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A STUDY OF VERTICAL AND HORIZONTAL EARTHQUAKE SPECTRA

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Directorate of Licensing
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Washington ,D.C.

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A STUDY OF

VERTICAL AND HORIZONTAL EARTHQUAKE SPECTRA

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prepared by

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I. INTRODUCTION

1.1 Object and Scope

The object of the study, as outlined in the work directive dated 18 August 1971 from the Division of Reactor Standards, U.S. Atomic Energy Commission, was essentially fivefold, namely as follows:

(a) Develop vertical and horizontal (two components) response spectra for a series of 14 strong motion earthquake records, including four San Fernando records, over the range of frequencies of interest, for 0.5, 2, 5 and 10 percent of critical damping. The records which were included as a part of the study are described in Section 1.2 of this report.

(b) Compare the vertical and horizontal responses obtained from these spectra.

(c) Determine the shape of the spectra in the high frequency range from 6 to 50 hertz, with special emphasis on site-dependent parametric effects.

(d) Suggest procedures for combining seismic stresses derived from horizontal and vertical responses.

(e) Summarize the above-noted studies in the light of recommendations for design.

All of the objectives noted have been accomplished with two minor exceptions, namely that after undertaking a comprehensive study of the available ground motion data, it was decided that the ground motion data were generally valid only in the frequency range of 0.05 to 30 hertz and accordingly the response spectra were plotted only for this range. Second, as a result of further studies on the site properties, and based on information that we had available from previous studies, we felt that it would be difficult to draw general conclusions about site dependence, since only a very few strong motion records on rock were available. Most of the available records are on alluvium. Nevertheless, some observations pertinent to site dependence were obtained as a part of our studies and comments are presented.

Near the end of this investigation it was recognized that the low intensity ground motions were causing a bias in the results. Accordingly studies were made including records corresponding to peak ground accelerations greater than a specified bound to demonstrate the bias. These findings are reported fully. The design response spectrum values reported herein are based on the "bounded" data.

The report that follows includes: (1) the description of the methods used in processing the data in Section 2; (2) a presentation and discussion of the results of the ground motion and special studies in Section 3; and (3) design recommendations and conclusions in Section 4. The procedure employed for adjusting the accelerogram records in this study is presented as Appendix A. The method used for normalizing response spectra is given in Appendix B.

1.2 Earthquake Records Studied

The studies were carried out for the following seismic events:

San Fernando seismic event

Pacoima Dam, 2-9-71, 0600 PST (Record IC 041)

Castaic, 2-9-71, 0600 PST (Record ID 056)

Holiday Inn (First Floor), 2-9-71, 0600 PST (Record IC 048)

15250 Ventura Boulevard (Basement), 2-9-71, 0600 PST (Record IH 115)

Other seismic events

El Centro, 5-18-40, 2037 PST (Record IA 1)

El Centro, 2-9-56, 0633 PST (Record IA 11)

El Centro, 4-8-68, 1830 PST (Record IA 19)

Hollywood Storage Basement, 7-21-52, 0453 PDT (Record IA 6)

Hollywood Storage PE Lot, 7-21-52, 0453 PDT (Record IA 7)

San Francisco Golden Gate Park, 3-22-57, 1144 PST (Record IA 15)

Ferndale, 10-7-51, 2011 PST (Record IA 2)

Ferndale, 12-21-54, 1156 PST (Record IA 9)

Eureka, 12-21-54, 1156 PST (Record IA 8)

Hollister, 4-8-61, 2323 PST (Record IA 18)

The accelerogram records used in this study were digitized by the Earthquake Engineering Research Laboratory of the California Institute of Technology; the CIT designation of the earthquake record is indicated in parentheses at the end of each listing. The records are available through the Department of Commerce or the California Institute of Technology.

2. PROCESSING OF DATA

2.1 Time-history

Since the digitized record from the instruments are in terms of acceleration time-histories, the corresponding velocity and displacement are obtained by integration. Adjustments in the records are normally required as illustrated by the following example. The acceleration, velocity, and displacement time-histories for a typical record, San Fernando earthquake, N69W component of Castaic, 2-9-71, 0600 PST are shown in Figs. 2.1-2.3. Since the motion during an earthquake is a to and fro type motion, the velocity time-history, Fig. 2.2, is obviously incorrect, and the corresponding displacement time-history, Fig. 2.3, also is in error. The figure indicates a displacement of 130 in. at 30 seconds. This displacement would have increased further had the computation continued.

