9pgs 22

10142 NOVEMBER 1973 PO2

JOURNAL OF
THE POWER DIVISION

Seismic Design Spectra for Nuclear Power Plants

By Nathan M. Newmark,[1] Hon. M. ASCE, John A. Blume,[2] F. ASCE, and Kanwar K. Kapur,[3] M. ASCE

Introduction

Statistical studies made recently of a number of earthquakes under the sponsorship of the Directorate of Licensing, U.S. Atomic Energy Commission, are reported herein with a view toward developing recommendations for design response spectra to be used for nuclear power plant facilities. The recommendations made herein are preliminary and are the results of conversations among the participants in the program, but represent the personal views of those conducting the work and are not to be construed as stating an official AEC position.

This report describes the general nature of the studies made, and gives in detail some of the significant features of the results. Recommended criteria and design spectra are given herein which differ somewhat from previous recommendations but which are in general accord with current practice based on previous recommendations.

Nature of Study

When the ground moves in an earthquake, the maximum responses of a dynamic system founded on the ground can be computed by standard methods of analysis. One of the most convenient ways of portraying the maximum responses of

Note.—Discussion open until April 1, 1974. To extend the closing date one month, a written request must be filed with the Editor of Technical Publications, ASCE. This paper is part of the copyrighted Journal of the Power Division, Proceedings of the American Society of Civil Engineers, Vol. 99, No. PO2, November, 1973. Manuscript was submitted for review for possible publication on May 9, 1973.

[1] Nathan M. Newmark Consulting Engrg. Services, Urbana, Ill.
[2] John A. Blume and Assocs., Engrs., San Francisco, Calif.
[3] Directorate of Licensing, U.S. Atomic Energy Commission, Washington, D.C.

the elements in a dynamic system involves the "response spectrum" (1,5). In the studies reported herein, the response spectra used give data for "maximum pseudo relative velocity," designated hereafter as "velocity;" "maximum relative displacement," designated hereafter as "displacement;" and "maximum pseudo absolute acceleration," designated hereafter as "acceleration." In general, these three quantities are plotted on a single chart against frequency in a so-called tripartite logarithmic plot, as in Fig. 1. Alternatively, dynamic amplification

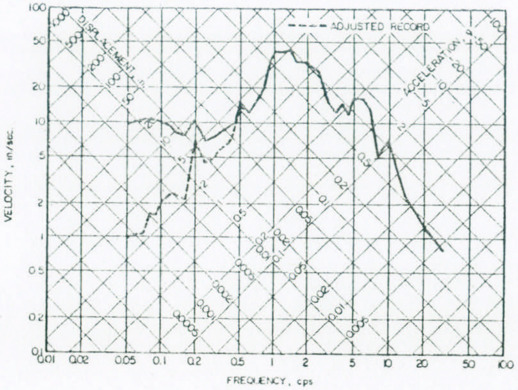

FIG. 1.—Response Spectra for San Fernando, Calif., February 9, 1971—Castaic N69W Unadjusted Record—0.5% of Critical Damping

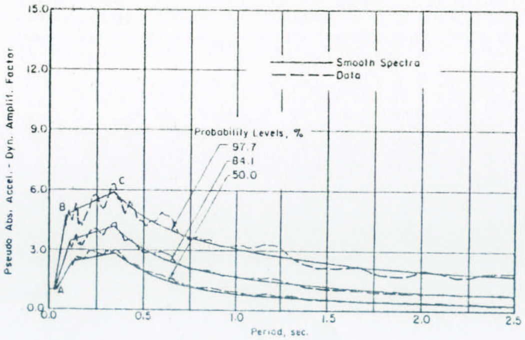

FIG. 2.—Comparison of Smooth Spectra with Data, Damping Ration = 0.02

factors can be plotted on an arithmetic plot against frequency or period, as in Fig. 2.

In making the calculations for a response spectrum, it is sometimes necessary to adjust the strong motion recording of acceleration to account for baseline shifts or other irregularities that give, for the unadjusted record, a velocity at the end of the input ground motion, or a terminal displacement that is unreasonably large because of the accumulation of small errors in the process of integration of the record. In general, however, for responses at intermediate and high frequencies, minor or no adjustement of the record is required. As

an illustration, Fig. 1 shows the unadjusted response spectrum for the motion recorded at Castaic in the San Fernando earthquake of 1971, compared with the response spectrum for the adjusted record. The results are typical in that the difference between the two response spectra is significant only for frequencies below about 0.4 Hz. In some few instances, discrepancies arise in other spectra at slightly higher frequencies.

In the calculation of response spectra, the influence of the spacing of frequencies for which calculations are made can affect the shape of the response spectrum. In general, however, this influence need not be large provided that a reasonably close spacing is used for the higher frequencies.

