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TIME DEPENDENT SPECTRAL ANALYSIS OF THIRTY-ONE STRONG-MOTION EARTHQUAKE RECORDS

by

VIRGILIO PEREZ

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TIME-DEPENDENT SPECTRAL ANALYSIS OF THIRTY-ONE STRONG-MOTION EARTHQUAKE RECORDS

Virgilio Perez

ABSTRACT

Velocity response spectral analysis as a function of time for 5 percent critical damping is presented for the horizontal components of thirty-one earthquake recrords (61 components). A nomograph that allows conversion of the velocity response envelope to a displacement response envelope and a pseudo-absolute acceleration response envelope spectrum is also presented. Included among the records analyzed are such important accelerograms as those from El Centro, 1940, Olympia, 1949, Taft, 1952, San Francisco, 1957, Parkfield, 1966, San Fernando, 1971 and Managua, 1972. Time-duration spectra showing the number of cycles for a particular period of the response envelope above different levels are presented. The effects of peak ground acceleration on the response envelope are examined.

1. INTRODUCTION

The response spectrum was first introduced into earthquake engineering by Benioff (1934) and refined by Biot (1941). With improvement and refinement by others (Alford et al., 1951; Housener et al., 1953; Hudson, 1956), this technique has become an important tool in the design of earthquake resistant structures when dealing with small buildings and special structures such as elevated water tanks. The response of each mode of multi-degree-of-freedom systems such as tall buildings, chimneys or towers can be calculated utilizing the same equation of motion used to obtain response spectra.

Each modal response can then be superposed to obtain the total response of the system (Merchant and Hudson, 1962). When the approximate design method utilizing response spectrum is not sufficiently accurate and the more involved and costly technique of time-history dynamic response is needed, a response spectrum can be used for the preliminary design. Considering the importance of response spectrum in seismic engineering, a maximum amount of information should be extracted from it. One method involves the study of response as a function of time (Perez, 1973a; Trifunac, 1971; Hays et al., 1973; Blume and Associates, 1973).

The response spectrum is a plot of maximum response for a given damping factor and a spectrum of frequencies. However, the relationship between ground motion and response is completely lost. Such relationships, obtained in time-dependent spectral analysis, would be of great help in understanding the effects of high ground acceleration on the response spectrum (Perez, 1973b). The understanding of high ground accelerations are critical, with values recorded as high as 1.25g for Pacoima Dam in 1971, and 0.7g for Melendy Ranch in 1972 (Morrill et al., 1974).

The most important information, from the structural engineering point of view, is to study the time duration of different response levels. Although certain levels of shaking may do minimal damage to structures at the onset of an earthquake, prolonged shaking at those levels could cause extensive damage. At the present time, the correlation of building damage versus levels of response and their respective time duration has not been developed. However, attempts in these two areas are being made by several investigators. For example, Matthiesen and Rojahn (1972) have made estimates of threshold structural damage levels for various classes of buildings. The structural response duration at different levels and its relation to structural damage by low-cycle fatigue has been studied by Kasiraj and Yao (1968); Suidan and Eubanks have studied the cumulative fatigue damage in seismic structures (1973); Popov et al., have studied cyclic loading of steel beams and connections (1973).

Perez (1973a) developed a time duration spectrum of response over a period range of interest to engineering. The response duration is given in terms of time and the number of cycles that occur during the earthquake. Time duration spectra calculated in the above manner for a large number of earthquake records are presented here to aid in the study of the limits of duration that can be expected over a range of response levels for different earthquakes that are of interest to the engineering community.

Although the time-dependent spectral analysis in this report is expressed in terms of the velocity response envelope, other important quantities such as displacement and absolute acceleration response have not been completely ignored. A nomograph has been constructed that allows conversion to displacement and absolute acceleration values from the velocity response envelope curves. The application of this nomograph is similar in theory to the tripartite logarithmic plots so commonly used by structural engineers to obtain displacement, pseudo-velocity and pseudo-absolute acceletation from the same set of original response information.

Little interpretation is presented in this report since the main objective is to briefly present a representative group of important earthquake accelerograms for which time-dependent spectral analysis has been calculated. Eventually a more extensive statistical sample will be presented from a large group of earthquakes relevant to structural engineering.

2. RESPONSE ENVELOPE SPECTRUM AS A FUNCTION OF TIME

Time-dependent spectral analyses were performed for the horizontal components of thirty-one earthquake accelerograms. Table I lists these earthquake records and other pertinent data such as epicentral distance, maximum intensity, magnitude, peak ground acceleration, and maximum response with its corresponding period.

2.1: Velocity Response Envelope Spectrum (VRES)

Response spectrum is based on the response of the single-degree-of freedom, viscously-damped, linear oscillator subjected to strong earthquake ground motion. Such an oscillator acts as a narrow-band filter which amplifies the input frequencies centered around the natural frequency of the oscillator (Trifunac, 1971). Furthermore, the amplitude of the response can be related to the specific ground acceleration that induced the motion.

To study the response spectrum as a function of time, the envelope of the response is used instead of the actual response. The envelope contains all of the important information required to calculate the maximum relative velocity as normally defined, while maintaining the history of the response as it varies in time.

TABLE I

Location Date and Time	Direction	Distance to Epicenter or Fault (miles)	Maximum Intensity	Mag.	Maximum Accel. (cm/sec^2)	Maximum Response (cm/sec)	Period of Response (sec)
1. El Centro, Calif. 12-30-34,0552PST	North East	40	IX	6.5	166 181	32 41	0.60 0.70
2. El Centro, Calif. 5-18-40,2037PST	North East	4 to fault	X	7.1	351 219	86 78	0.95 3.00
3. Olympia, Wash. 4-13-49,1156PST	S04E S86W	10	VIII	7.1	179 300	50 55	1.20 3.20
4. Santa Barbara,Ca. 7-21-52,0453PDT	N42E S48E	51	XI	7.7	88 132	45 60	1.50 2.00
5. Taft, Calif. 7-21-52,0453PDT	N21E S69E	25			173 193	46 45	0.70 1.70
6. Eureka, Calif. 12-21-54,1156PST	S11E N79E	15	VII	6.6	171 277	62 70	3.80 0.65
7. Ferndale, Calif. 12-21-54,1156PST	S44W N46W	25			163 205	102 69	1.60 1.40
8. Oakland, Calif. City Hall,Bsmt. 3-22-57,1144PST	N26E S64E	15	VII	5.3	46 29	5.5 4.8	1.20 0.50
9. San Francisco,Ca. Alex.Bldg.Bsmt. 3-22-57,1144PST	N09W N81E	10	VII	5.3	49 54	8.6 7.6	0.30 0.35
10. San Francisco,Ca. Golden Gate Pk. 3-22-57,1144PST	N10E N80W	7			103 124	11.8 13.3	0.30 0.25

TABLE I (CON'T)

Location Date and Time	Direction	Distance to Epicenter or Fault (miles)	Maximum Intensity	Mag.	Maximum Accel. (cm/sec^2)	Maximum Response (cm/sec)	Period of Response (sec)
11. San Francisco, Ca. State Bldg. 3-22-57, 1144PST	N09W N81E	9			101 65	15.8 13.6	0.30 0.70
12. San Francisco, Ca. S.P.Bldg.Bsmt. 3-22-57, 1144PST	N45E N45W	10			47 47	13.7 19.6	1.25 1.15
13. Hollister, Ca. 4-8-61, 2323PST	S01W N89W	13	VII	5.6	75 185	27 37	0.75 0.45
14. Olympia, Wash. 4-29-65, 0728PST	S04E S86W	31	VII	6.5	158 224	30 35	0.60 1.60
15. Cholame-Shandon Calif., No. 2 6-27-66, 2026PST	N65E	.05 to fault	VII	5.6	499	150	0.65
16. Cholame-Shandon Calif., No. 5 6-27-66, 2026PST	S05W N85E	3.3 to fault	VII	5.6	395 458	66 68	0.50 0.40
17. Cholame-Shandon Calif., No. 8 6-27-66, 2026PST	N50E N40W	5.7 to fault			274 271	28 32	1.05 0.85
18. Temblor, Calif. 6-27-66, 2026PST	N65W S25W	4 to fault			277 402	45 72	0.45 0.40
19. El Centro, Calif. 4-8-68, 1830PST	South West	42	VII	6.5	139 60	60 37	1.80 2.20

TABLE I (CON'T)

Location Date and Time	Direction	Distance to Epicenter or Fault (miles)	Maximum Intensity	Mag.	Maximum Accel. (cm/sec^2)	Maximum Response (cm/sec)	Period of Response (sec)
20. Castaic, Calif. Old Ridge Rt. 2-9-71, 0600PST	N21E N69W	18	XI	6.6	329 283	54 63	0.50 0.90
21. 250 E. First St. L.A., Ca., Bsmt. 2-9-71, 0600PST	N36E N54W	25			106 130	42 36	3.40 1.35
22. 445 Figueroa St. L.A., Calif. Sub-basement 2-9-71, 0600PST	N52W S38W	25			146 127	49 51	1.05 3.60
23. 646 E. Olive L.A., Ca., Bsmt 2-9-71, 0600PST	S53E S37W	26	XI	6.6	247 202	43 57	1.25 3.60
24. 8244 Orion Blvd. L.A., Ca., 1st fl., 2-9-71, 0600PST	North West	12			253 135	112 112	1.70 3.00
25. Pacoima Dam, Calif. 2-9-71, 0600PST	N76W S14W	5			1,225 1,216	208 226	0.50 1.30
26. Melendy Ranch Calif., 9-4-72 1104PDT	N61E N29W	5.5	VI	4.6	475 688	58 53	0.20 0.20
27. Stone Canyon, Calif. 9-4-72, 1104PDT	S03E N87E	2.5			222 161	29 26	0.25 0.25