The errors in earthquake records may arise from any number of sources such as (a) the instrument errors, including effects associated with mounting and instrument housing; and (b) the processing of the record where the initial conditions (some motion is required to trigger the mechanism) and the zero acceleration line (baseline) are not known. The errors in the velocity and displacement time-histories arising from integration of the accelerogram are largely associated with the latter category. In order to minimize the record processing errors, the initial conditions are taken as zero, and a baseline correction is applied to the accelerogram record.(1) Among various baseline adjustment procedures, one which minimizes the square of the error in the velocity is most commonly used. This procedure assumes a polynomial, usually a second degree, for the correct acceleration baseline. In some instances the record processing errors are further reduced by using different polynomials for acceleration baseline in different portions of the record. This procedure is explained in detail in Appendix A.

Each component of the 14 earthquakes considered in this study was adjusted by the procedure given in Appendix A. A second degree polynomial was used as the acceleration baseline in all cases, with "segmental" adjustments used occasionally as described in Appendix A. The adjusted velocity and displacement time-histories were computed by integrating the adjusted acceleration time-history and they were plotted on a Calcomp plotter. An examination of the accelerogram records used in this study indicated that the strong motion portion of the record is included within the first 20 seconds of the record. For consistency the computation and plotting of time-histories were carried out for the first 30 seconds of each record.

As a general illustration of the effects of adjustment, the unadjusted and the adjusted acceleration, velocity, and displacement ground motion time-histories for a typical record of the San Fernando earthquake, N69W component of Castaic, 2-9-71, 0600 PST are shown in Figs. 2.1-2.6.

2.2 Response Spectra

After the adjusted time-history was obtained for each record, the time-history was used as a base motion input to a single-degree-of-freedom damped oscillator and the response of the oscillator as a function of the frequency of the oscillator was computed. In this way a response spectrum is generated. The computation of response spectra is well documented in the literature[2,3] and is not repeated here. In computing the response spectra, the adjusted time-history was used because the spectral ordinates computed from the unadjusted record may be in error for low frequencies. The response spectra for 0.5 percent of critical damping for both the adjusted and unadjusted records of the San Fernando earthquake, N69W component of Castaic, 2-9-71, the example used in Section 2.1, are shown in Fig. 2.7. It is seen that adjusting the record affects the spectral ordinates for low frequencies. Although as a general rule the adjustment has little effect for frequencies of interest for nuclear reactors, in order to provide a better basis for comparisons reported later herein, the computations of response spectra were carried out using the adjusted time histories.

The response computations were carried out for 38 frequencies having a range of 0.05 to 30 hertz. In computation of the response spectra, the interval in the frequency range over which the computations are carried out influences the shape of the spectra. Generally this influence is not large if small intervals in frequency are used in computations. A comparison between two response spectra for El Centro, California, 5-18-1940, NS component, one computed by the California Institute of Technology[4] using 91 frequencies and the other computed by the authors using 38 frequencies, is shown in Fig. 2.8. In general the agreement between the two spectra is quite good. The difference between the two spectra for frequencies below 0.3 hertz is due to different procedures used for baseline adjustment of the accelerogram. Another comparison between the two spectra for the same earthquake, a coarse frequency interval (38 frequencies), and a fine frequency interval (81 frequencies), both computations being carried out by the authors, is shown in Fig. 2.9.

Response computations at higher frequencies were not carried out since the validity of ground motion data for frequencies greater than 30 hertz is questionable. In addition, the response computation at high frequencies (small periods) require very small integration time steps which are time-consuming computationally. For each component of the record, the response computations were carried out for 0, 0.5, 2, 5 and 10 percent of critical damping. After the results from the response computations were examined, they were plotted on a Calcomp plotter. Plots of the response spectra are included as Figs. 2.10-2.51; the maximum ground motions are shown by three straight-line segments in each figure, and correspond to the values given in Table 3.1.

2.3 Amplification Factors

Since the ground motions for earthquake records differ from each other, the computed response quantities cannot be compared on an absolute basis. One method of making a meaningful comparative study involves normalization of the response spectra by equating the area under the response spectra between any two frequencies.(5) Another method of normalizing the response spectra is to compute the amplification factor -- the ratio of the computed response to the maximum ground motion -- for displacement, velocity, and acceleration at each frequency for the range of interest. With this procedure, the amplification factors can be used to develop design response spectra for a given ground motion. This procedure was followed and is described in Chapter 3. The procedure for normalizing the response spectra is explained in Appendix B.

2.4 Statistical Analysis

For damping coefficients of 0.5, 2, 5 and 10 percent of critical, and for each frequency, the mean and the standard deviation for both the horizontal and vertical components of the 14 earthquakes were computed. Since there are two horizontal components for each earthquake, the sample size for the horizontal components is twice that for the vertical components. Therefore, on a numerical basis the statistical values for the horizontal components are more reliable than the corresponding values for the vertical components. Initially the statistical studies were carried out as a function of frequency bands; subsequently it was found necessary to carry out the statistical computation at each frequency instead of within frequency bands in order to account accurately for the variation of amplification factors as a function of frequency.