From our studies spectra similar to those in Figs. 1 or 2 were determined. The processing of the records led to the general conclusion that the important features of the response spectra, for design purposes, could be represented by a conventionalized or simplified curve having the shape shown in Fig. 3. In this response spectrum the various regions are represented by straight lines

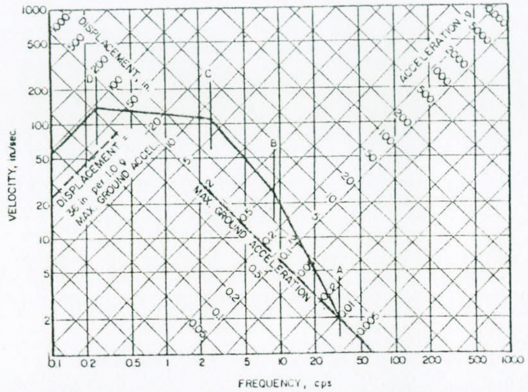

FIG. 3.—Design Spectrum Showing Control Frequencies

on a tripartite logarithmic plot, and the control frequencies A, B, C, and D designate the transitions from one straight line segment to another. Further comments on the design spectrum will be made later.

Both of the studies involved independent calculations of response spectra for a number of earthquakes, and then the processing of these results by statistical methods. Generally, the statistical processing involved calculation, over the entire frequency range, of the mean and the standard deviation of response spectrum values scaled or normalized to some predetermined parameter in such a way that the results could be compared. In the studies made by John A. Blume and Associates, all comparisons were based on values normalized to the same value of maximum ground acceleration, with primary consideration given to the high and intermediate range of frequencies. In the Nathan M. Newmark Consulting Engineering Services study, the normalizations were made either to maximum ground acceleration, maximum ground velocity, or maximum ground displacement over the entire range of frequencies; but primary consideration was given to the normalization relative to maximum velocity for intermediate

TABLE 1.—Earthquake Accelerograms Considered

Earthquake (1)	Year (2)	Recording station (3)	Component[a] (4)	Peak ground acceleration, in g units (5)
El Centro[b,c]	1940	El Centro, Calif.	NS	0.33
			EW	0.22
			Vertical	0.28
El Centro[b]	1934	El Centro, Calif.	NS	0.26
			EW	0.18
Kern County[b]	1952	Taft, Calif.	N21°E	0.18
			S69°E	0.16
Olympia[b]	1949	Olympia, Wash.	N4°W	0.19
			S86°W	0.31
Helena[b]	1935	Helena, Mont.	NS	0.13
			EW	0.16
San Francisco[b,c]	1957	Golden Gate Park, Calif.	N10°E	0.11
			N80°W	0.13
			Vertical	0.051
Parkfield[b]	1966	Cholame-Shandon No. 2, Calif.	N65°E	0.51
			S25°W	Not recorded
Parkfield[b]	1966	Cholame-Shandon No. 5, Calif.	N5°W	0.40
			N85°E	0.47
Tokachi-Oki[b]	1968	Hachinohe, Japan	NS	0.19
			EW	0.23
Lima[b]	1966	Lima, Peru	N8°E	0.42
			N82°W	0.27
San Fernando[b,c]	1971	Castaic, ORR, Calif.	N21°E	0.34
			S69°E	0.29
			Vertical	0.18
San Fernando[b,c]	1971	Bank of California, California	N11°E	0.23
			N79°W	0.14
			Vertical	0.108
San Fernando[b]	1971	Universal—Sheraton, Calif.	NS	0.18
			EW	0.13
San Fernando[b,c]	1971	V.N. Holiday Inn, California	NS	0.28
			EW	0.15
			Vertical	0.177
Eureka[b,c]	1954	Eureka, Calif.	N79°E	0.26
			N11°W	0.18
			Vertical	0.11
Olympia[b]	1965	Olympia, Wash.	S4°E	0.20
			S86°W	0.16
Parkfield[b]	1966	Temblor, Calif.	N65°W	0.28
			N25°E	0.33
El Centro[c]	1956	El Centro, Calif.	NS	0.036
			EW	0.055
			Vertical	0.016
El Centro[c]	1968	El Centro, Calif.	NS	0.142
			EW	0.058
			Vertical	0.036

TABLE 1.—*Continued*

(1)	(2)	(3)	(4)	(5)
Kern County[c]	1952	Hollywood Storage Basement, California	NS	0.059
			EW	0.046
			Vertical	0.023
Kern County[c]	1952	Hollywood Storage PE Lot, California	NS	0.063
			EW	0.043
			Vertical	0.023
San Fernando[c]	1971	Pacoima Dam, California	S74°W	1.250
			S16°E	1.241
			Vertical	0.718
Ferndale[c]	1951	Ferndale, Calif.	N46°W	0.120
			S44°W	0.123
			Vertical	0.032
Ferndale[c]	1954	Ferndale, Calif.	N46°W	0.209
			N44°E	0.166
			Vertical	0.045
Hollister[c]	1961	Hollister, Calif.	S01°W	0.076
			N89°W	0.189
			Vertical	0.056

[a] Vertical components were considered in the Mohraz-Hall-Newmark study only.
[b] Blume-Sharpe-Dalal study.
[c] Mohraz-Hall-Newmark study.

frequencies, and relative to maximum acceleration for high frequencies.

