are the maximum ground acceleration and the duration of strong motion at the site for the specified OBE. The ratio D/d_o , termed the seismic fatigue intensity, is plotted in figure 2.

The expected value of the cumulative fatigue damage is defined by

$$E(D) = k E(A^b) E(T) \quad (9)$$

$$\text{where } E(A^b) = \int_{a_e}^{a_2} a^b f_A(a) da \quad (10)$$

$$\text{and } E(T) = \int_{t_1}^{t_2} t f_T(t) dt. \quad (11)$$

f_A and f_T are the probability density functions for the independent random variables A and T.

By substituting equations (8) and (9) into equation (5), we obtain the following expression for the number of equivalent OBE's that are expected to occur during the service life of the nuclear facility

$$n_o = \frac{1}{a_o^b t_o} n E(A^b) E(T). \quad (12)$$

MAXIMUM GROUND ACCELERATION

We seek the probability density function for the random site acceleration A. Following the development by Cornell⁽³⁾, we first obtain the conditional probability that A will exceed some acceleration, a, given the occurrence of an earthquake of magnitude $M=m$. We assume an acceleration - attenuation relationship of the form

$$A = b_o R^{-c_o} \exp(c_1 M + c_2 M^2) \quad (13)$$

in which b_o , c_o , c_1 and c_2 are empirical constants. R is the uncertain focal distance. A similar relation, illustrated in figure 3, was developed for earthquakes on firm ground⁽⁴⁾. Using equation (13) and assuming that M and R are statistically independent random variables

$$P [A > a | M = m] = P \left[R < \frac{\exp(c_1 M + c_2 M^2 + \ln b_o - \ln a)}{c_o} \right] = F_R(r) \quad (14)$$

where F_R is the distribution function for R.

In order to incorporate the probability of occurrence of all earthquakes of interest we integrate

$$P [A > a] = 1 - F_A(a) = \int_{m_1}^{m_2} P [A > a | M=m] f_M(m) dm \quad (15)$$

where f_M is the density function for M .

The density function for A follows by differentiation of the distribution function F_A . Once the density function for A is defined, we evaluate equation (10) numerically to obtain $E(A^b)$.

DURATION OF STRONG MOTION

In equation (12) it is observed that the number of equivalent OBE's depends on $E(T)$, the expected value of the duration of strong motion at the site. The following expression has been proposed for the duration of a white noise of constant intensity per unit time, equivalent to an earthquake of given magnitude and focal distance⁽²⁾

$$T = d_1 \exp(d_2 M) + d_3 R \quad (16)$$

in which d_1 , d_2 , and d_3 are empirical constants. This relation is plotted in figure 4.

From equation (16)

$$E(T) = d_1 \int_{m_1}^{m_2} \exp(d_2 m) f_M(m) dm + d_3 \int_{r_1}^{r_2} r f_R(r) dr \quad (17)$$

where f_M is the density function for M , and f_R is the density function for R .

EARTHQUAKE MAGNITUDE AND FOCAL DISTANCE

The distribution of earthquake magnitudes in the region can be derived from equation (3). An expression for the density function for M has the form⁽⁵⁾

$$f_M(m) = \left[1 - e^{-\beta(m_2 - m_1)} \right]^{-1} \beta e^{-\beta(m - m_1)} \quad m_1 < m < m_2 \quad (18)$$

in which m_1 is some earthquake magnitude small enough so that the effects at the site of earthquakes of lesser magnitude are negligible, and m_2 is an upper bound on M . The parameter $\beta = b_2 \ln 10$, where b_2 appears in equation (3). f_M is plotted in figure 5 for $\beta = 2.08$, $m_1 = 4$ and $m_2 = 9$.

Density functions for the uncertain focal distance R can be obtained for a variety of earthquake sources⁽³⁾. The plan view of a hypothetical site for a nuclear power facility, illustrated in figure 6, depicts two possible sources of earthquakes: a circular areal source and a fault or line source. For the case of a circular areal source with the site at the center, f_R is given by

$$f_R(r) = \frac{2r}{h^2 + x^2} \quad r_1 \leq r \leq r_2 \quad (19)$$

where h is the focal depth and x is the radius of the circle.

When the site is located symmetrically with respect to a fault of length y and depth h ,

$$f_R(r) = \frac{2r}{y\sqrt{r^2-h^2}} \quad r_1 \leq r \leq r_2. \quad (20)$$

NUMERICAL EXAMPLE

As an illustration, consider the hypothetical site shown in figure 6. The site is a candidate for a proposed nuclear power plant with an anticipated service life of fifty years. The OBE postulated for the site is characterized by a maximum ground acceleration of .10g and a duration of strong motion of fifteen seconds. We seek the total number of equivalent OBE's that are expected to occur at the site during the service life of the facility. This information is required to evaluate the seismic contribution to the fatigue damage for the power plant components. We shall confine our attention to the circular area surrounding the site having a radius of 250 kilometers. Earthquakes emanating from sources outside this region are assumed to have an insignificant effect on the site and, therefore, they are neglected.

