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Development of Instrumental Response Spectra with Equal Probability of Exceedance for SONGS Unit 1

PREPARED FOR

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1.0 SUMMARY AND FINDINGS

1.1 Summary

The objective of this study was to provide basic input data to be used in evaluating the probabilities of exceeding the design spectrum for San Onofre Nuclear Generating Station (SONGS) Unit 1. Specifically, this study provides instrumental response spectra with equal probabilities of exceedance for use in judging the probabilities of exceedance of the SONGS Unit 1 design spectrum.

The approach to evaluating probabilities of exceeding various levels of a ground motion parameter is shown schematically in Figure 1-1 and described in Section 2. The basic input requires the following information:

- Identification of seismicity sources and characterization of activity of each source;
- Specification of magnitude-rupture length relationships;
- Selection of attenuation relationships for peak ground acceleration and spectral ordinates at selected structural periods.

The assessment of these input items is discussed in Section 3. The results of the probability of exceedance calculations are described in Section 4.

The analyses results presented herein are a product of a carefully carried out evaluation of existing data. Best estimate and in some cases conservative input parameters with approproriate probability distributions were considered in the initial analysis as described to the NRC staff in Washington on 20 March 1980 (results shown in Sections 2 through 4). Subsequent to that meeting and in response to NRC concerns expressed during the meeting, sensitivity analyses were carried out on various input parameters. The results of these studies are discussed in Section 5. All cited references are listed in Section 6.

1.2 Findings

The results of the probability analyses as described in Sections 2 through 4 are summarized in Figure 1-2 in the form of equal probability spectra. Specifically, instrumental response spectra with equal probabilities of exceedance corresponding to peak accelerations of 4/10-, 1/2- and 2/3-g are presented. The corresponding probabilities of exceedance are 2×10^{-3}, 6×10^{-4} and 1×10^{-4}. These results are consistent with those presented in the 20 March 1980 NRC meeting. After consideration of the results of sensitivity studies on various input parameters (Section 5), it is concluded that the results presented in Figure 1-2 reflect a reasonable but conservative estimate of equal probability of exceedance spectra for the SONGS site consistent with the regional historic seismicity data as well as the geologic constraints on prehistoric seismicity.