The various studies indicate that the distribution function for the normalized spectral values or for the amplification factors relative to the maximum ground motion is of a type that can be characterized as either a normal or a log-normal probability distribution. Comparisons of the relative order of rank of the amplification values at a particular frequency, as well as statistical significance tests, were made in some instances, and the results indicated that the normal or log-normal distribution functions checked quite accurately with the relative rank of the numerical values.

Although various partitions of the data were made for the study of factors such as geologic conditions, intensity of motion, etc., valid statistical inferences about the nature of these differences could not be made from the data, and generally, all of the data were considered in drawing the conclusions reported herein.

Earthquakes Considered

The earthquake records used in the study are summarized in Table 1. In the Blume study two components of horizontal motion were used for each of 16 earthquakes, and one component for an additional earthquake. Thus a total of 33 different earthquake records were considered. The maximum ground acceleration for these earthquakes ranged from 0.11 g to 0.51 g, in which g is the acceleration of gravity.

In the Newmark study 14 earthquakes were considered, with two components

TABLE 2.—Recommended Spectral Shape Factors—Horizontal, Blume-Sharpe-Dalal Study

Probability level, as a percentage (1)	Damping, percentage critical (2)	Point A		Point B		Point C	
		Period, in seconds (3)	Amplification factor (4)	Period, in seconds (5)	Amplification factor (6)	Period, in seconds (7)	Amplification factor (8)
50	0.5	0.03	1.0	0.12	3.2	0.35	4.0
	1.0	0.032	1.0	0.12	2.8	0.35	3.5
	2.0	0.034	1.0	0.12	2.5	0.35	2.9
	5.0	0.036	1.0	0.12	2.0	0.35	2.3
	7.0	0.038	1.0	0.12	1.85	0.35	2.0
	10.0	0.040	1.0	0.12	1.7	0.35	1.75
84.1	0.5	0.028	1.0	0.11	5.1	0.35	6.2
	1.0	0.029	1.0	0.11	4.1	0.35	5.0
	2.0	0.030	1.0	0.11	3.5	0.35	4.2
	5.0	0.031	1.0	0.11	2.6	0.35	3.1
	7.0	[illegible]	1.0	0.11	2.2	0.35	2.6
	10.0	0.033	1.0	0.11	2.0	0.35	2.3

TABLE 3.—Horizontal Design Spectral Values for Mohraz-Hall-Newmark Study

Quantity (1)	Probability level, as a percentage (2)	Damping, Percentage Critical			
		0.5 (3)	2.0 (4)	5.0 (5)	10.0 (6)
Amplification factor					
D	50	1.97	1.68	1.40	1.15
	84.1	2.99	2.51	2.04	1.62
V	50	2.58	2.06	1.66	1.34
	84.1	3.81	2.98	2.32	1.81
A	50	3.67	2.76	2.11	1.65
	84.1	5.12	3.65	2.67	2.01
Spectral bounds—Alluvium					
D, in inches	50	71	60	50	41
	84.1	108	90	73	58
V, in inches per second	50	124	99	80	64
	84.1	183	143	111	87
Spectral bounds—Rock					
D, in inches	50	24	20	17	14
	84.1	36	30	25	19
V, in inches per second	50	72	58	46	38
	84.1	107	83	65	51

1 in. = 25.4 mm.

Transition from amplified to ground acceleration begins at 6 Hz for all damping values and ends at 40 Hz, 30 Hz, 20 Hz, 20 Hz, respectively, for damping values of 0.5%, 2.0%, 5.0%, and 10.0%.

of horizontal motion and one component of vertical motion being used for each earthquake. The maximum ground acceleration varied from 0.016 g to 0.718 g in the vertical direction and from 0.036 g to 1.25 g in the horizontal directions. Fourteen vertical records and 28 horizontal records were used in the calculations.

Although an attempt was made to characterize the site descriptions for the various earthquakes, as rock, alluvium, or otherwise, these descriptions are not completely dependable due to a lack of satisfactory information about the geologic conditions at most of the sites where strong motion instruments have been located.

General Nature of Results of Blume Study

Details of the John A. Blume and Associates study are given in Ref. 2. Table 2 partly presents recommended spectral shape factors for a spectrum shape only slightly different than the one in Fig. 3. Slight differences arise from the fact that the linear relationships, AB and BC, are shown on an arithmetic plot in Ref. 3, whereas Fig. 3 depicts them on a tripartite log plot. The values in Table 2 are for amplification factors relative to maximum ground acceleration at control frequencies A, B, and C.