TABLE I (CON'T)

Location Date and Time	Direction	Distance to Epicenter or Fault (miles)	Maximum Intensity	Mag.	Maximum Accel. (cm/sec^2)	Maximum Response (cm/sec)	Period of Response (sec)
28. Managua, Nicaragua Banco Central, Bsmt 1-4-68, 0405AM	N84.5W S05.5W	3 to 6 miles	VII	4.6	122 95	21 19	0.40 0.40
29. Managua, Nicaragua ESSO Refinery 12-23-72, 0629GCT	South East	2.8	IX	6.2	322 373	94 75	0.40 0.65
30. Managua, Nicaragua ESSO Refinery 12-23-72, 0719GCT	South East	2.8	--	5.2	326 283	57 69	0.40' 1.90
31. Managua, Nicaragua U.N.A.N. 3-31-73, 2013GMT	E-W N-S	3 to 6 miles	--	Less than 4	580 246	100 38	0.40 0.20

Since the response is highly sinusoidal, the time duration of its envelope above any given level can be converted to approximate the number of cycles above that level (i.e., in Figure 1, the 3.5 second duration above 100 cm/sec is approximately equal to 3.5 cycles). Once the response has been calculated, its envelope requires fewer points to describe its variation in time. Thus, the computer storage and required calculations are greatly reduced. A three dimensional drawing of the resulting velocity response envelope spectrum (VRES) is shown in Figure 2. Qualitatively, the top part of the figure shows the peaks and valleys of the VRES as they vary in time and period. The bottom part of the drawing shows a projection of this figure onto a flat plane to form a contour map of various levels of this response. The VRES are shaded to show the initiation and time duration of the different velocity ranges. Approximations to intermediate levels can be obtained by linearly interpolating between any two contour levels.

To evaluate the significance of various response levels, a criteria for threshold structural damage would be needed. Matthiesen and Rojahn (1972) indicate that for structures designed according to the current design practice, initiation of general yielding in terms of shear and bending distortions is a function of building period and type of structure. Their spectra indicate there is no simple relation between the threshold of general yielding and level of response, although initial building damage can be expected for velocity response greater than 20 cm/sec for some classes of structures.

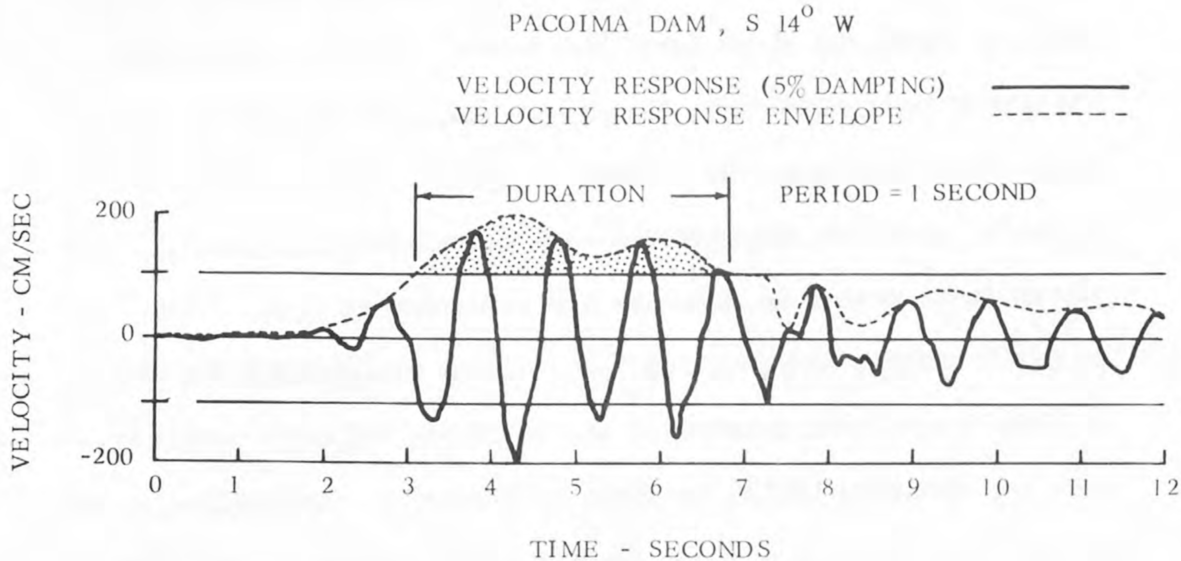

Figure 1.-Relative velocity response and its envelope for an oscillator with a natural period of 1 sec for Pacoima Dam, 2/9/71 earthquake.

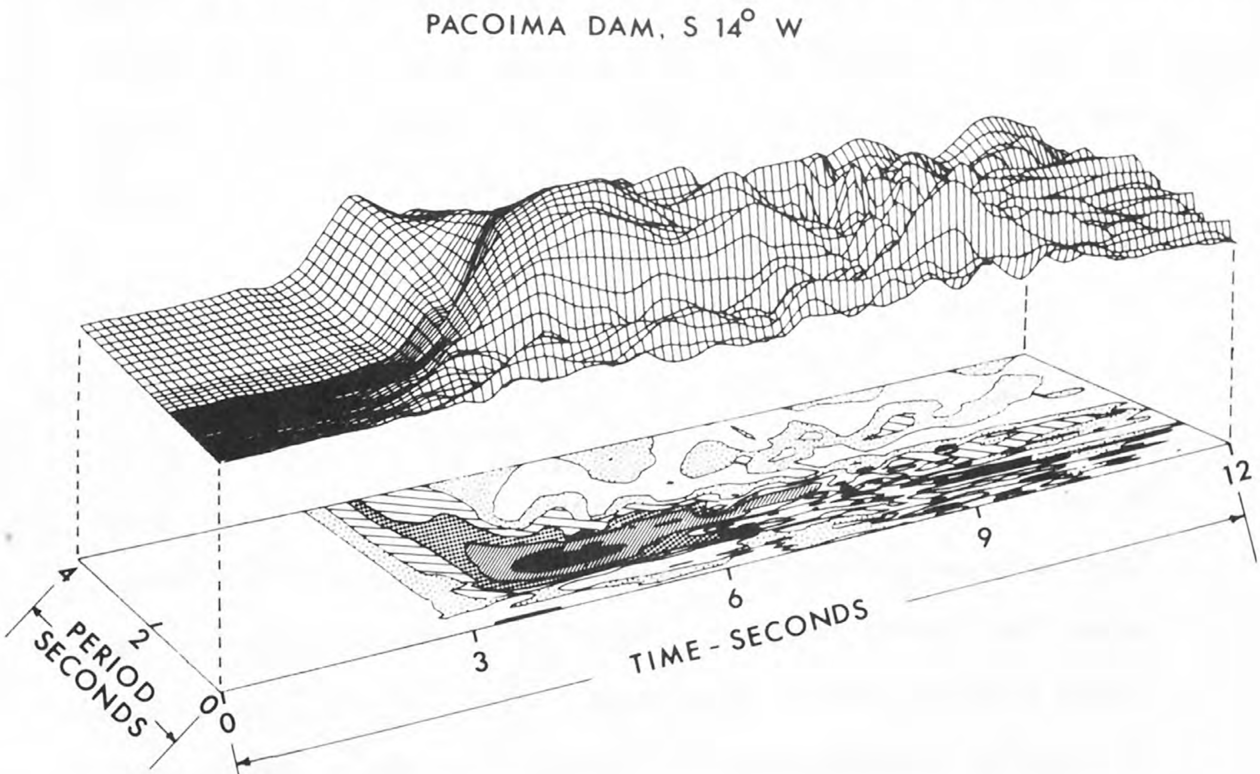

Figure 2.-Relative velocity response envelope for 42 periods at 5 percent critical damping for Pacoima Dam, 2/9/71 earthquake.

2.11: Computational Values Used

The following method was used to calculate the VRES as a function of time. The oscillator response was computed for 42 natural periods. The periods selected were: from 0.2 to 1.5 seconds at 0.05 second intervals; from 1.5 to 2.0 seconds at 0.1 second intervals; and from 2.0 to 4.0 seconds at 0.2 second intervals. This scheme was chosen to obtain an equitable density distribution at the higher frequency end of the spectrum. Note Figure 2. For each period the response envelope was approximated by connecting the absolute value of the response curve peaks. The envelope curve was then interpolated at equal intervals of 0.1 seconds for records of 16 seconds or less in length and equal intervals of 0.2 seconds for records greater than 16 seconds.

These 42 periods, with their respective VRES calculated at equal time intervals, generated a rectangular grid of spectral values. Contours of equal amplitude were produced by plotting interpolated values from the grid, giving a topographic map of the VRES amplitude values as a function of time and period (Figure 3). The maximum relative velocity response spectrum is plotted to the right of each contour map. The topographical map shows the peaks and valleys of the VRES as a function of time and period, while the maximum relative response spectrum shows the silhouette of the peaks. The input acceleration is plotted below the contour map to show the relationship between acceleration and the VRES as they vary in time.