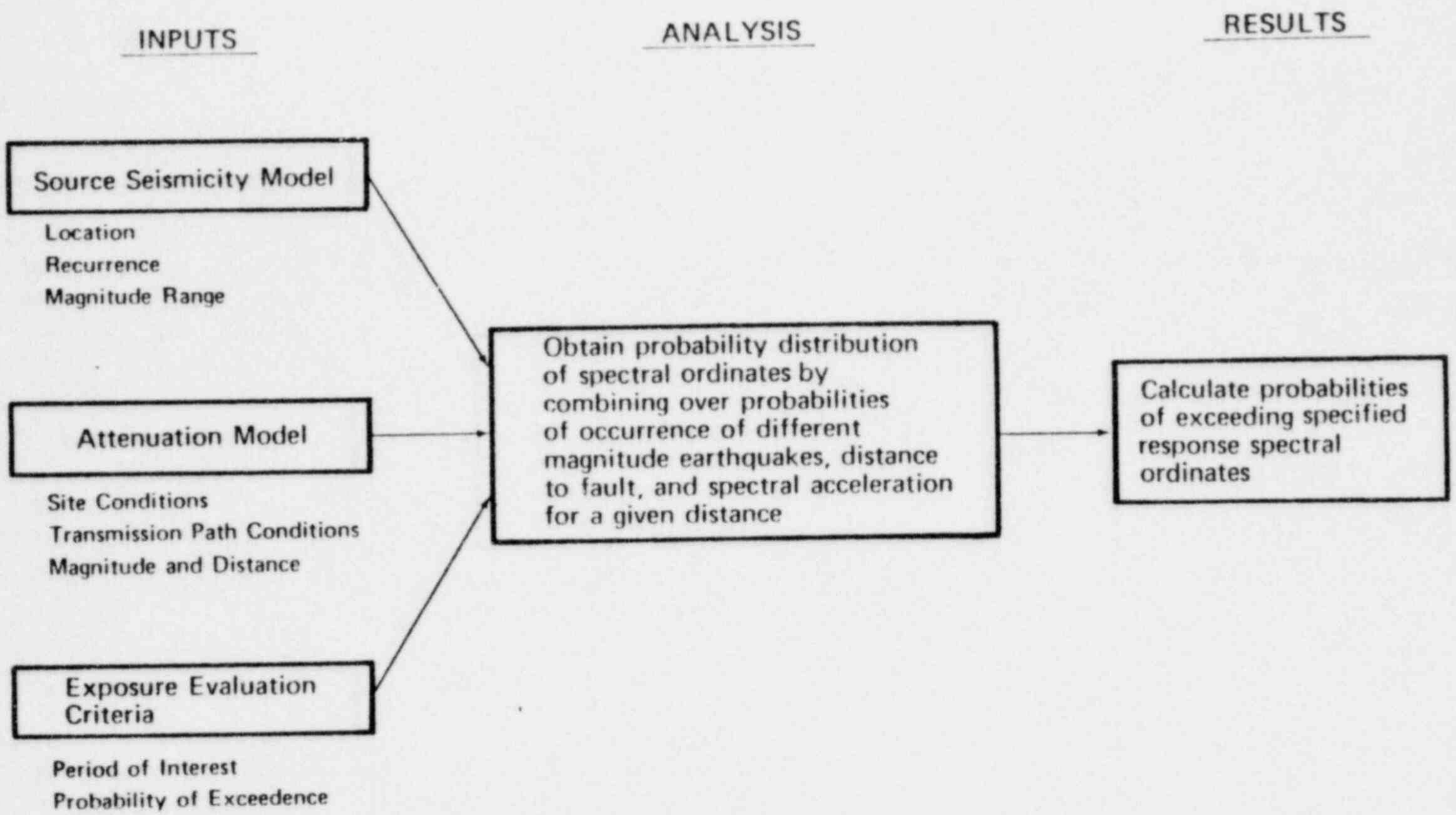

Figure 1-1 – Schematic Representation of Approach

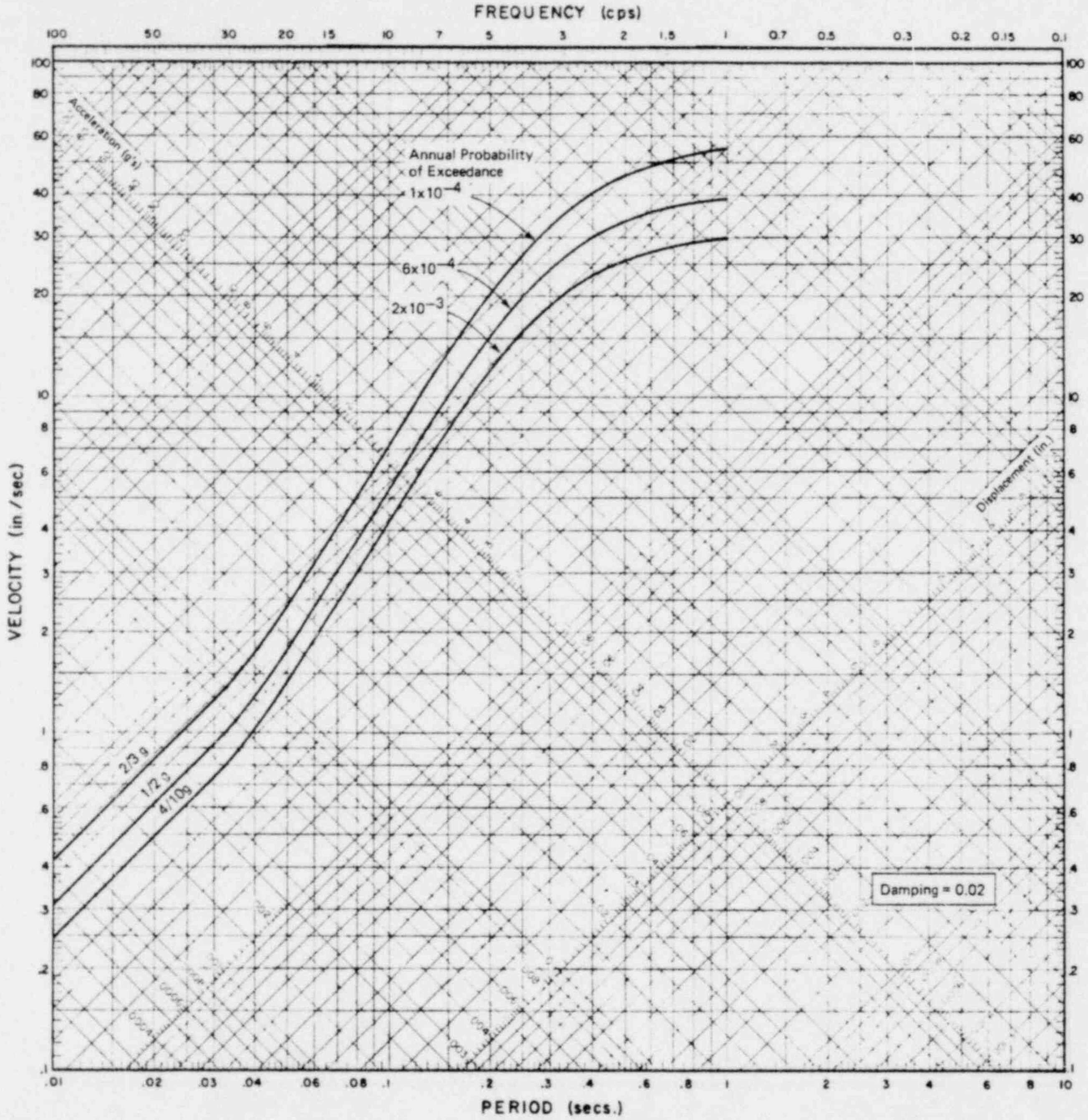

Figure 1-2 – Instrumental Response Spectra Associated with Various Annual Probability of Exceedance Levels

2.0 METHODOLOGY

This section provides a description of the methodology that was used to calculate probabilities of exceeding different levels of ground motion transmitted to the site from future earthquakes. The basic components of this methodology are described below.

2.1 Identification of Seismicity Sources

The sources which can generate earthquakes within the study region were identified and the geometry of these sources was delineated.

2.2 Characterization of Activity of Seismicity Sources

A Poisson model was assumed for the occurrence of earthquakes. The parameter of this model is the average number of earthquakes of different magnitude per unit time. This parameter is assessed from the Gutenberg-Richter relationship expressed as

$$\log N(M) = a - bM \qquad (2\text{-}1)$$

in which N(M) = number of earthquakes greater than or equal to magnitude M in unit time

a and b = empirical constants.

The constants a and b were estimated from the analysis of historic seismicity and geologic data. For engineering purposes, bounds on earthquake magnitude, M, may be used. The lower bound is the minimum magnitude of engineering significance (for example, a magnitude 4). The upper bound represents the magnitude of a maximum credible earthquake that each fault is capable of generating. Equation 2-1 was modified to account for the lower and upper bounds on earthquake magnitude.

2.3 Characterization of Attenuation of Ground Motion

The attenuation of ground motion was assumed to follow a relationship of the type shown below:

$$S = b_1 e^{b_2 M} (R + C)^{-b_3} \varepsilon \qquad (2\text{-}2)$$

in which S = ground motion parameter of interest (peak acceleration and spectral velocity for several periods up to 1 sec)

M = earthquake magnitude

R = source-to-site distance

b_1, b_2, b_3 = coefficients

C = magnitude-dependent constant = $K_1 e^{K_2 M}$ (2-3)

ε = random error term

2.4 Specification of Earthquake Magnitude Versus Rupture Length Relationship

The approach used in the present analysis incorporates a line-source model which includes the length of rupture during the earthquake in a manner similar to that suggested by Der Kiureghian and Ang., 1977. The release of earthquake energy was assumed to be along a line rupture of the fault. Closest distance from the site to the fault rupture was used in calculating the attenuation of earthquake ground motion. The following form of relationship was used for the rupture length, L_R for an earthquake of magnitude M:

$$L_R = \exp (C_1 + C_2 M), \text{ for } M \leq M_1 \qquad (2\text{-}4)$$

$$= \exp (C_3 + C_4 M), \text{ for } M > M_1 \qquad (2\text{-}5)$$

The constants C_1, C_2, C_3 and C_4 were estimated from historic data.

2.5 Calculation of Probabilities of Exceedance

The mean number of events in which a given level of ground motion parameter is exceeded at the site during the period of interest was calculated. Contributions of different magnitude earthquakes occurring on various sources and at different distances from the site were included in this calculation. The mean number of events was then used to calculate the probability that at least one such event would occur at the site during the specified period of interest.

The computer program SEEP developed by Woodward-Clyde Consultants (Kulkarni et al., 1979) was used to perform the probability calculations. The program displays the overall probability of exceeding a specified level of a ground motion parameter. In addition, contributions to the overall probability from the different sources, earthquake magnitudes, and distances are also displayed.