TABLE 4.—Vertical Design Spectral Values for Mohraz-Hall-Newmark Study

Quantity (1)	Probability level, as a percentage (2)	Damping, Percentage Critical			
		0.5 (3)	2.0 (4)	5.0 (5)	10.0 (6)
Amplification factor					
D	50	1.86	1.65	1.40	1.16
	84.1	2.78	2.41	2.01	1.62
V	50	2.52	1.97	1.51	1.17
	84.1	3.81	2.91	2.18	1.64
A	50	4.02	2.80	2.05	1.59
	84.1	6.15	4.13	2.82	2.08
Spectral bounds—Alluvium					
D, in inches	50	61	54	46	38
	84.1	92	80	66	54
V, in inches per second	50	73	57	44	34
	84.1	110	84	63	48
A, g	50	2.68	1.87	1.37	1.06
	84.1	4.10	2.75	1.88	1.09
Spectral bounds—Rock					
D, in inches	50	20	18	15	13
	84.1	31	27	22	18
V, in inches per second	50	43	33	26	20
	84.1	65	49	37	28
A, g	50	2.68	1.87	1.37	1.06
	84.1	4.10	2.75	1.88	1.09

1 in. = 25.4 mm.

Transition from amplified to ground acceleration begins at 10 Hz and ends at 50 Hz for all damping values.

A log-normal distribution was found statistically acceptable for the spectral shape data. Parameters for the log-normal distribution were determined from sample moments, such as mean and standard deviation. Spectral shapes for probability levels of 50% (median), 84.1% (equivalent to mean + one standard deviation), and 97.7% (equivalent to mean + two standard deviations) were derived using the log-normal distribution at each of 108 frequencies over a range of 0.4 Hz to 25 Hz. The spectral shapes for a 2% damping ratio are shown by the broken lines in Fig. 2. The recommended smoothed shapes (solid lines)corresponding to Table 2 are also presented in the figure. The smooth curves closely match the data. Spectrum shapes were also developed for damping ratios of 0.5%, 1%, 5%, 7%, and 10%. A study to develop an acceleration time history compatible with the recommended shapes indicated that a properly chosen single time history gives response spectra that closely match the curves for all damping ratios.

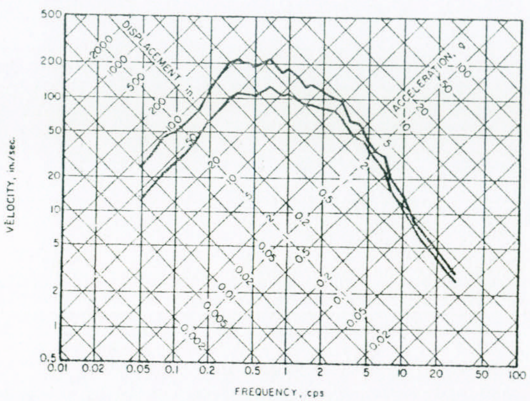

FIG. 4.—Mean and Mean Plus One Standard Deviation Acceleration Amplification Horizontal Components—2.0% of Critical Damping

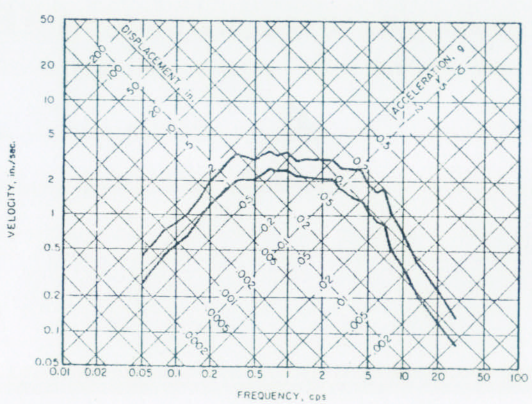

FIG. 5.—Mean and Mean Plus One Standard Deviation Velocity Amplification Horizontal Components—2.0% of Critical Damping

The study also considered spectral shape data grouped in three different ways: by peak ground acceleration, by site-soil impedance, and by epicentral distance to the recording station. Sample moments for different groups were computed and are presented in Ref. 2. Because the parameter data are sparse and because no apparent significant trends were displayed by the partitioned data, it was concluded that these results should not be used until further reliable data are available and are analyzed.

General Nature of Results of Newmark Study

The results of the study made by Nathan M. Newmark, Consulting Engineering Services, are reported in Ref. 3 in detail. From that study, tables and figures are selected to present the data in a form useful for comparison with the results of the Blume study. Table 3 gives the horizontal design spectral values for

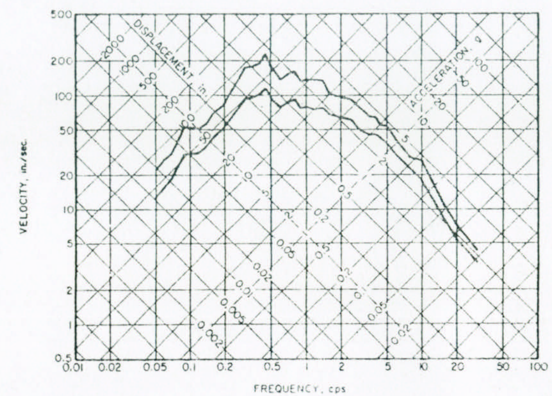

FIG. 6.—Mean and Mean Plus One Standard Deviation Acceleration Amplification Vertical Components—2.0% of Critical Damping