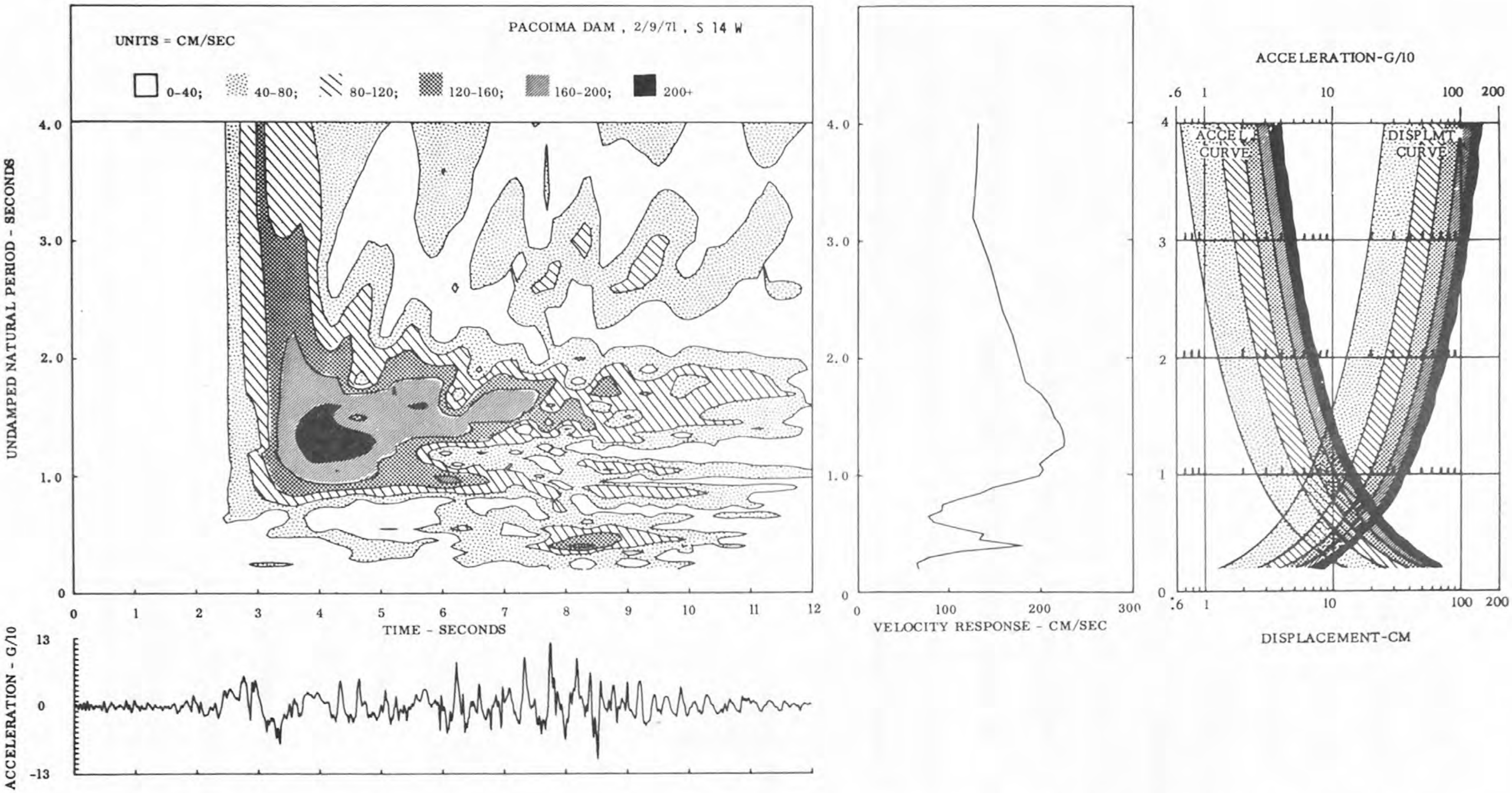

Figure 3.-Velocity response envelope spectrum (VRES) at 5 percent critical damping for Pacoima Dam, 2/9/71 earthquake, S 14° W component (left); maximum velocity response spectrum (center); nomogram converting relative velocity response to relative displacement and pseudo-absolute acceleration response (right).

In most instances, connecting the peaks of the response is a good approximation to the response envelope. In three cases (Melendy, N 29°W, Figure 4; Banco Central, N 84.5°W, Figure 5; and Managua, U.N.A.N., E-W, Figure 6), high frequency content in the response gave an envelope of these high frequencies and not of the period being analyzed. In all three cases, the lowest level represented in the VRES exhibited a periodicity for periods greater than two seconds. This modified "envelope" represents closely the actual response and not the true envelope. For example, Melendy Ranch shows a periodicity of about 2 seconds for the 4 second period. This 2 second periodicity is equal to the half cycle of the 4 second period. A better approximation to the envelope of the response would be obtained by filtering out frequencies appreciably higher than the ones being studied, without altering either the phase or the magnitude of the response of a given oscillator. That refinement has not been developed in the VRES analysis presented in this report.

The number of levels used for the drawings of the VRES are identical for each particular component and were chosen to provide clarity, yet keeping the characteristics of the response. Using the approximate threshold structural damage level as a guide, levels of multiples of 10, 20, or 40 cm/sec were used for most accelerograms examined in this presentation. Lower levels of response were used for the San Francisco earthquake records of March 22, 1957 because some of the maximum amplitudes were less than 10 cm/sec.

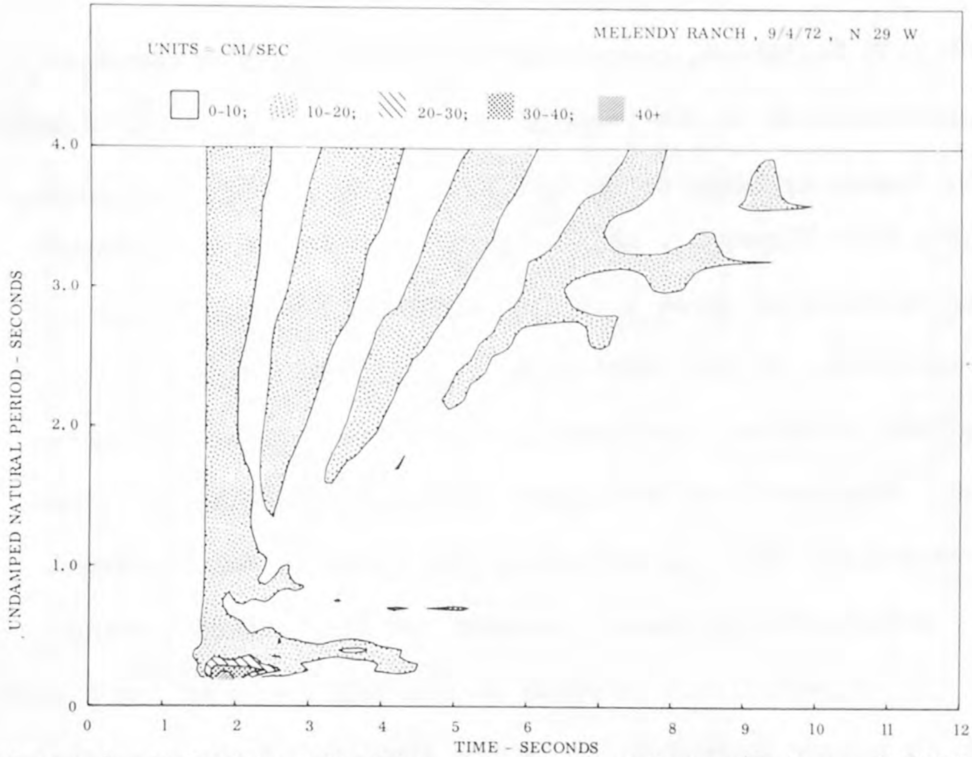

Figure 4.-Relative velocity response envelope spectrum (VRES) at 5% critical damping, Melendy Ranch, Ca. 9/4/72, N 29°W component.

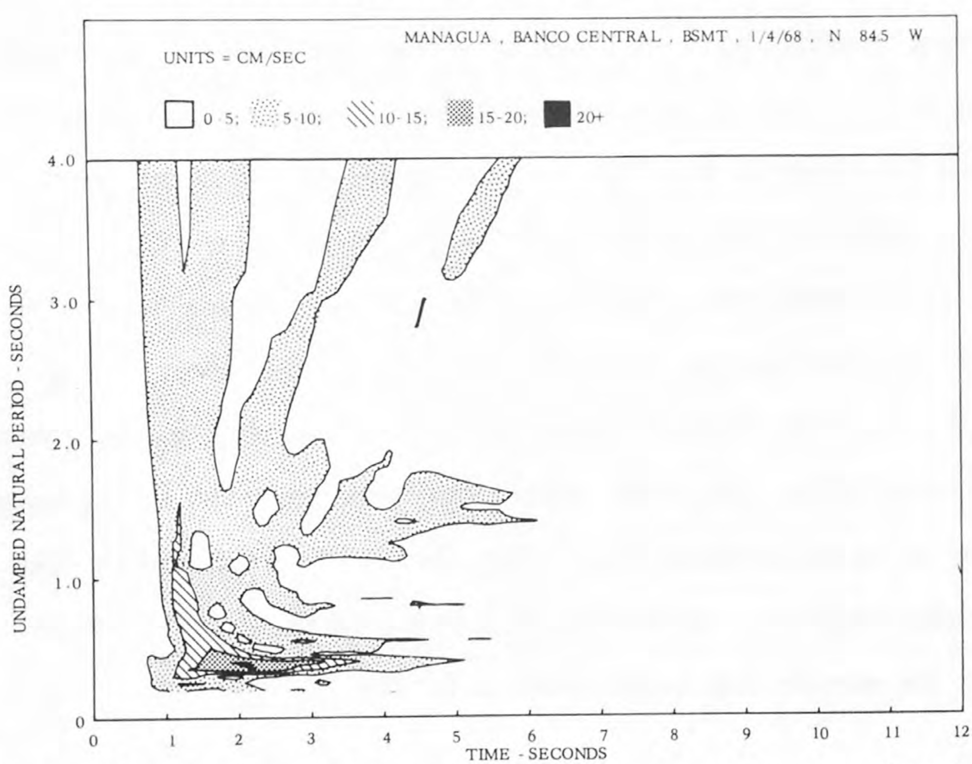

Figure 5.-Relative velocity response envelope spectrum (VRES) at 5% critical damping, Banco Central, Managua, Nicaragua, 1/4/68, N 84.5° W component.