The region possesses two active faults. The longer fault, located thirty kilometers from the site at its closest point, has a mean frequency of 25 earthquakes per fifty years having Richter magnitude greater than four. The shorter fault, situated seventy kilometers from the site, has a mean frequency of 35 earthquakes in fifty years. Earthquakes have also occurred at other locations within the region, so that the entire circular area is treated as a possible source for future earthquakes. In fifty years, the mean number of earthquakes exceeding a magnitude of four for the circular areal source is estimated at fifty.

From data on past earthquakes in the region, we select the acceleration-attenuation relationship of equation (13) for each source. The duration of strong motion at the site for earthquakes originating on the longer fault and in the circular area is related to M and R by equation (16) where $d_1=.010$, $d_2=.740$, and $d_3=.149$. The corresponding relation assumed for the shorter fault has $d_1=.017$, $d_2=.740$, and $d_3=.257$. The density function describing the distribution of earthquake magnitudes in the region has the form of equation (18) with $m_1=4.0$, $m_2=9.0$, and $\beta=2.08$.

Employing the design fatigue curve of figure 1, the parameter b in equation (6) equals 3.25. The integration in equation (10) is carried out over all site accelerations in excess of .05g. Incorporating the above data into the previous development, and performing the indicated integrations numerically on the computer, one obtains the results presented below:

Source	$E(A^b)$	$E(T)$	n_0
Longer Fault	5.45×10^{-7}	20.2	1.6
Shorter Fault	1.04×10^{-7}	23.9	0.5
Circular Area	3.85×10^{-7}	25.4	2.9

Total=5.0

Hence the total number of equivalent operational basis earthquakes that are expected to occur at the site during the service life of the facility is 5.

The above calculations are based on the mean frequency of occurrence of earthquakes in the region. If one adopts the Poisson process of equation (4) for the distribution of equivalent OBE's at the site, then the probability is .001 that n_0 will exceed 13.

CONCLUSION

A procedure leading to the number of equivalent operational basis earthquakes that are expected to occur at a nuclear power plant site during the lifetime of the facility has been presented. The approach is used to develop seismic fatigue design criteria for the components of a proposed nuclear power plant. In addition, the method can be used to aid engineers in performing site comparisons of possible locations for proposed nuclear power plants.

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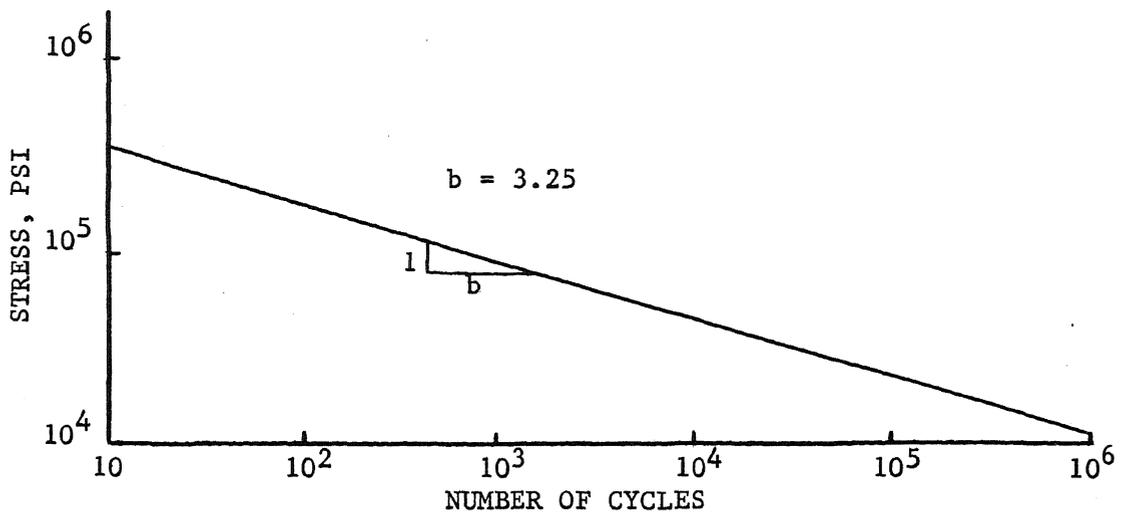