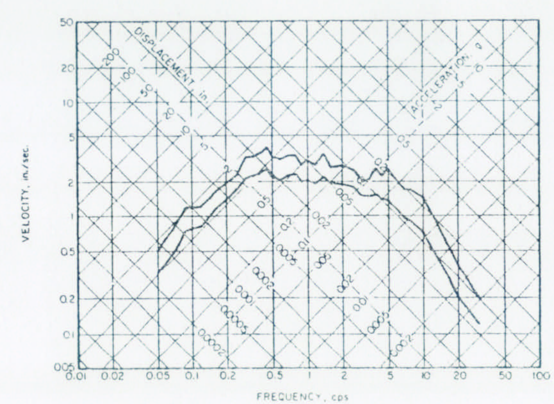

FIG. 7.—Mean and Mean Plus One Standard Deviation Velocity Amplification Vertical Components—2.0% of Critical Damping

the two probability levels corresponding to the mean or median, and one standard deviation from the mean. In this study, a normal distribution was used, in which the mean and the median are the same. The results are stated in terms of separate amplification factors for the average value over particular frequency ranges of the amplification factors for ground displacement, ground velocity, and ground acceleration, individually, to lead to the response spectral values determined in the calculation.

Also given in Table 3 are the spectral bounds for alluvium and for rock, based on the observation that for alluvium the values of maximum ground velocity generally average about 48 in./sec (1,200 mm/s) for a 1-g maximum ground acceleration, and for rock about 28 in./sec (710 mm/s) for a 1-g maximum ground acceleration. The maximum displacement values used were 36 in. (910 mm) for alluvium and 12 in. (300 mm) for rock, respectively, for 1 g maximum ground acceleration. The rock values are for competent crystalline rock, and should not be used for shale or other soft rocks. The horizontal acceleration spectral bounds for alluvium and rock are the same as the amplification factors for acceleration for the 1-*g* acceleration, and are not reported separately in the table.

Table 4 is essentially the same as Table 3 but it summarizes the vertical spectral values. The ground motion values for the spectral bounds, however, are given for ground motions of 2/3 g for acceleration for both alluvium and rock, velocities of 29 in./sec (740 mm/s) for alluvium and 17 in./sec (430 mm/s) for rock, and displacements of 33 in. (840 mm) for alluvium and 11 in. (280 mm) for rock, in determining the spectral bounds in Table 4.

The data summarized in Tables 3 and 4 are based on the simplification that the spectral bounds for acceleration, velocity, and displacement, in the various regions of the spectrum for which they are applicable, are parallel to the lines of constant value of acceleration, velocity, and displacement, respectively, in the tripartite logarithmic spectrum. However, the bounds are really not parallel to these lines, and for this reason, and in order to have a better understanding of the way in which the amplification values vary with frequency, Figs. 4-7 are shown.

Fig. 4 shows the mean value and the mean plus one standard deviation value of the complete horizontal response spectra normalized to a 1.0-g maximum horizontal ground acceleration. Fig. 5 shows the complete spectra normalized to a 1.0-in./sec (25-mm/s) maximum horizontal ground velocity. Figs. 6 and 7 reproduce the same pattern, but are for vertical motions and vertical response spectra.

The observation can be made that normalization to the maximum ground acceleration gives a standard deviation that increases rather uniformly from high frequencies to low frequencies, whereas normalization to maximum ground displacement (not reported in this paper) shows a standard deviation that increases practically uniformly from low frequencies to high frequencies. Normalization to maximum ground velocity shows a nearly constant standard deviation over the whole range of frequencies. The smallest standard deviations are obtained in each region when the normalization is made to the particular ground motion parameter for which the response spectrum bound is most nearly parallel to the coordinate. This suggests, therefore, that perhaps the most consistent set of data would be obtained by normalizing to maximum ground acceleration for high frequencies, normalizing to maximum ground velocity for intermediate frequencies, and normalizing to maximum ground displacement for low frequencies. However, since the relations among maximum ground velocity, displacement, and acceleration also are statistical variables, some complications are involved in the selection of a normalization parameter. Nevertheless, the Newmark study concludes that more consistent data could be obtained over a wide frequency range if one were to use maximum ground velocity as the single parameter describing an earthquake intensity rather than maximum ground acceleration.

Analysis of Results of Computation

It is interesting to note that, despite the differences in the procedures used in the studies, the results of the calculations made by the two organizations are in substantial agreement. The procedures involved differences in the number of points or number of frequency intervals used and arrangement of these, and in the ways in which the calculations were conducted. The Blume studies used input motions normalized to maximum ground acceleration, and the Newmark studies used adjusted input motions normalized to one of the several maximum ground motion parameters. Both studies involved statistical treatment of the data.