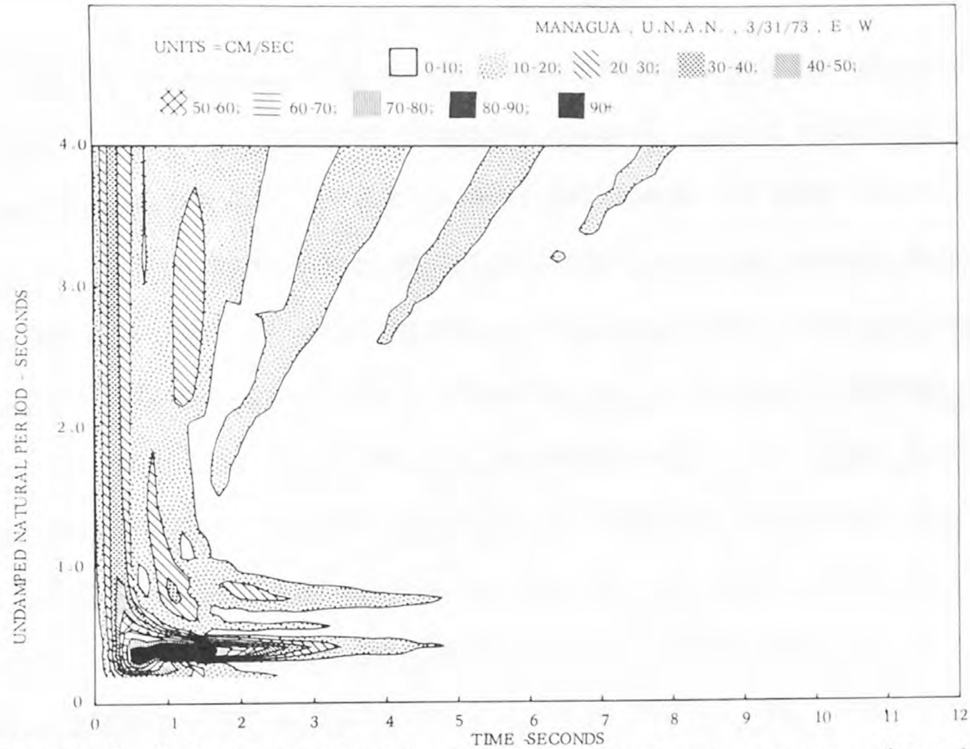

Figure 6.-Relative velocity response envelope spectrum (VRES) at 5% critical damping, U.N.A.N., Managua, Nicaragua, 3/31/73, E-W component

2.2: Displacement and Pseudo-Absolute Acceleration Response Envelope Spectra (DRES and ARES)

Time-dependent spectral analysis may be expressed not only as relative velocity (VRES), but also as relative displacement (DRES) and absolute acceleration (AREA). Relative displacement is important because the shear force exerted by the columns of a structure on the ground are directly proportional to the displacement. The absolute acceleration measures the seismic forces acting on the mass of a structure.

A partial solution to obtain VRES, DRES, and ARES is to approximate these quantities through a calculation commonly used by structural engineers. If the response is assumed to be sinusoidal, then the displacement response can be approximated by dividing the velocity response by $\omega_o = 2\pi/T_o$, (T_o is the natural period of the oscillator) and the absolute acceleration response can be approximated by multiplying the velocity by ω_o. Because velocity response is calculated as a function of time for specified levels, a nomograph may be constructed with curves relating velocity to the corresponding values of displacements and pseudo-absolute accelerations (Figure 3). The method is somewhat similar to the tripartite logarithmic plots used by structural engineers. The curves of the nomograph are based on the different levels of the relative velocity response envelope as a function of time. Note the ordinate of the nomograph in Figure 3 is drawn to the same scale as the contour map and the maximum response spectrum. The left side of the nomograph's contour level represents the lower velocity ranges (i.e., the left side of the shaded area of the nomograph in Figure 3 represents velocity level of 40 cm/sec). An example of using the nomograph is as follows: for a velocity level of 40 cm/sec and 3.0 second period, the equivalent pseudo-absolute acceleration is about 0.09g; for the same velocity level and same period, the equivalent displacement is about 19 cm. The start of intermediate levels of the DRES and the ARES, not shown in the nomograph, can be approximated by logarithmically interpolating between contour of the nomograph and comparing them with the corresponding velocity obtained through interpolation of the VRES contour map.

2.3 Comments on the Velocity Response Envelope Spectra from Thirty-one Accelerograms

The VRES from the thirty-one accelerograms are shown in Figures A-1 through A-61 in Appendix A. These accelerograms were generated by earthquakes ranging from less than 4 to 7.7 Richter Magnitude and varying in distance from near ground rupture to 51 miles from the epicenter.

The VRES plots serve to show the relationship between the response and the ground acceleration. An examination of these figures indicate that peak response is not necessarily induced by maximum acceleration. Figure 7 is a plot of the time of occurrence of maximum ground acceleration versus maximum velocity response. Since this study deals with response in the period range between 0.2 sec and 4.0 sec, then the harmonic theory indicates that the response delay should be no more than .05 to 1 sec (i.e., T/4). Only twenty-seven of the recorded peak accelerations were within this range and may have induced maximum velocity response. In thirteen cases the velocity response delay was more than 4 sec. In six cases, maximum velocity response preceded maximum acceleration.

Absolute acceleration response appears to have a better correlation to ground acceleration. Figure 8 is a plot of time of occurrence of maximum ground acceleration versus maximum absolute acceleration response. Forty of the components are within the expected range of 0.05 to 1.0 sec. Thirteen components have delays between 1 and 4 seconds, and in 8 cases, the maximum absolute acceleration response preceded maximum acceleration.

The samples cited above clearly indicate that maximum velocity response as well as absolute acceleration response are frequently unrelated to the peak recorded accelerations. To better understand this phenomenon, the velocity response of oscillators with 0.1, 0.2,

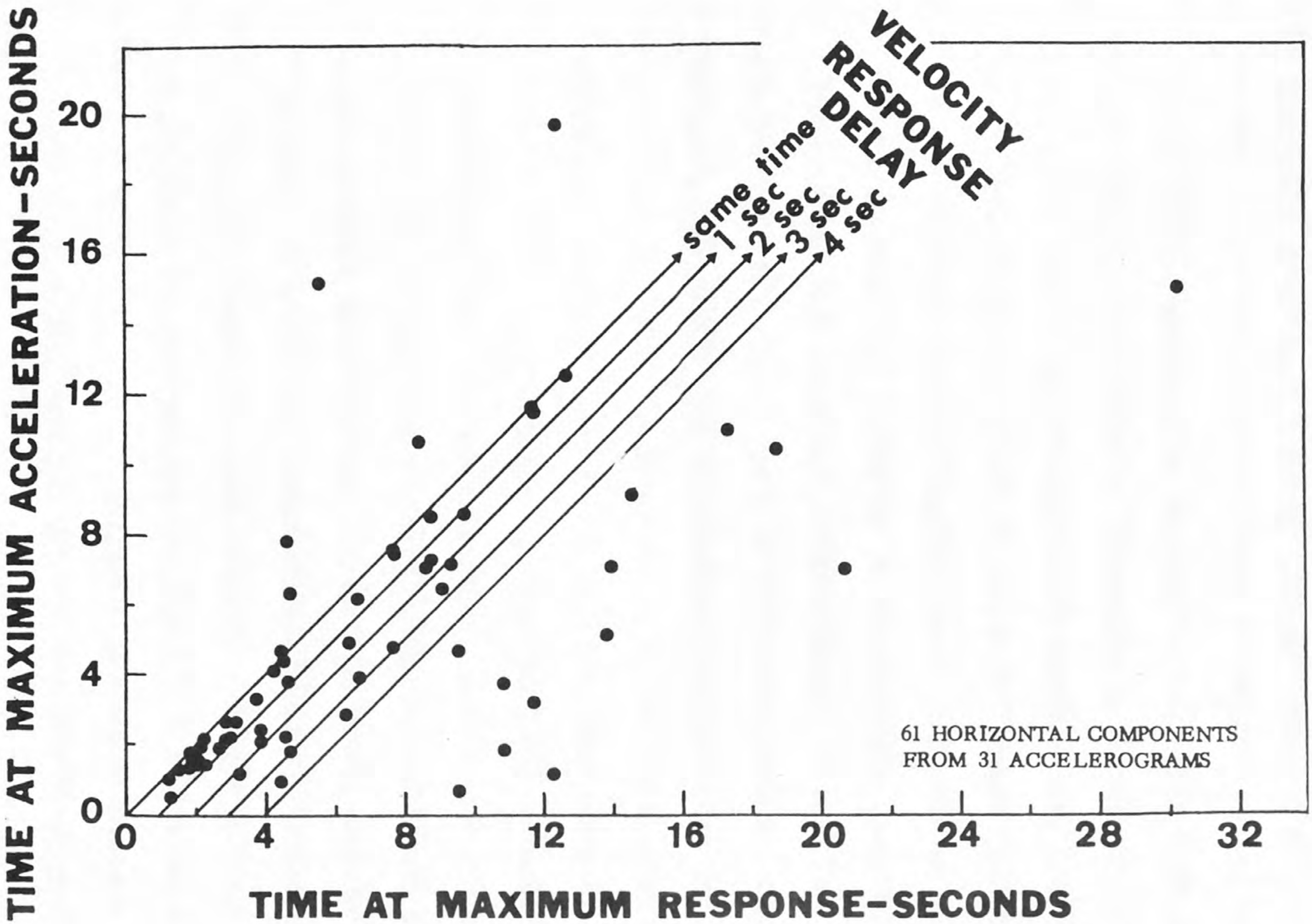

Figure 7.- Relationship between occurrence time of maximum ground acceleration and maximum velocity response, 5 percent critical damping.