3.0 ASSESSMENT OF INPUT DATA

3.1 Geometry of Sources

Table 3-1 lists fault lengths, closest distance to each fault from the site of SONGS Unit 1, and the maximum magnitude assessed for each fault in the study region. The San Andreas, San Jacinto, Whittier-Elsinore, Palos Verdes faults, and the hypothesized OZD were selected for this analysis because the maximum earthquakes on these faults are expected to produce significant ground motions at the SONGS site.

Fault lengths were obtained principally from Jennings (1975), with more recent maps consulted as applicable. The closest point from the site to each fault was obtained by measuring a line from the site to the fault and perpendicular to the trend of the fault. In order to measure the endpoints of the faults, the faults were approximated by straight lines, with no bends. This approximation is generally close to the actual fault geometry. The approximate lines were structured such that the distance to the part of the fault closest to the site remained unchanged.

3.2 Activity of Sources

The magnitude-frequency relationship for each fault was determined from its moment rate using the method of Anderson (1979). In this method, all slip is assumed to occur seismically. Then the total moment rate (i.e. the product of slip rate, fault length, fault width, and shear modulus) is partitioned among events of different magnitude assuming the Gutenberg-Richter magnitude-frequency relationship, which must be truncated at some maximum magnitude.

The magnitude scale used with the method of Anderson (1979) is the moment magnitude scale (Hanks and Kanamori, 1979). These magnitude values do not differ significantly from M_S except for magnitudes greater than 7.5. A moment magnitude of 8.0 was used to represent the maximum magnitude on the San Andreas fault. This value is compatible with the moment magnitude of 7.9 for the 1857 Fort Tejon earthquake obtained by Hanks and Kanamori (1979).

Using the slip rate, maximum magnitude, fault length values, and an assumed fault width of 15 km, shear modulus of $3x10^{11}$ dyne/cm^2, and 'b' value of 0.85, the 'a' value of each fault was calculated. Table 3-2 shows the inputs used in the probability analysis.

The central segment of the San Andreas fault (north of Wrightwood) is judged to be more active than the southern segment. However, for the analysis, an average 'a' value was assumed for the entire fault. This is conservative, since the more active central segment is farther away from the site.

The selected 'a' value and the 'b' value for the combined faults and the corresponding number of large earthquakes calculated from the Gutenberg - Richter relationship are compared with other estimates for Southern California in Table 3-3. It can be seen that the expected number of large earthquakes calculated using the selected 'a' and 'b' values is only exceeded significantly by the number obtained from Anderson (1979) for an equivalent set of faults. Therefore, the selected recurrence parameters are conservative compared to those obtained from seismicity data. It should be noted that the estimates from siesmicity data generally pertain to much larger areas than that of the present study.

3.3 Attenuation Relationships

The form of the attenuation relationship given in Equation 2-2 was used for the present study. The parameters in this relationship were estimated for tectonic environment, transmission path characteristics, and local site conditions appropriate to SONGS. Expressions were derived for attenuation of peak ground acceleration and spectral velocities for several selected periods. Figure 3-1 shows the attenuation relationships for peak ground acceleration. Figure 3-2 illustrates the attenuation relationships for spectral velocity at a period of 0.4 seconds. An upper bound on each ground motion parameter was specified through a truncated distribution as described in Kulkarni et al., 1979. The upper bound values of the ground motion parameters used in this truncation accommodate an uncertainty band of greater than 3σ about the mean.

3.4 Magnitude-Rupture Length Relationship

The calculation of the closest distance to site requires the extent of fault rupture length for a given magnitude earthquake. For magnitudes greater than approximately 6-1/4, the dimension of the rupture surface was established based on the relationship for strike-slip faults given in Slemmons (1977). For magnitudes less than 6-1/4 the relationship given in Patwardhan and others (1975), which was derived on the basis of correlation between earthquake magnitude and length of aftershock zone, was selected.

TABLE 3-1

FAULT PARAMETERS USED IN SEISMIC EXPOSURE ANALYSIS

Fault or Zone of Deformation	Length (km)	Distance from SONGS Site to Closest Point on Fault (km)	Estimated Maximum Magnitude
San Andreas	540	92	8-1/4
San Jacinto	260	69	7-1/2
Whittier-Elsinore	230	37	7
Hypothesized OZD	200	8	6-1/2
Palos Verdes	100	18	6-1/2

TABLE 3-2

DATA ON SEISMIC ACTIVITY OF SOURCES USED IN SEISMIC EXPOSURE ANALYSIS

Fault or Zone of Deformation	Maximum Earthquake	Average Number of Earthquakes Greater than $M_s = 4$ in One Year on the Entire Fault	Slope 'b' for the Gutenberg-Richter Relationship $\log_{10}N(M) = a - bM$
Central and Southern San Andreas	8-1/4	15.04	0.85
San Jacinto	7-1/2	3.39	0.85
Whittier-Elsinore	7	2.04	0.85
Hypothesized OZD	6-1/2	0.82	0.85
Palos Verdes	6-1/2	0.41	0.85

TABLE 3-3

COMPARISON OF DIFFERENT ESTIMATES OF a AND b VALUES

FOR SOUTHERN CALIFORNIA

Source	Region	Time Interval	a	b	Normalized w.r.t. this study N(M>6)	Normalized w.r.t. this study N(M>7)
1. This study	S. California (specific faults)	(Pleistocene slip rate)	4.74	0.85	(0.44/yr) 1	(0.062/yr) 1
2. Anderson (1979)	S. California	(Pleistocene)	4.99	0.86	1.56	1.52
3. Richter (1958)	S. California (300,000 km^2)	1934 - 1943	4.77	0.85	1.09	1.07
4. Ryall et al. (1966)	Southern California (60,000 km^2)	before 1932	2.53	0.55	0.39	0.78
5. Ryall et al. (1966)	Southern California (60,000 km^2)	1932 - 1961	4.30	0.79	0.83	0.96
6. Hileman et at. (1973)	S. California (238,600 km^2)	1932 - 1971	5.36	0.98	0.69	0.52
7. Hileman et al. (1973)	Los Angeles Area	1932 - 1971	4.33	0.93	0.63	0.62
	Imperial Valley		4.27	0.85		
	Parkfield		3.64	0.80		