FIG. 1. LINEAR APPROXIMATION TO DESIGN FATIGUE CURVES FOR CARBON, LOW-ALLOY AND HIGH TENSILE STEELS. (6)

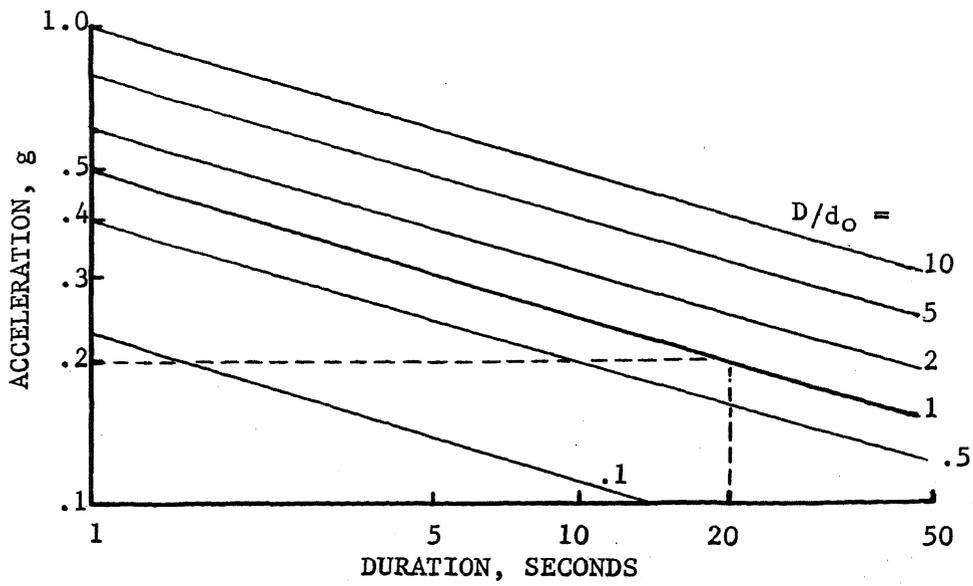


FIG. 2. SEISMIC FATIGUE INTENSITY D/d_0 FOR $a_0 = .20g$, $t_0 = 20$ AND $b = 3.25$.

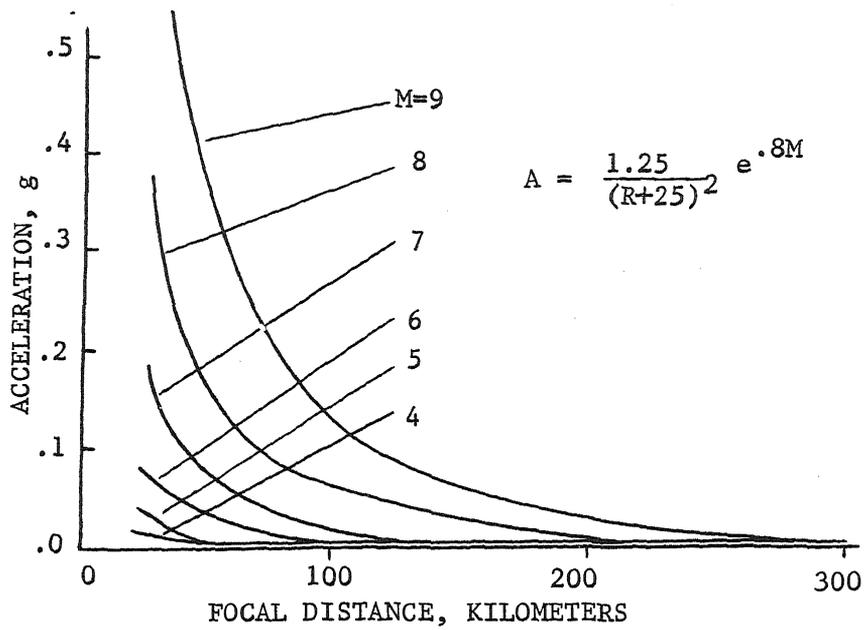


FIG. 3. MAXIMUM GROUND ACCELERATION. (4)