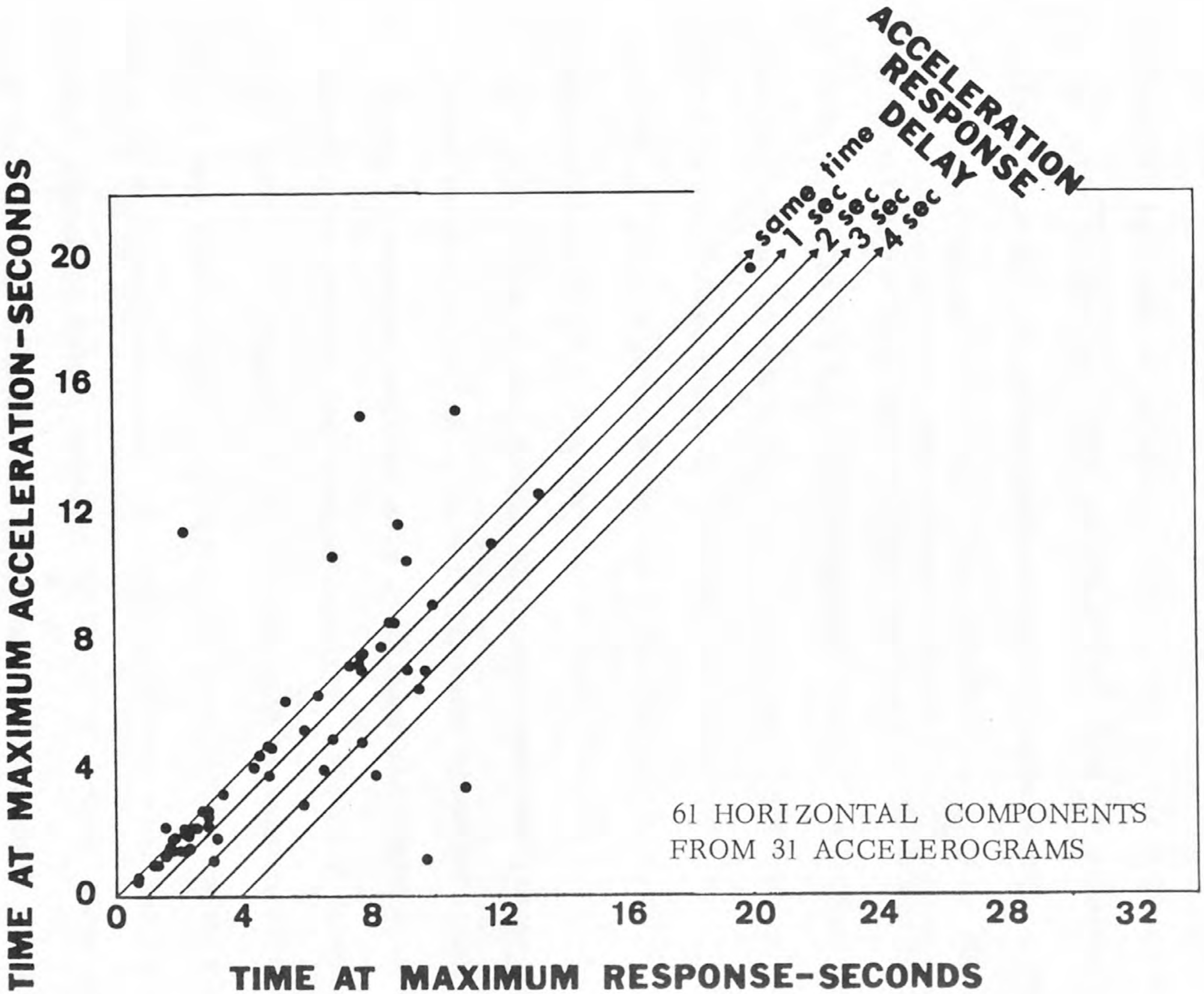

Figure 8.- Relationship between occurrence time of maximu ground acceleration and maximum absolute acceleration response, 5 percent critical damping.

0.5, 1, 2, 5 and 10 second periods was calculated and plotted at the same time scale as the ground accelerations recorded at Pacoima Dam on February 9, 1971 (Figures 9 and 10). As anticipated, the response at times approaches sinusoidal motion at a period nearly equivalent to the oscillator period. Note that the ground acceleration of the S 14° W component was also nearly sinusoidal with a dominant period of 1.4 sec between 2.3 and 4.0 sec after the record began. During this interval, the forcing motion is nearly in phase with the 1 sec oscillator and somewhat in phase with the 2 sec oscillator. Although by definition a resonance condition (i.e., the requirement of sinusoidal input motion and a $\pi/2$ delay in the response) does not exist, the near sinusoidal ground motion does force the 1 sec oscillator to increase its response during this interval similar to a resonance condition, with maximum response of about 200 cm/sec at 4.25 sec. Maximum response and maximum acceleration appear to be related in the case of the 0.1 second oscillator for both horizontal components. But note that in both cases the maximum amplitudes are less than 40 cm/sec. The peak accelerations introduce high-frequency components into the response curves at longer periods, but they are significant in enlarging the response only if they are in phase at that particular moment. When the forcing motion is of short duration and out of phase with the response, interference will occur. This may be observed in Figure 9 for the 1 sec oscillator, where the motion occurring at 8 sec is small. Another example of this interference phenomenon may be seen in Figure A-49. Thus, the high accelerations experienced at Pacoima Dam, although large, do

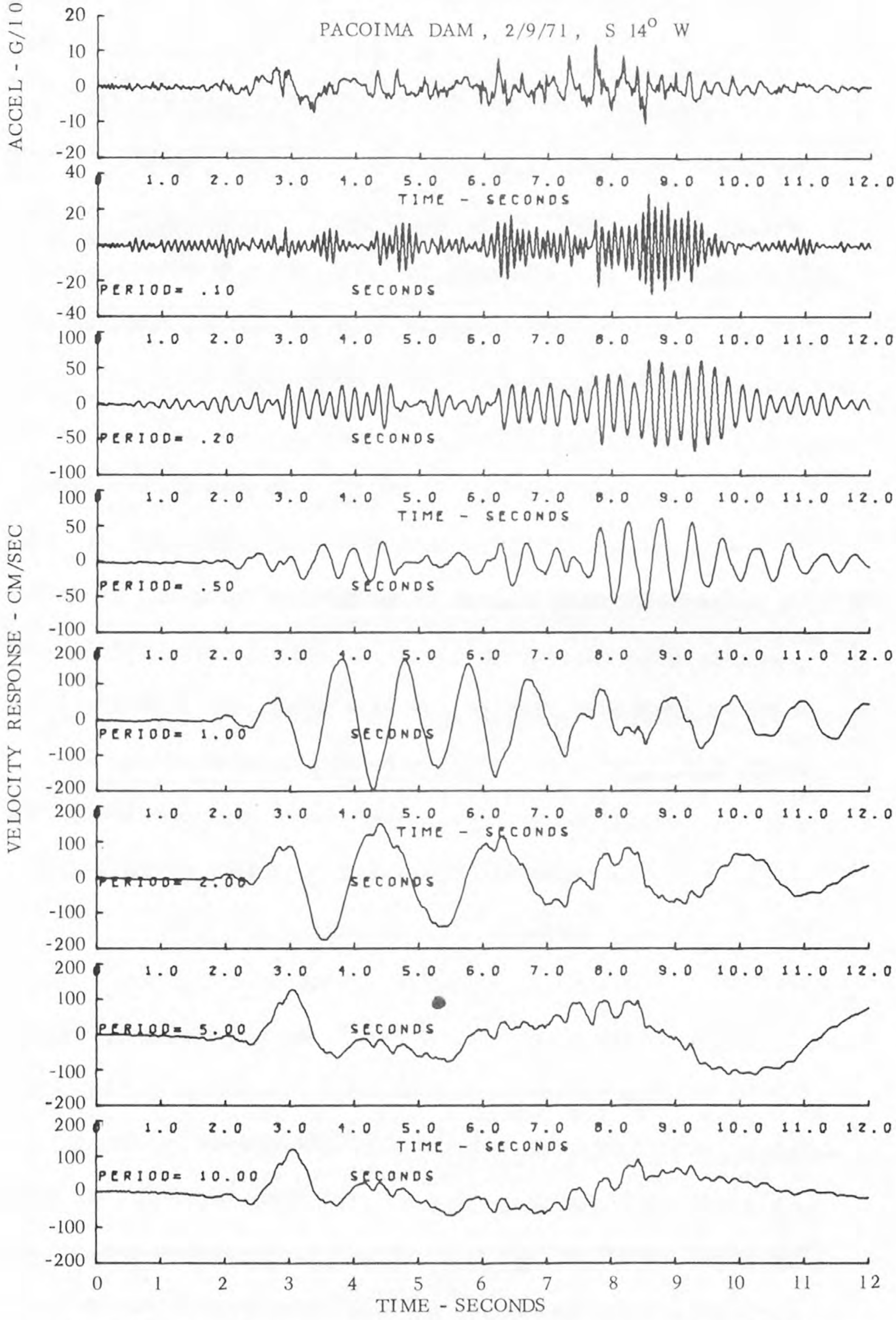

Figure 9.- Ground acceleration and relative velocity response at 5% critical damping, Pacoima Dam, 2/9/71, S 14° W component.