An example of the general agreement is indicated in Fig. 8, in which the data from Tables 2 and 3 are compared for horizontal ground motion values. The solid line marked "Recommended" in Fig. 8 is based essentially on the data in Table 2. The dotted line marked "Sediment" in Fig. 8 is the value for alluvium in Table 3. These results are in good agreement, taking note of the fact that the Mohraz-Hall-Newmark study attempted to keep the segments of the design spectrum parallel to the coordinate system of the tripartite logarithmic plot, whereas the Blume study was based solely on the empirical data. The values labeled "Competent Rock" in Fig. 8 are substantially lower for the same maximum acceleration, but this does not imply that response spectra in rock are necessarily lower than in sediments. The maximum acceleration in competent crystalline rock could be higher than in sediments and the response spectra should be compared on the basis of the actual maximum values corresponding to the proper values of maximum ground accelration rather than on the amplification factors from a few samples of data.

Based on the general nature of the agreement in the results, and the small statistical significance of the data for other than sediments, it was concluded that a single recommendation could be made, using the design spectrum shape shown in Fig. 3. It was concluded that the transition from amplified acceleration to the ground acceleration value at control frequency A, should be taken as 33 Hz. Similarly, it was concluded that the beginning of the transition region, at control frequency B, should be taken as 9 Hz. Control frequency C, where the transition occurs from an amplification of nearly constant velocity value to one of nearly constant acceleration value, was taken as 2.5 Hz. At points A, B, and C, acceleration amplification factors were used. However, at control frequency D it was inconvenient to use such a factor and the decision was made to use a displacement amplification factor, assuming that the maximum ground displacement was 36 in. (910 mm) per 1.0-g maximum ground acceleration.

Control frequency D was taken as 0.25 Hz.

One further point involves the probability level recommended for use as a design value. The nature of the calculations, involving a distribution of the various amplification factors at a single frequency, implies that at any probability level, portions of different spectra control the design level. For example, if one were to use the rank order probability values at each frequency, the 97 percentile value would be the same as using the upper bound of the amplification

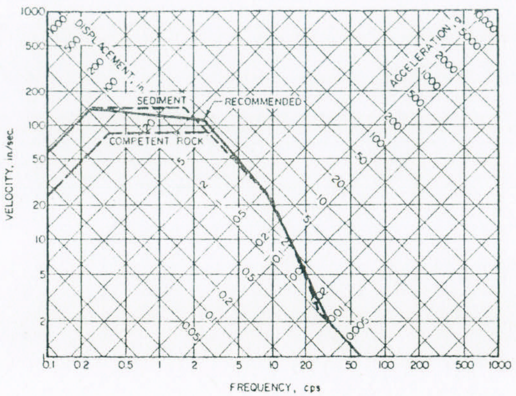

FIG. 8.—Comparison Between Design Spectra—Present Recommendation and Mohraz-Hall-Newmark Study

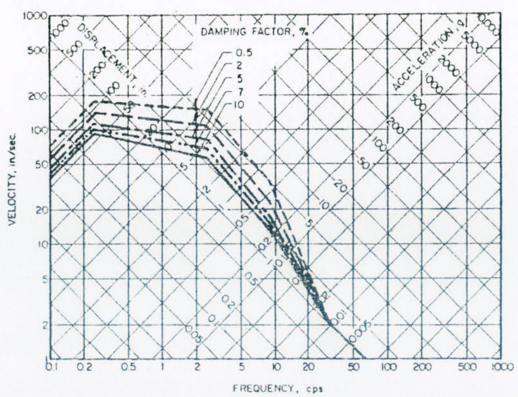

FIG. 9.—Design Spectra for Various Damping Factors

values of all of the 28 or 33 spectra as a design spectrum. Therefore, any single spectrum will have substantial regions in which it lies well below such an upper bound level, or even below any other selected probability level for the design spectral value. Consequently, the actual safety factor is considerably larger, on the average, than that corresponding to the probability level assigned to the design spectrum selected. For this reason, it appears appropriate not to base the design recommendations on a level that is near the upper bound

of the various distributions. It is also not apropriate to use either the average or the median amplification value since these levels would obviously be exceeded about half the time. For these reasons, and because of other conservative factors in seismic design, it was considered desirable to use the mean plus one standard deviation value, or the 84.1% probability level, as the design spectrum probability level.

Recommended Design Spectra and Design Criteria

Fig. 9 and Table 5 summarize the recommended amplification factors for the design spectrum frequency control points. The values in Fig. 9 are nearly the same as those found in Table 2, with a slight modification to permit plotting as straight lines the values for points B and C on a semilogarithmic plot. Line D is taken from Table 3, also with slight modifications to permit drawing it as a straight line. To permit interpolation for damping values other than those in Table 5, one can use either a linear interpolation in Table 5, or, alternatively, the following equations:

Point B, 9 Hz

$$A_B = 4.25 - 1.02 \ln\beta \quad (1)$$

Point C, 2.5 Hz

$$A_C = 1.2\, A_B = 5.1 - 1.224 \ln\beta \quad (2)$$

Point D, 0.25 Hz

$$D_D = 2.85 - 0.5 \ln\beta \quad (3)$$

in which A_B = acceleration amplification at point B; A_C = acceleration amplification at point C; D_D = displacement amplification at point D; and β = damping factor, as a percentage of critical value.