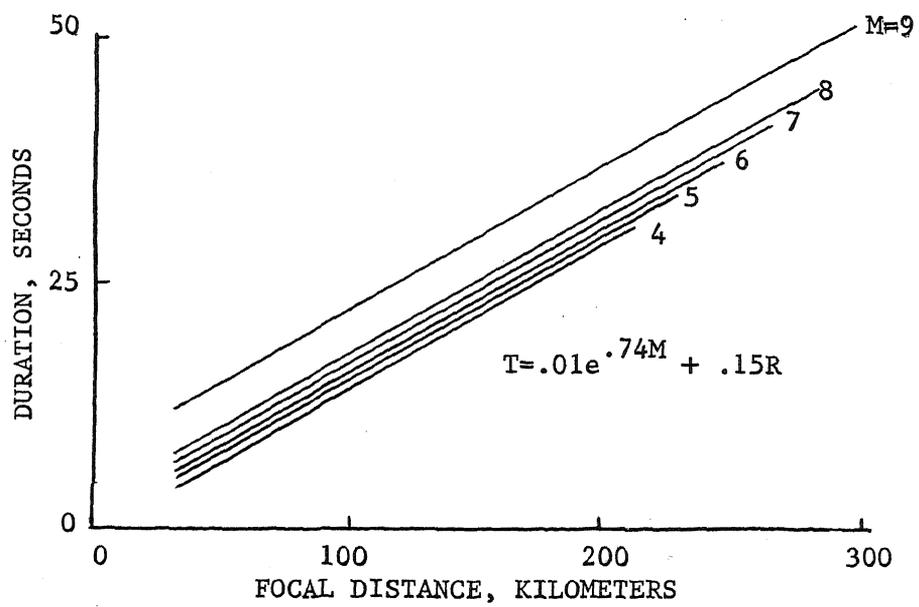


FIG. 4. DURATION OF STRONG MOTION.

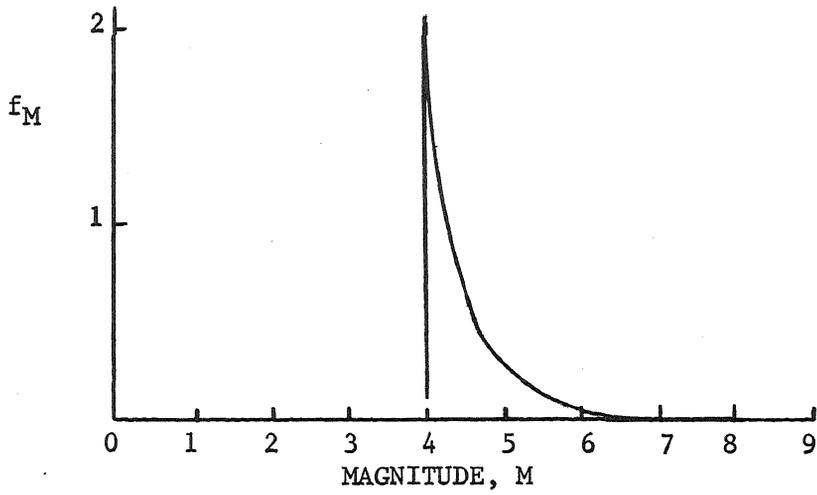


FIG. 5. PROBABILITY DENSITY FUNCTION FOR EARTHQUAKE MAGNITUDE. (5)

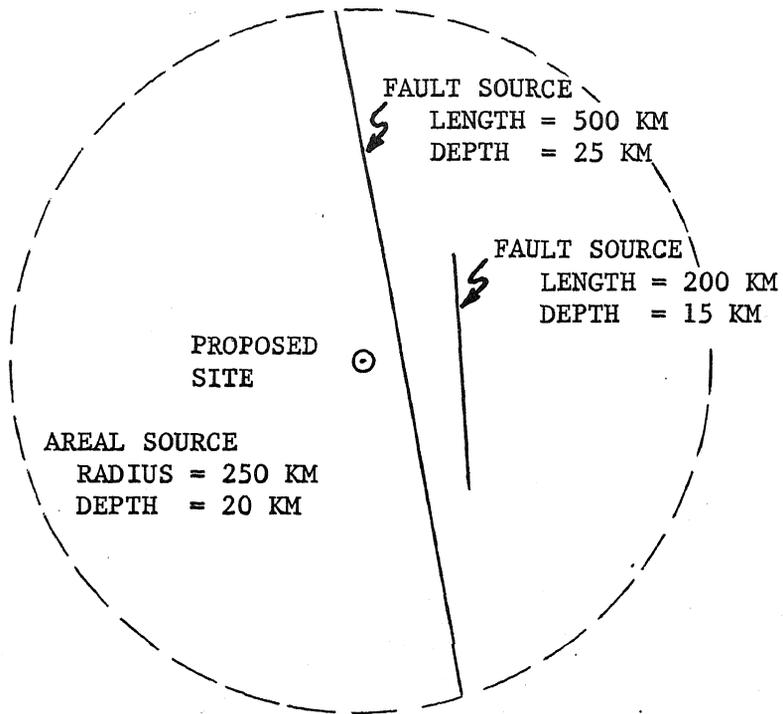


FIG. 6. PLAN VIEW OF HYPOTHETICAL SITE.