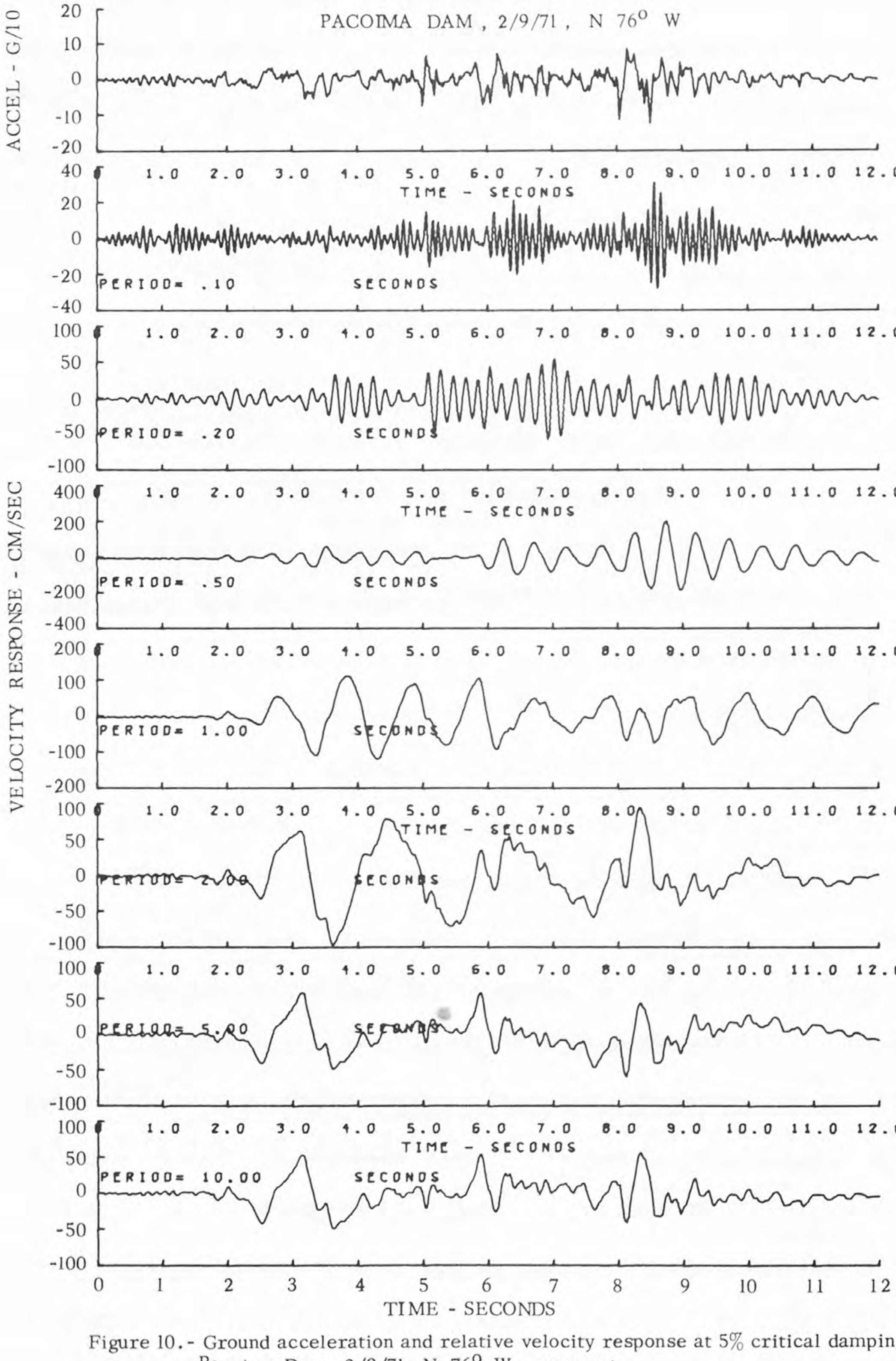

Figure 10.- Ground acceleration and relative velocity response at 5% critical damping, Pacoima Dam, 2/9/71, N 76° W component.

not have a great effect on the response because the time duration is short or relatively non-sinusoidal.

3. TIME DURATION SPECTRUM OF THE RESPONSE ENVELOPE

From an engineering point of view, it is important to study not only the peak response and time of occurrence, but also the time-duration above a given level of response. An example of time-duration spectrum of the velocity response envelope is shown in Figure 11. The time-duration spectrum is defined as the cumulative total time that the VRES equaled or exceeded a given level for the entire acceleration record. An important corollary to this concept expresses the total time-duration of different amplitude levels of the VRES in terms of the number of cycles that occurred at a particular level. Due to the filtering properties of a simple harmonic oscillator, the period of the velocity response is approximately equal to the natural period of the oscillator. Therefore, by dividing the duration by the period of the oscillator, a family of straight lines indicating the number of cycles for a given velocity response level can be generated. An example of these families of straight lines is also shown in Figure 11.

The nomograph in Figure 11 may be used to convert time duration of the velocity response envelope to corresponding envelope levels of displacement and pseudo-absolute acceleration response. Because sinusoidal motion is assumed for the velocity response, the time duration and the number of cycles for a given amplitude level also hold true for the displacement and the pseudo-absolute acceleration

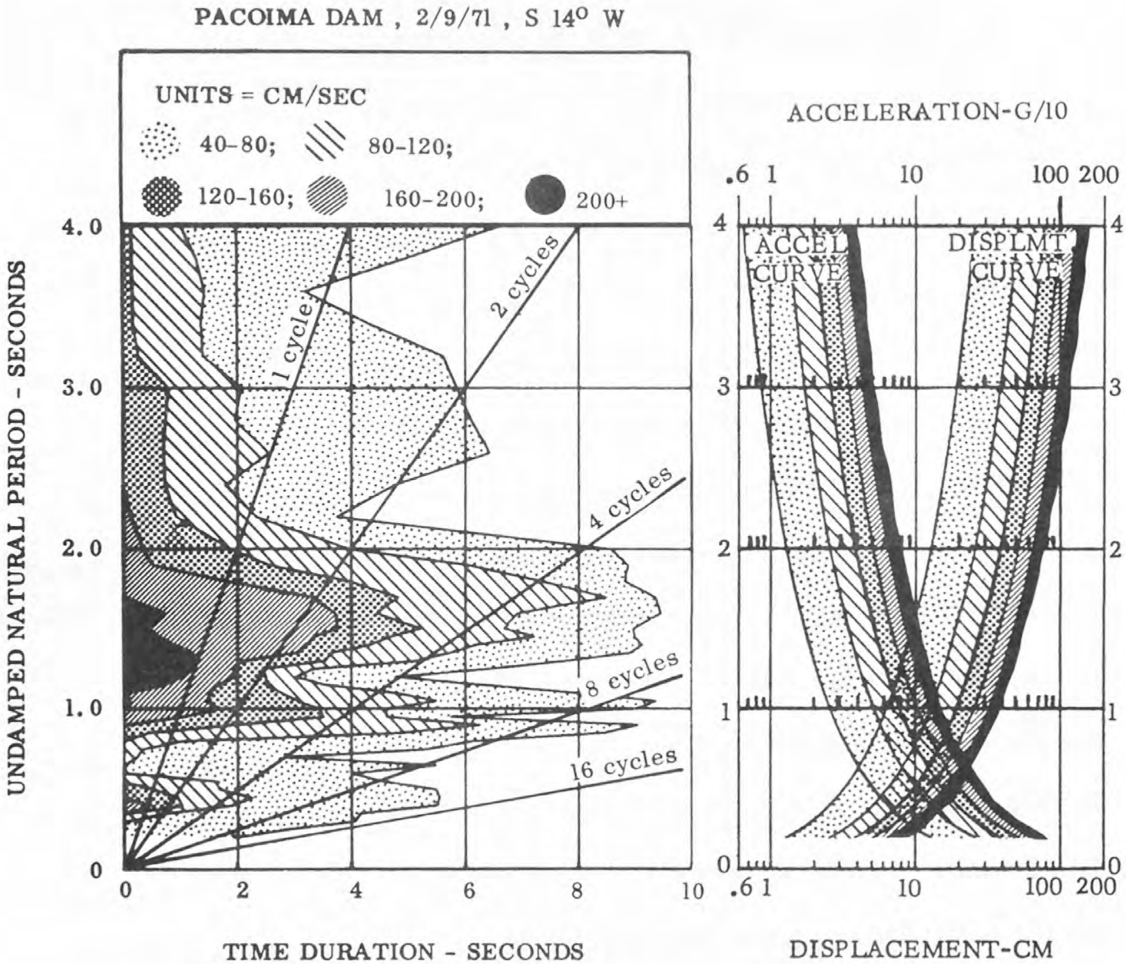

Figure 11.-Time duration spectrum of the response envelope at 5% critical damping, Pacoima Dam, 2/9/71, S 14° W component (left); nomogram converting relative velocity response to relative displacement and pseudo-absolute acceleration response (right).

response envelope. The time duration and the number of cycles for other levels omitted in the nomograph can be obtained by logarithmic interpolation. Comparison of the corresponding interpolated velocity response will provide an approximation of the time duration and the number of cycles for that level.