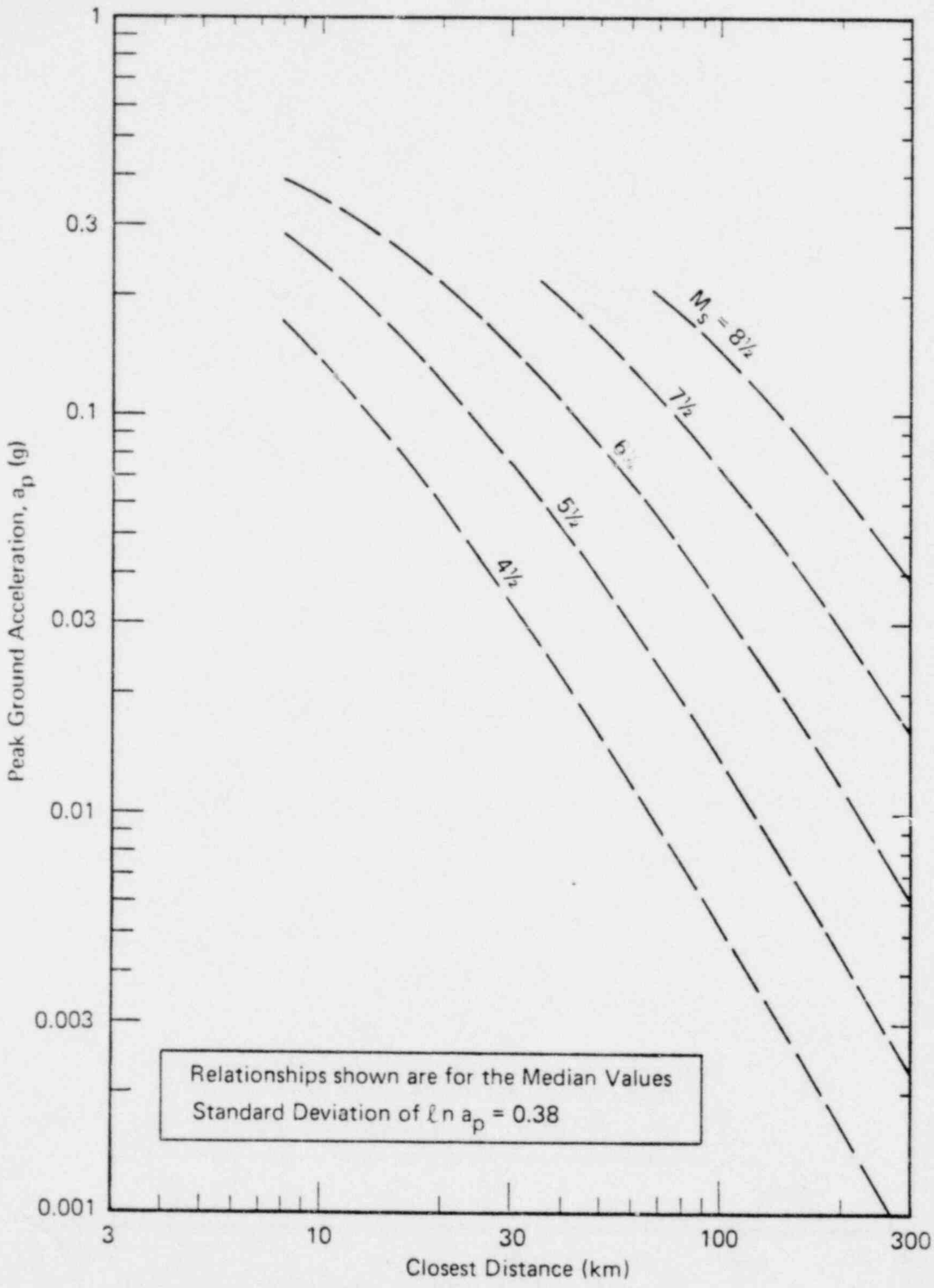

Figure 3-1 – Attenuation Relationships for Peak Ground Acceleration

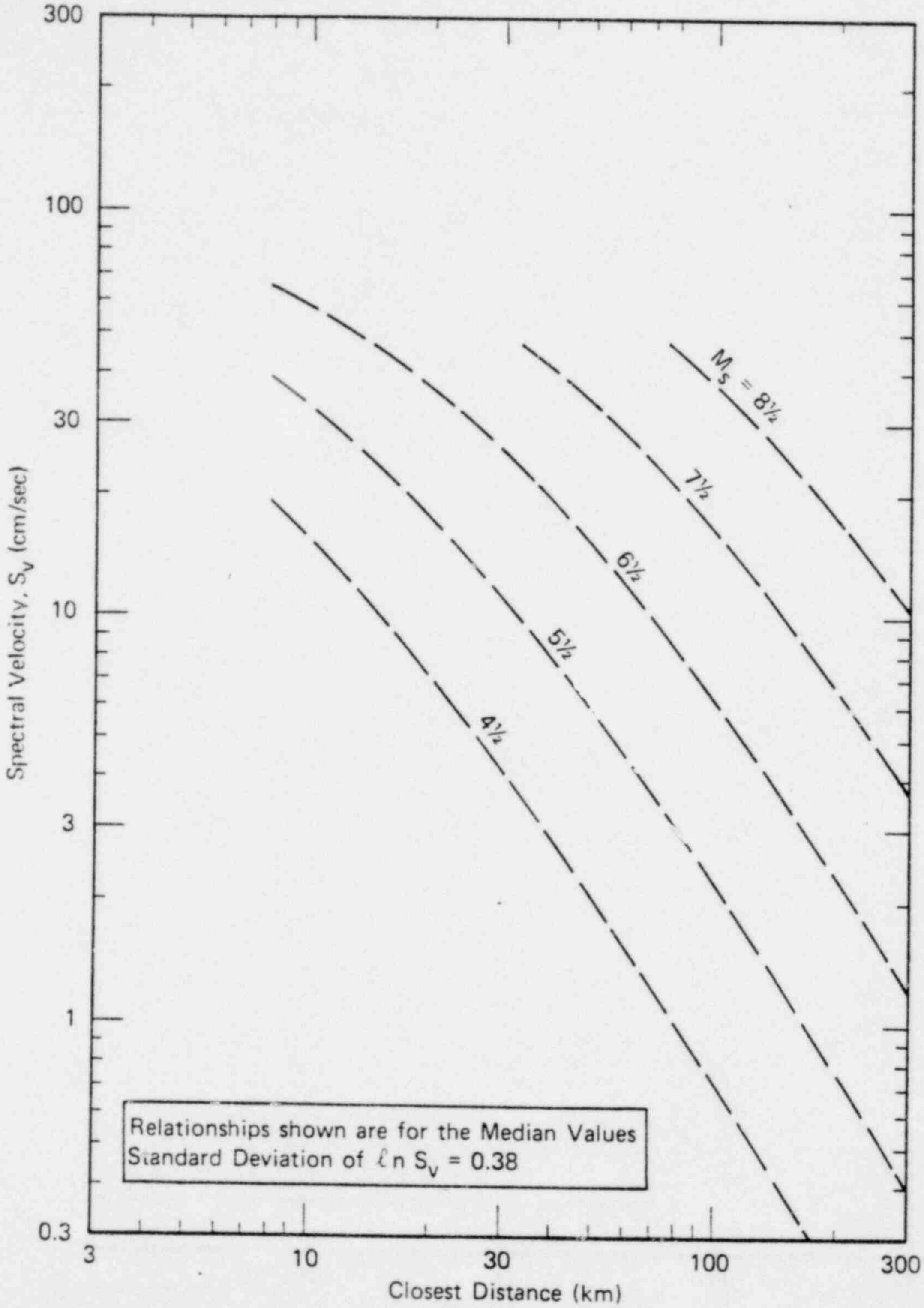

Figure 3-2 – Attenuation Relationships for Response Spectral Velocity
(Period = 0.4 seconds, Damping = 0.02)