The design spectra obtained by use of these amplification factors, using the shape for the design spectra shown in Fig. 3, are plotted in Fig. 9 for damping factors ranging from 0.5% to 10% critical. For sites judged to be significantly responsive to ground motion components with periods longer than 0.5 sec, the preceding shapes should not be used without appropriate modifications for the particular site conditions at these longer periods.

Note that the validity of Eqs. 1, 2, and 3 is limited to the range from about 0.5% to 10% damping values. Obviously, the amplification factor may become less than 1 for high values of damping, but it cannot become negative under any circumstances.

Data are available from Table 5 to indicate the relationship for vertical response spectra compared to horizontal response spectra. However, the vertical response spectrum has been drawn, as indicated in Fig. 10, by taking two-thirds of the horizontal design spectrum from very low frequencies through points D′ and C′, both of which lie at the same frequencies as points D and C, but at two-thirds of the values of amplification. Line D′C′ is extended to point C″, at which the vertical design spectrum becomes equal to the horizontal design spectrum. Thus the complete horizontal design spectrum is given by line DCBA and then merges into the horizontal ground acceleration value. The complete vertical design spectrum is given by line D′C″BA and then merges into the value of vertical ground acceleration of approximately two-thirds the horizontal ground acceleration at line G, which it intersects at a frequency of about 50 Hz.

It is interesting to compare the present recommendations with certain previous design spectra. Fig. 11 shows such comparisons for 2% damping, in which the current recommendations are shown as a solid line. The recommendations made by Newmark and Hall in the 1967 conference sponsored by the International

TABLE 5.—Recommended Amplification Factors for Design Spectrum Control Points

Damping, percentage critical (1)	AMPLIFICATION FACTORS FOR CONTROL POINTS: Acceleration[a] A (33 Hz) (2)	Acceleration[a] B (9 Hz) (3)	Displacement[a] C (2.5 Hz) (4)	Displacement[a] D (0.25 Hz) (5)
0.5	1.0	4.96	5.95	3.20
2.0	1.0	3.54	4.25	2.50
5.0	1.0	2.61	3.13	2.05
7.0	1.0	2.27	2.72	1.88
10.0	1.0	1.90	2.28	1.70

[a] Maximum ground displacement is taken proportional to maximum ground acceleration, and is 36 in. (910 mm) for ground acceleration of 1.0 g.

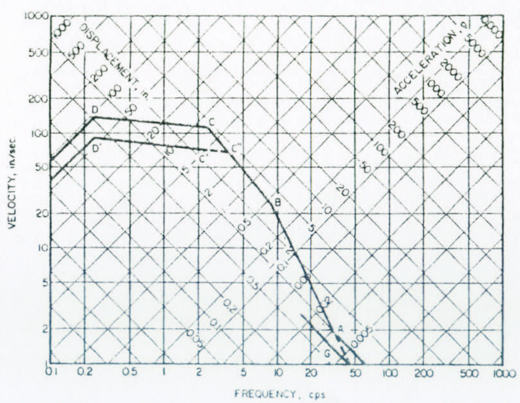

FIG. 10.—Relation Between Vertical and Horizontal Design Spectra

Atomic Energy Agency in Japan, and printed in substantially the same form in Ref. 4, is shown by the dashed line, and the previous AEC minimum criteria are shown by the dotted line. The ground motions consistent with the Newmark-Hall criteria are shown as a light solid line in Fig. 11. The differences between the spectra are not negligible but they are relatively small. Generally, the Newmark-Hall 1967 provisions are more conservative than the current recommendations, except for the range of frequencies from about 8 Hz to 25 Hz, but even here the differences are almost negligible. The previous AEC minimum criteria are only slightly less conservative in the range of frequencies from

about 2 Hz to 25 Hz or 30 Hz, and below about 0.4 Hz. In the latter region the difference is of no concern in general for nuclear reactor facilities. Fo the other region, the difference is essentially proportional to the differenc between the acceleration amplification factor in the previous AEC criteria, which implied an amplification factor of 3.5, instead of the Newmark-Hall recommen

TABLE 6.—Recommended Damping Values

Item, equipment, or structure (1)	Damping, Percentage Critical: Operating basis earthquake (OBE) (2)	Safe shutdown earthquake (SSE) (3)
Equipment and large diameter piping systems,[a] diameter greater than 12 in. (300 mm)	2	3
Small diameter piping systems,[b] diameter less than or equal to 12 in. (300 mm)	1	2
Welded steel structures	2	4
Bolted steel structures	4	7
Prestressed concrete structures	2	5
Reinforced concrete structures	4	7

[a] Includes both material and system damping. If piping system comprises only one o two spans, with little system damping, use values for small diameter piping.