3.1 Comments on the Time Duration Spectra from Thirty-one Accelerograms

The time duration spectra for the horizontal components of the thirty-one accelerograms listed in the last section are shown in Figures B-1 to B-31. Note that levels of response chosen for the computation of the VRES plots are identical to those chosen for the time duration spectrum. A nomograph has been inserted between each pair of horizontal components in order to facilitate the conversion of the velocity to displacement and pseudo-absolute acceleration response.

One may question whether the time duration of the different levels of response is continuous or not. Figures A-1 to A-61 indicate that generally the time duration at higher levels of response is indeed continuous. In some cases this continuity appears to hold true for all or part of the period range at lower levels of response. In the cases when the lower levels are not continuous the duration of the response are added as if they were continuous. Whether the cumulative adding of non-continuous time duration of the response is equivalent or approximately equivalent to a continuous time duration cannot be answered at this time. Therefore, as the VRES plots generally indicate, the time-duration spectrum can be considered to represent an approximation of a continuous time-duration, particularly at higher levels of response.

An examination of the time duration spectra indicates that limits or bounds may be stated on the relationship between the predominant time-duration for selected amplitude levels of the velocity response envelope, their corresponding periods, and the magnitude of the earthquake. Figure 12 shows the predominant time-duration of a given component plotted against its period for levels of response equal or greater than 20 cm/sec. A log-log plot of the same data (but including consideration of the earthquake magnitudes), is shown in Figure 13.

Three observations can be made from these data: 1) larger earthquakes generally induce longer response durations as expected, 2) larger earthquakes tend to produce predominant response durations at longer periods, and 3) as a consequence of the last two observations, longer periods have greater corresponding time durations. Considering the number of cycles of predominant response durations, it appears (1) that no correlation with period exists, and (2) the maximum number of cycles is generally in the range of ten to sixteen cycles.

When the predominant time duration for levels of response equal to 40 to 60 cm/sec is plotted (see Figures 14 and 15 respectively), the patterns seen in the 20 cm/sec level plot emerges again but with much greater scatter in the data.

The time duration spectra shown in Figures B-1 to B-31 were plotted to provide good detail in the time duration plane. As a

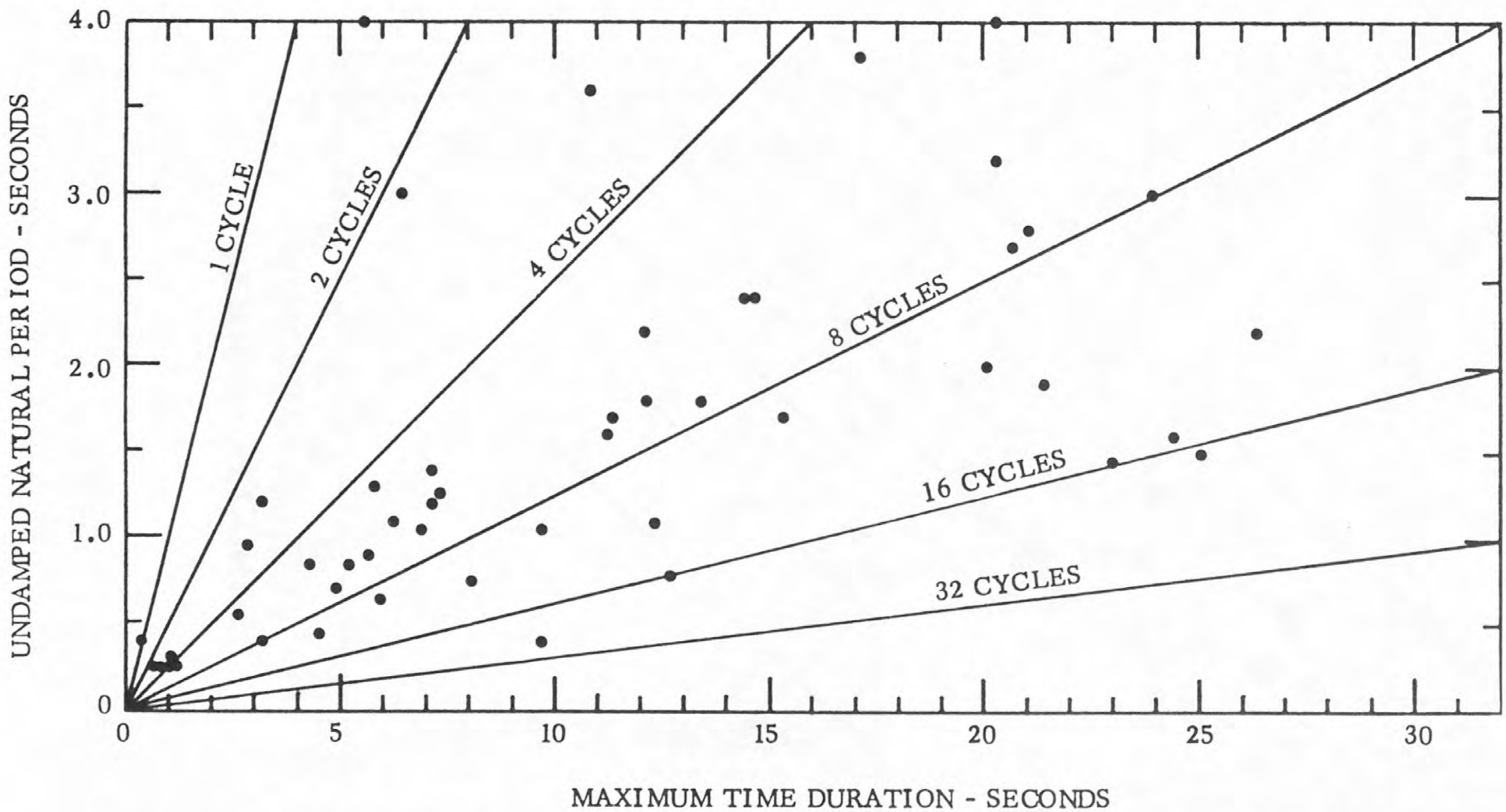

Figure 12.- The predominant time duration obtained from the time duration spectra for levels of response equal or greater than 20 cm/sec.

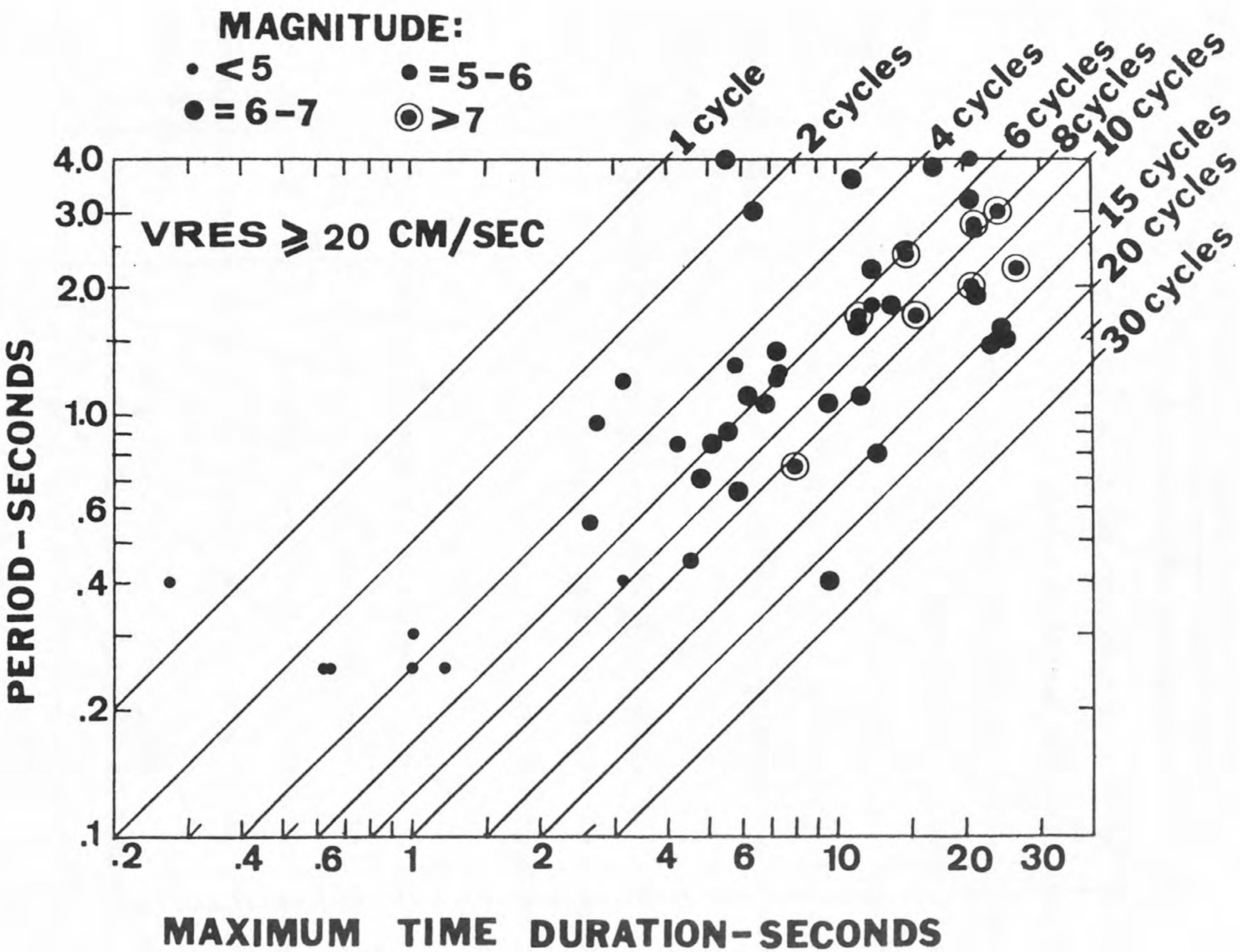

Figure 13.- The predominant time duration obtained from the time duration spectra for levels of response equal or greater than 20 cm/sec.