4.0 RESULTS

This section describes briefly the main results of the probabilistic evaluation of seismic exposure.

4.1 Probability of Exceedance Relationships for Ground Motion Parameters

The mean number of events per year, λ, in which a given level of a ground motion parameter is exceeded at the site was obtained directly from the output of the computer program. The annual probability of exceedance, p_A, was then calculated from

$$p_A = 1 - e^{-\lambda}. \qquad (4\text{-}1)$$

The annual probabilities of exceeding different levels of peak ground acceleration are shown in Figure 4-1. Figures 4-2 through 4-5 show the annual probabilities of exceeding different levels of spectral velocity at selected periods.

4.2 Development of Equal Probability Instrumental Response Spectra

Instrumental response spectra associated with desired annual probability of exceedance levels were obtained from relationships shown in Figures 4-1 through 4-5 for various periods. The spectral values corresponding to annual probability of exceedance levels of 2×10^{-3}, 6×10^{-4} and 1×10^{-4} are presented below.

	S_v (cm/sec) corresponding to		
Period	$P_A = 2 \times 10^{-3}$	$P_A = 6 \times 10^{-4}$	$P_A = 1 \times 10^{-4}$
0	ZPA = 0.4g	ZPA = 0.5g	ZPA = 2/3g
0.1	10.8	13.5	17.6
0.2	30	38	50
0.4	59	76	103
1.0	75	100	140

The instrumental response spectra corresponding to these three annual probability of exceedance levels are shown in Figure 1-3.

4.3 Contribution of Source, Magnitude and Distance to Probability of Exceedance

The annual probability of exceedance values presented above include all of the contributions from the different magnitude earthquakes which could occur along the lengths of the sources examined in this study. Each source, distance, and earthquake magnitude combination contributed a different amount to the total exposure. As can be observed from the table below, the total probability of exceedance was dominated by the contribution from the Hypothesized OZD.

Period	Relative Contribution from the Hypothesized OZD to the Total Probability of Exceedance
0-0.04 sec.	94 - 99 percent
0.1	93 - 99
0.2	92 - 98
0.4	84 - 96
1.0	50 - 60

Earthquakes with magnitudes 5-1/2 to 6-1/2 rupturing to distances within 8 to 12 kilometers of the site provided the vast majority of these contributions from the Hypothesized OZD. For each other source, most of its contributions similarly came from the larger magnitude earthquakes with rupture at the closest distance from the site.

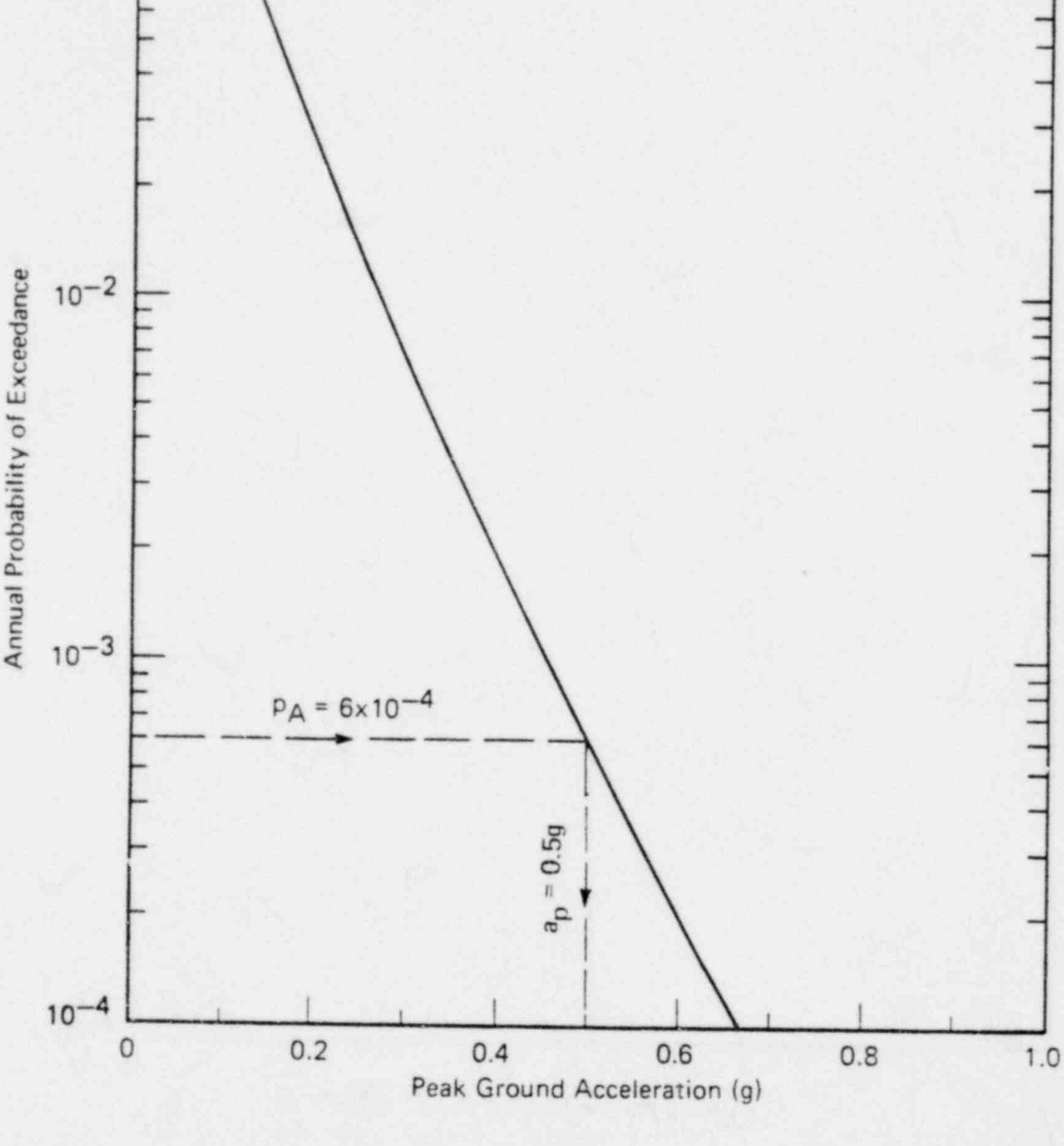

Figure 4-1 – Annual Probabilities of Exceeding Different Levels of Peak Ground Acceleration