[b] Assumes damping is composed primarily of material damping with negligible system damping.

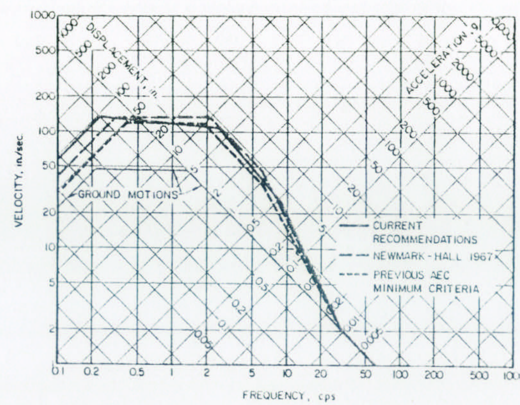

FIG. 11.—Comparison of Design Spectra for 2% Damping

dation over the same region of 4.3. However, the previous AEC criteria were generally used with more conservative (i.e., lower) damping values than the Newmark-Hall criteria, and in actual design the three sets of design curves lead to nearly the same results.

Similar comments can be made about spectra for damping factors other than 2%. However, generally, all the previous recommendations are somewhat less conservative than the current recommendations for high values of damping, say 7% and greater, and were based on less extensive evidence.

Since design response spectra are highly dependent on damping values, it is desirable to consider values to be used for damping factor for the various elements, structures, or equipments in a nuclear reactor facility. Guidance may be obtained from Table 6 with regard to damping values. These are generally consistent with the values recommended for use in Refs. 4 and 6, but are restated in what is believed to be a more useful form for nuclear reactor facility design.

The studies indicate that the design spectrum has an equal probability of occurrence in any horizontal direction, and the records show that earthquake motions occur in all three directions simultaneously, without consistent relations among the motions in the various directions. Thus, it is recommended that the *effects* of earthquakes on structures, components, or elements be computed by taking the square root of the sum of the squares of the particular maximum effects or responses at a particular point caused by each of the three components of motion (two horizontal motions at right angles to one another, and one vertical motion).

If time histories of motion are used for the computation of response, such time histories should lead to response spectra that are consistent with the design spectra recommended herein. However, if the maximum response is computed by means of a step-by-step integration of the equations of motion with respect to time, the time histories used for each of the three directions of input motion should not, in general, be systematically related to one another.

Conclusions

It is believed that these recommendations for seismic design spectra for nuclear power plants are more rational than previous recommendations because they are consistent with the results of a larger number of observations, and will generally tend to agree with response spectrum calculations made for the same earthquake history with different levels of damping more uniformly than was the case with previous recommendations.

Acknowledgments

The studies reported herein were made independently by the firm of John A. Blume and Associates, Engineers, of San Francisco, Calif., and the firm of Nathan M. Newmark, Consulting Engineering Services, of Urbana, Ill. The contract monitors for the Atomic Energy Commission were David F. Lange (deceased), and more recently, Kapur.

The work for John A. Blume and Associates was conducted by Blume, Roland L. Sharpe, and Jagat S. Dalal. The work for Nathan M. Newmark, Consulting Engineering Services, was carried out by Bijah Mohraz, William J. Hall, and Newmark. The writers make grateful acknowledgment to their associates for their major part in the development of the calculational techniques and the generalizations of the results of the analyses which enabled pertinent conclusions and recommendations to be made as a result of the studies.

Appendix.—References

1. Blume, J. A., Newmark, N. M., and Corning, L. H., *Design of Multistory Reinforced Concrete Buildings for Earthquake Motions*, Portland Cement Association, Chicago, Ill., 1961.
2. Blume, J. A., Sharpe, R. L., and Dalal, J. S., "Recommendations for Shape of Earthquake Response Spectra," John A. Blume and Associates, Engineers, San Francisco, Calif., *USAEC Contract No. AT(49-5)-3011*, Feb., 1973.
3. Mohraz, B., Hall, W. J., and Newmark, N. M., "A Study of Vertical and Horizontal Earthquake Spectra," Nathan M. Newmark, Consulting Engineering Services, Urbana, Ill., *USAEC Contract No. AT(49-5)-2667*, 1972.
4. Newmark, N. M., and Hall, W. J., "Seismic Design Criteria for Nuclear Reactor Facilities," Proceedings, 4th World Conference on Earthquake Engineering, Vol. II, Santiago, Chile, 1969, pp. B5-1 to B5-12.
5. Newmark, N. M. and Rosenblueth, E., *Fundamentals of Earthquake Engineering*, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1971.
6. Newmark, N. M., "Earthquake Response Analysis of Reactor Structures," *Nuclear Engineering and Design*, Vol. 20, No. 2, July, 1972, pp. 303–322.