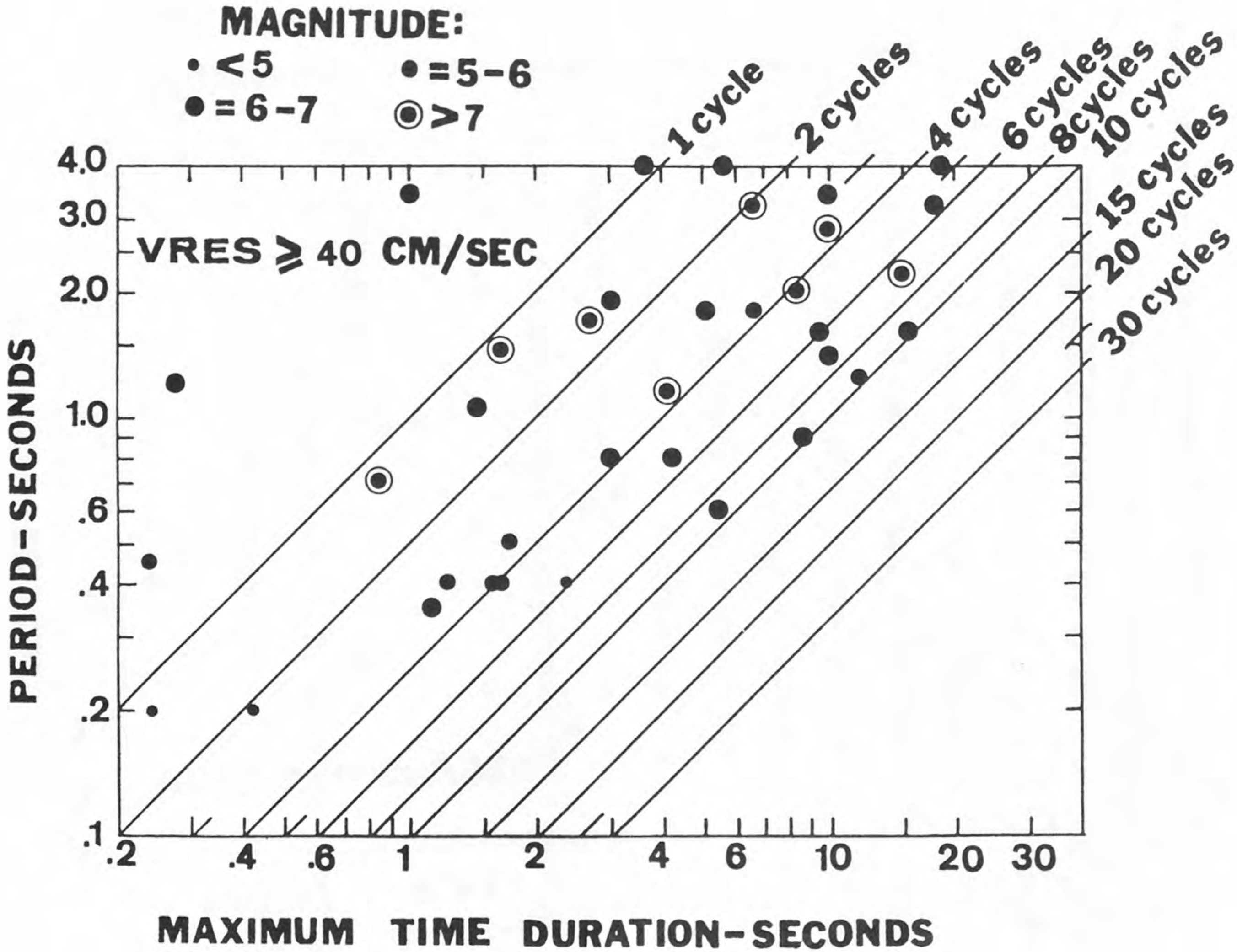

Figure 14.- The predominant time duration obtained from the time duration spectra for levels of response equal or greater than 40 cm/sec.

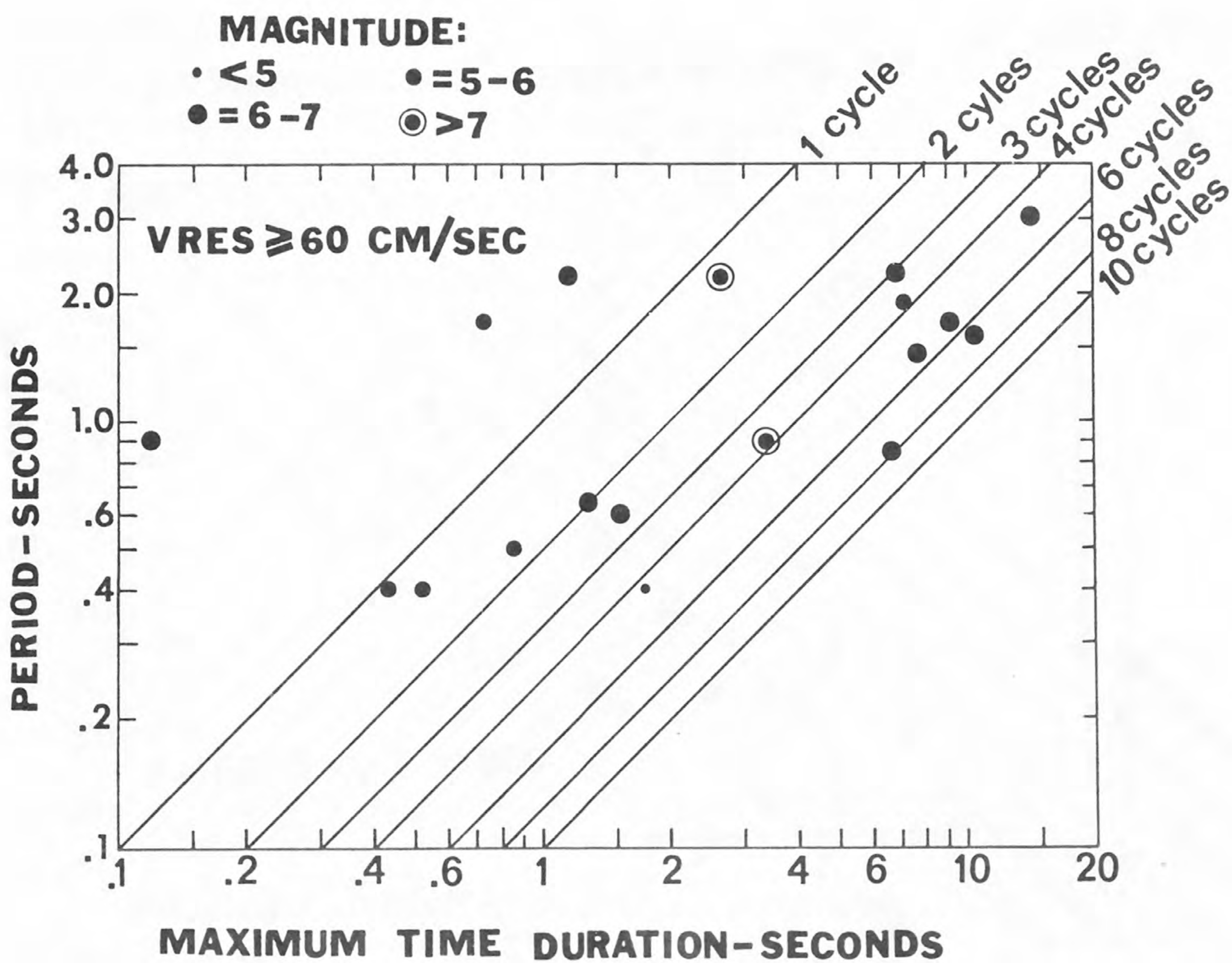

Figure 15.- The predominant time duration obtained from the time duration spectra for levels of response equal or greater than 60 cm/sec.

result, the time duration scale varies from plot to plot. In order to make quick comparison between the different time duration plots, the time duration spectra were drawn to a constant scale of 30 seconds. These are shown in Figures B-32 to B-47 in Appendix B. When comparing time duration from different earthquakes, care must be taken to see that the levels of interest have the same amplitude values.

In this report, no attempt was made to systematically examine the displacement or the pseudo-absolute acceleration. The nomographs are included to serve the basic function of allowing quick conversions of velocity to displacement and pseudo-absolute acceleration response. Because displacement and acceleration functions are important in structural engineering, future studies will hopefully include not only a larger number of accelerograms but a study of all three quantities.

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APPENDIX A

Illustrations for the Response Envelope as a Function of Time