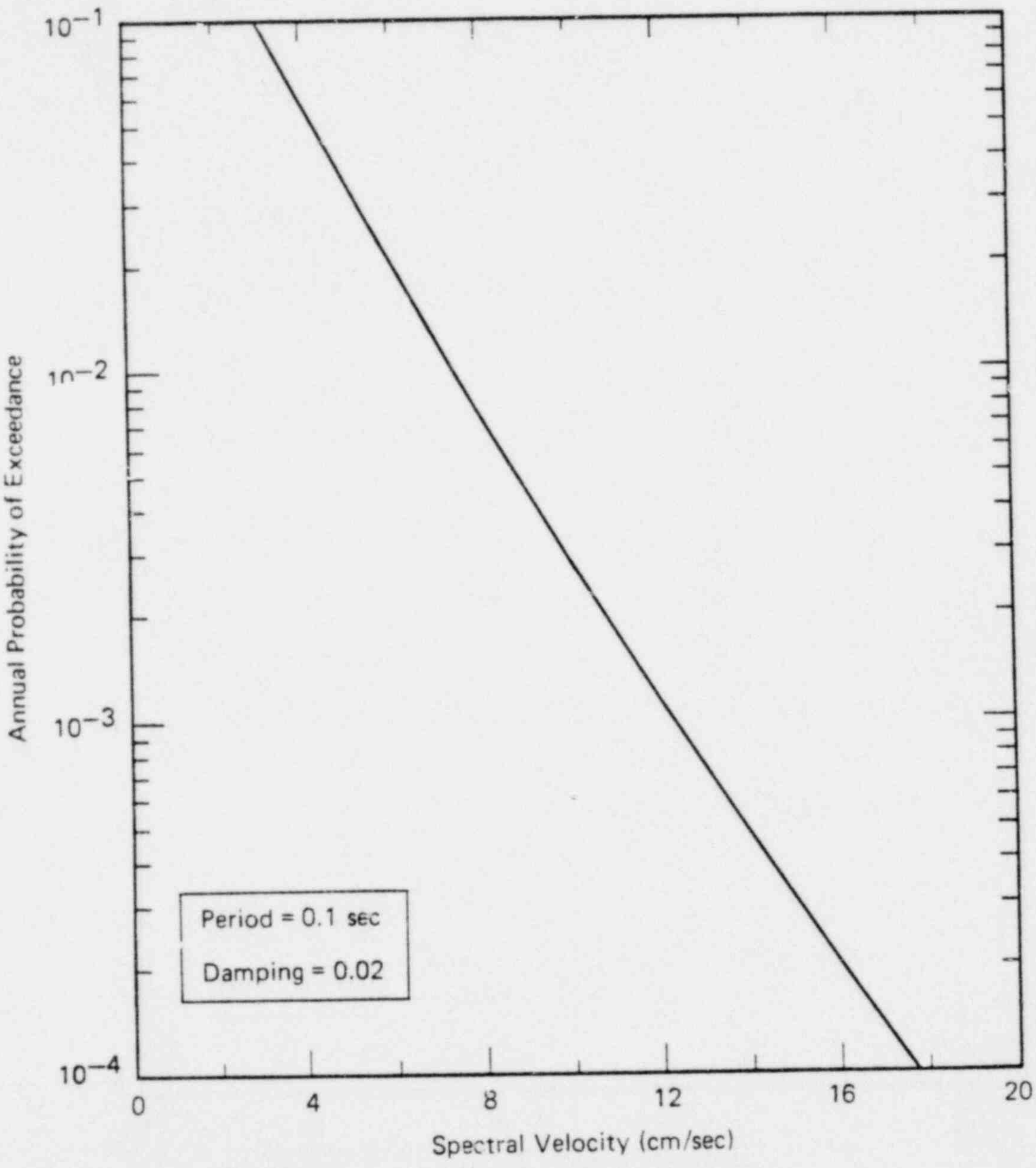

Figure 4-2 – Annual Probabilities of Exceeding Different Levels of Spectral Velocity (Period = 0.1 sec, Damping = 0.02)

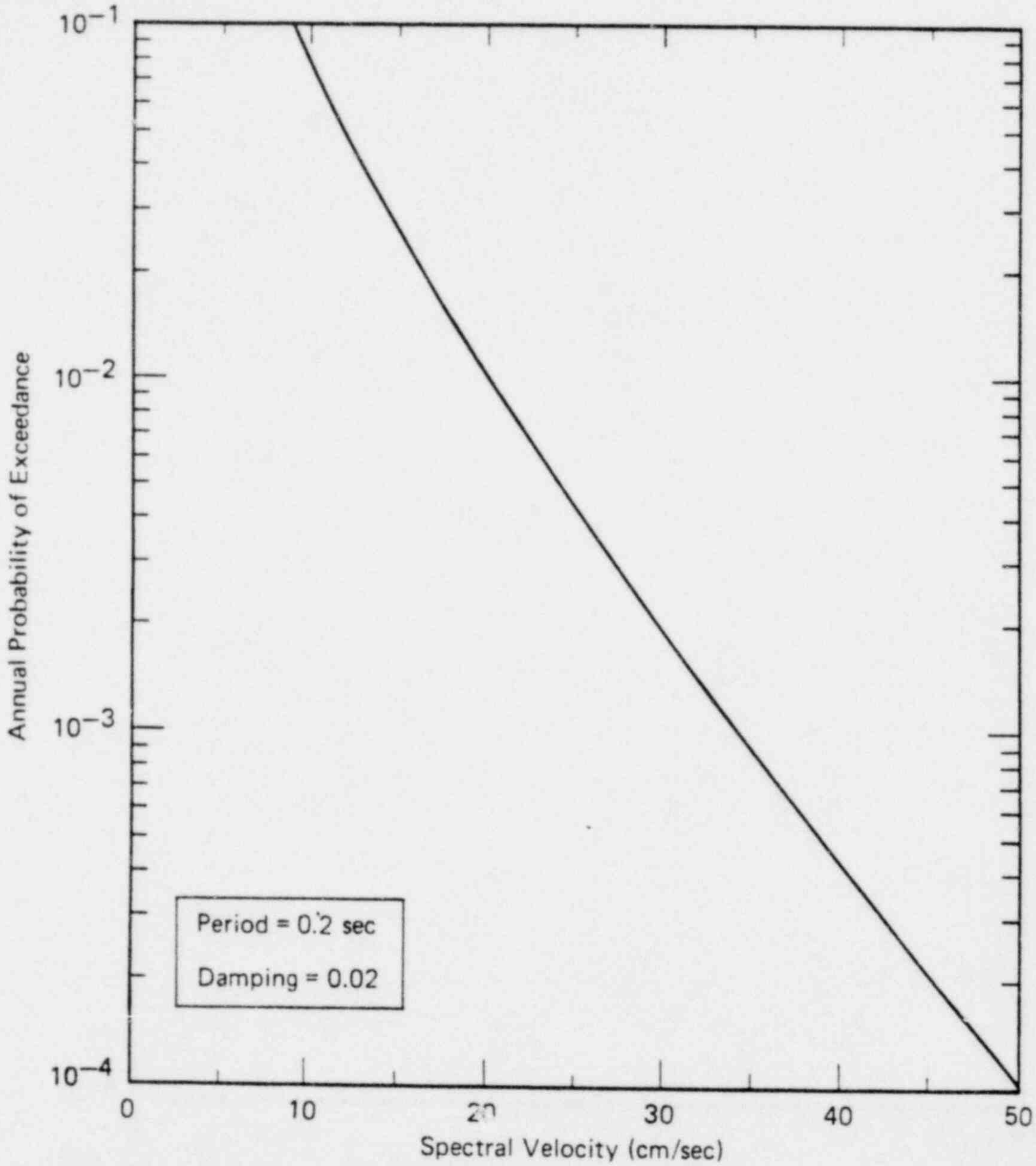

Figure 4-3 – Annual Probabilities of Exceeding Different Levels of Spectral Velocity (Period = 0.2 sec, Damping = 0.02)

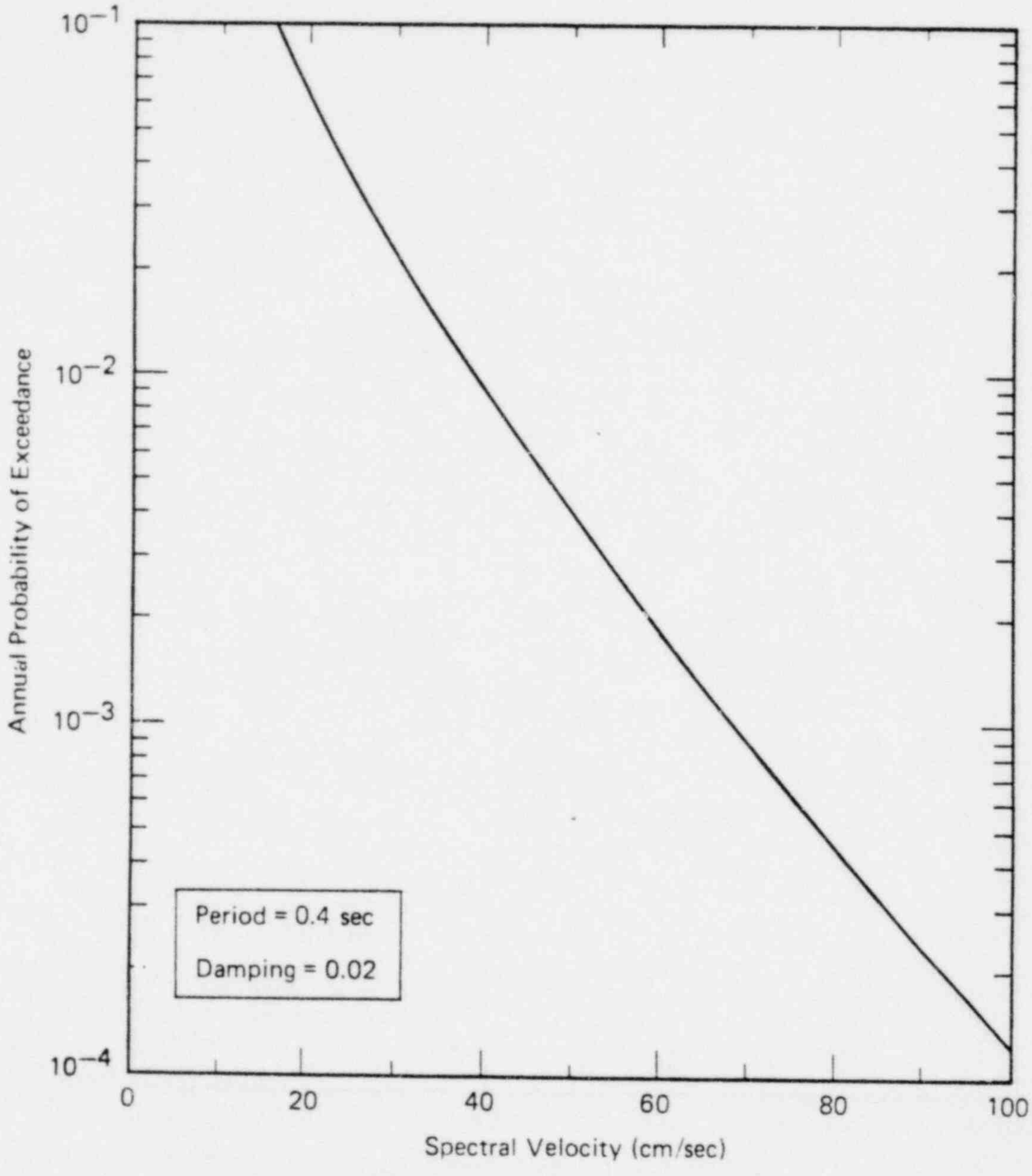

Figure 4-4 — Annual Probabilities of Exceeding Different Levels of Spectral Velocity (Period = 0.4 sec, Damping = 0.02)

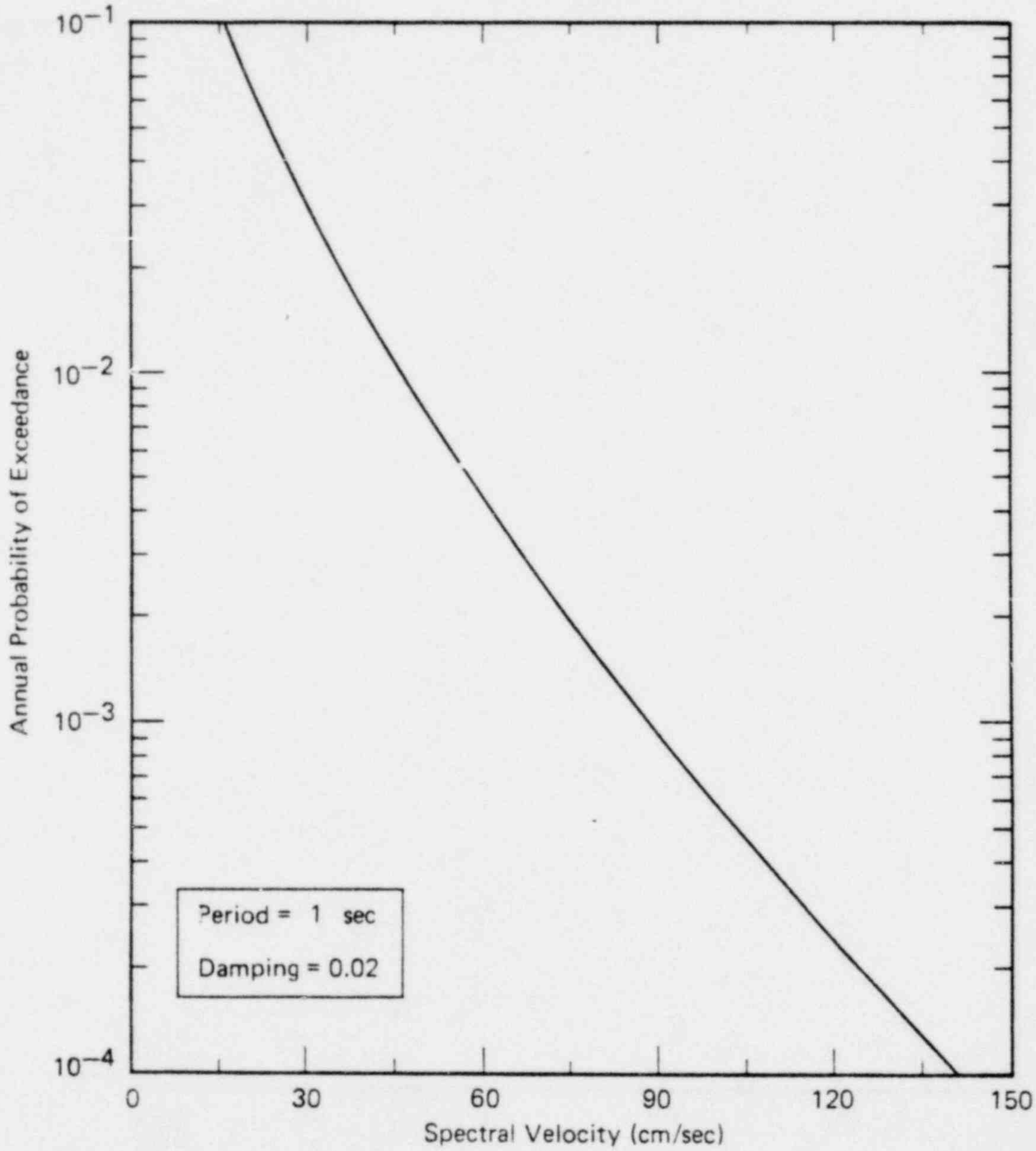

Figure 4-5 – Annual Probabilities of Exceeding Different Levels of Spectral Velocity (Period = 1 sec, Damping = 0.02)

5.0 SENSITIVITY OF THE PROBABILITY OF EXCEEDANCE TO INPUT DATA VARIATION

5.1 Introduction

The expected values of annual probability of exceedance presented above were based on the best estimates of the input data from the assessment described in Section 3. To examine the sensitivity of those results to variations of the input data, the probabilities of exceeding various levels of instrumental peak ground accelerations have also been evaluated for extreme ranges of the various input parameters. In these sensitivity analyses, variations have been limited to the data pertaining to the Hypothesized OZD rather than the entire study region because, as discussed in Section 4.3, the Hypothesized OZD dominates the total exposure of the site.

5.2 Results of Sensitivity Analyses

The results of the analyses for an instrumental peak acceleration of 0.5 g, which are typical for other levels of instrumental peak acceleration, are summarized below:

- for slip rate variations within the 0.30 to 0.68 mm/year range assigned to the Hypothesized OZD (value in analysis documented in Section 4 was 0.5 mm/year), the annual probability of exceedance ranges between 4×10^{-4} and 8×10^{-4};

- for values of the parmeter 'b' (of the Gutenberg-Richter relationship) between 0.7 and 1.0, the annual probability of exceedance varies from 3×10^{-4} to 8×10^{-4};

- for a maximum magnitude earthquake of M_s = 7 on the Hypothesized OZD together with the maximum slip rate for the Hypothesized OZD, the annual probability of exceedance was calculated to be within 10% of that calculated for M_s 6-1/2;

- using dispersion values varying with magnitude from 0.62 for magnitudes 4 to 4-1/2 to 0.38 for magnitudes 6 to 6-1/2 with the mean attenuation relationships presented in Section 3, has minor effect (approximately 20 percent increase) on the annual probability of exceedance for the magnitude range 5-1/2 to 6-1/2 which, as discussed in Section 4.3, provides the vast majority of the Hypothesized OZD contribution;

The use of this type of dispersion relationship, i.e. decreasing with increasing magnitude, is consistent with the observed trend of the empirical data. Donovan and Bornstein (1978) provide dispersion values as a function of acceleration level (varying from 0.3 for accelerations greater than 0.3 to 0.48 for an acceleration of 0.05 g). Also, the use of dispersion values (larger than 0.38) with the mean attenuation relationship selected for SONGS would be too conservative. In general, published relationships with higher reported dispersions exhibit a correspondingly lower mean peak acceleration and cover a wider range in site conditions than the attenuation relationship used in the present study (Idriss, 1978 contains a summary of widely used attenuation relationships). As a result, the calculated probabilities of exceedance using a lower mean acceleration level would be decreased providing little or no effect on the calculated probabilities.

Considering the observations above, the annual probability of exceedance for an instrumental peak ground acceleration of 0.5 g was found to be in the range of 3×10^{-4} to 9×10^{-4} for reasonable variations of the input data. Because this represents a small variation in probability from the calculated 6×10^{-4} and because the variations evaluated above are considered extreme, the calculated equal probability spectra shown on figure 1-3 are considered reasonable and conservative for the SONGS site.

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