With the means (or averages) and the standard deviations at various frequencies, the percentile amplifications from a normal distribution curve were computed from

$$x_p = \bar{x} + c\sigma$$

where x_p, $\bar{x}$, and σ are, respectively, the percentile amplification, the mean amplification, and the standard deviation at a given frequency. The values of the coefficient c for various probability levels are given in Table 2.1. The percentile amplifications at each frequency were used to obtain average amplification coefficients within frequency bands of interest (see Section 3.2).

Percentile amplification computations were also carried out by ranking the data. For large sample sizes the two procedures give results which are generally in close agreement with each other.

Table 2.1 Normal Deviations from Mean, in a Normal Distribution, in Terms of Standard Deviation, as a Function of Cumulative Probability P

P	$c = \frac{\text{deviation from mean}}{\text{standard deviation}}$
0.999	3.09023
0.998	2.87816
0.995	2.57583
0.990	2.32635
0.980	2.05375
0.970	1.88079
0.950	1.64485
0.900	1.28155
0.850	1.03643
0.800	0.84162
0.750	0.67449
0.700	0.52440
0.650	0.38532
0.600	0.25335
0.550	0.12566

Source: Table 11.2, p. 670, "Statistical Methods in Quality Control," by Dudley J. Cowden, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1957.

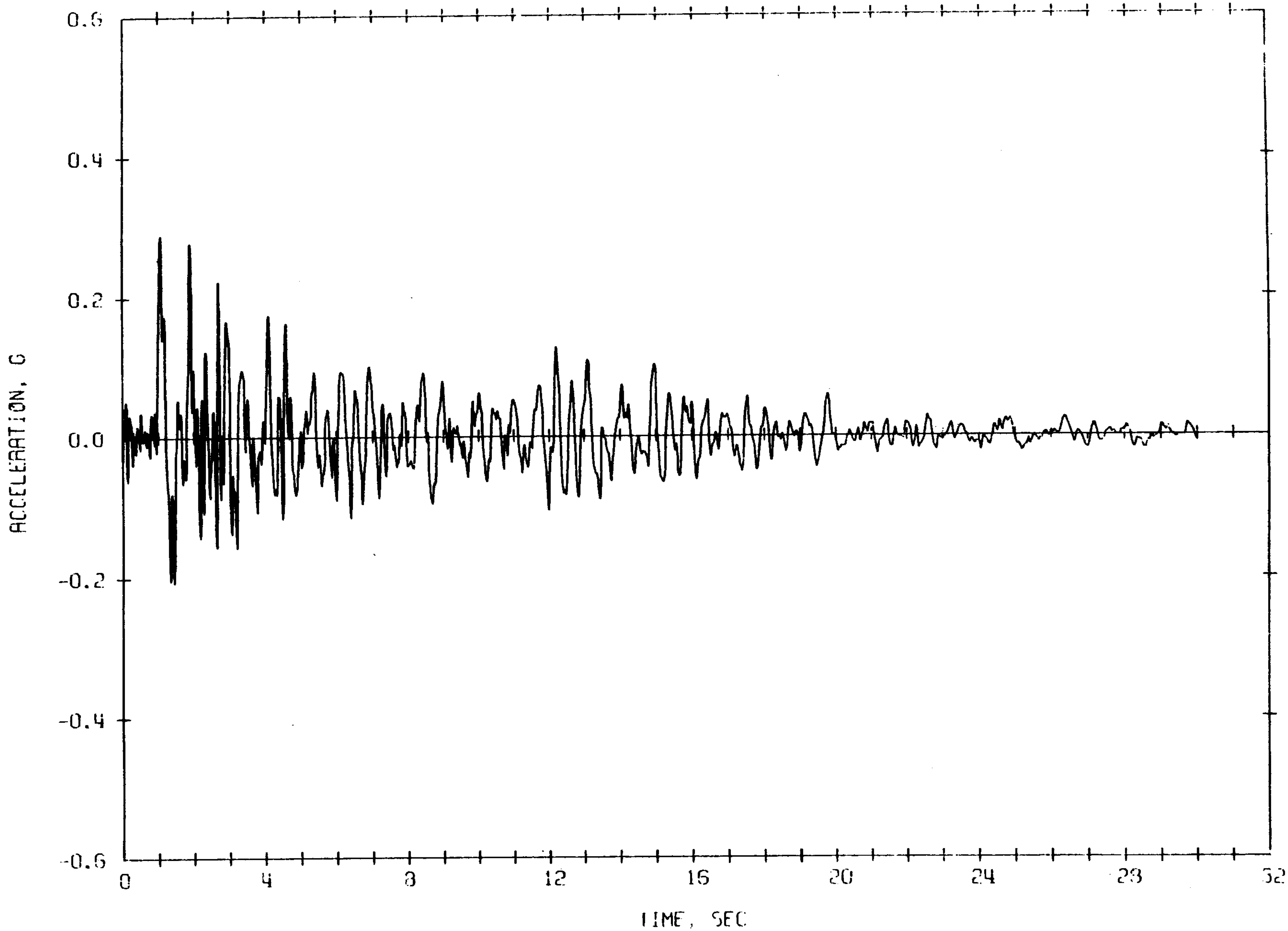


FIG.2.1 ACCELERATION - TIME HISTORY. SAN FERNANDO. CALIF., 2/9/1971
CASTAIC N69W - UNADJUSTED RECORD

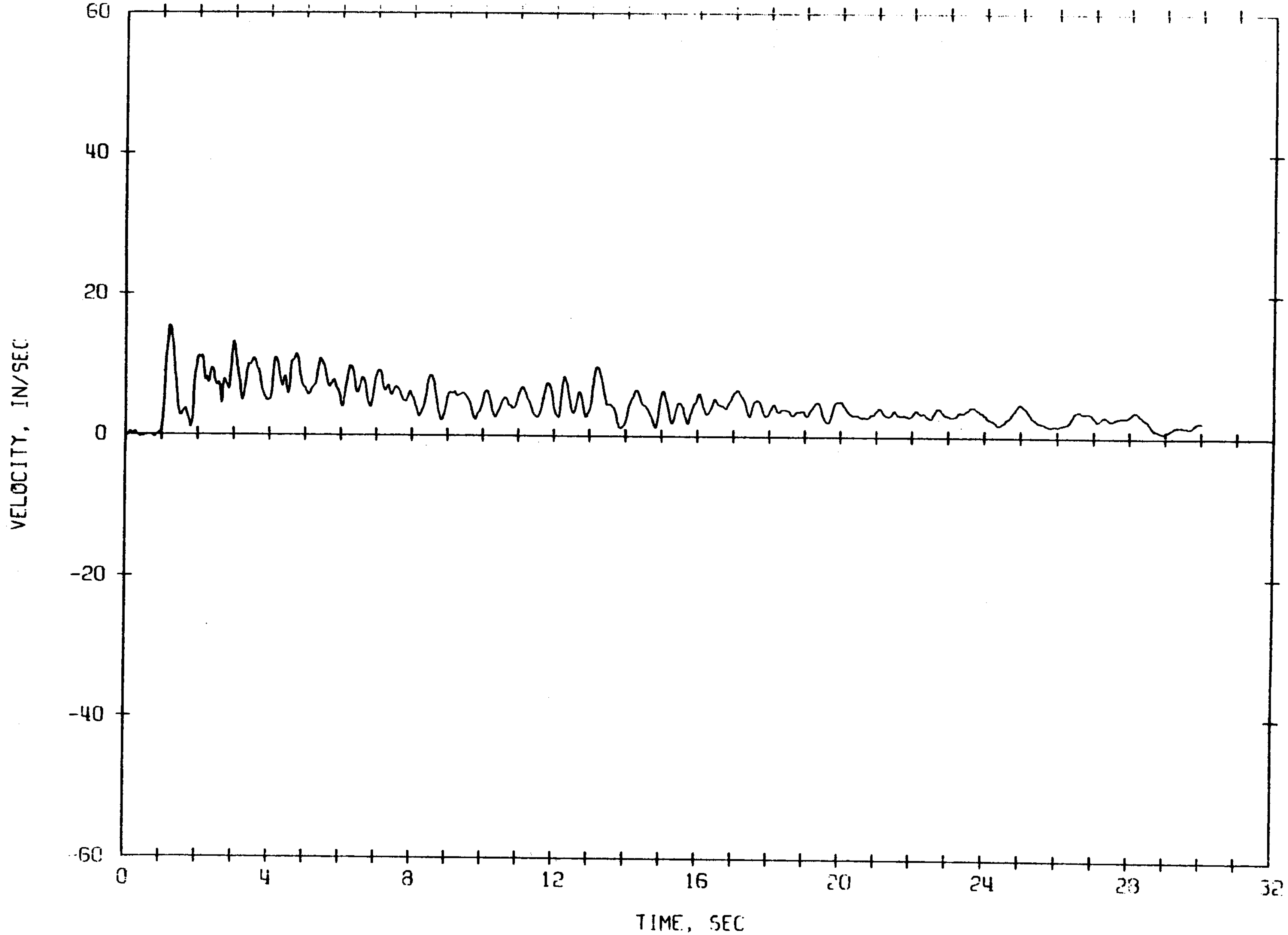


FIG.2.2 VELOCITY - TIME HISTORY, SAN FERNANDO, CALIF., 2/9/1971
CASTAIC N69W - UNADJUSTED RECORD

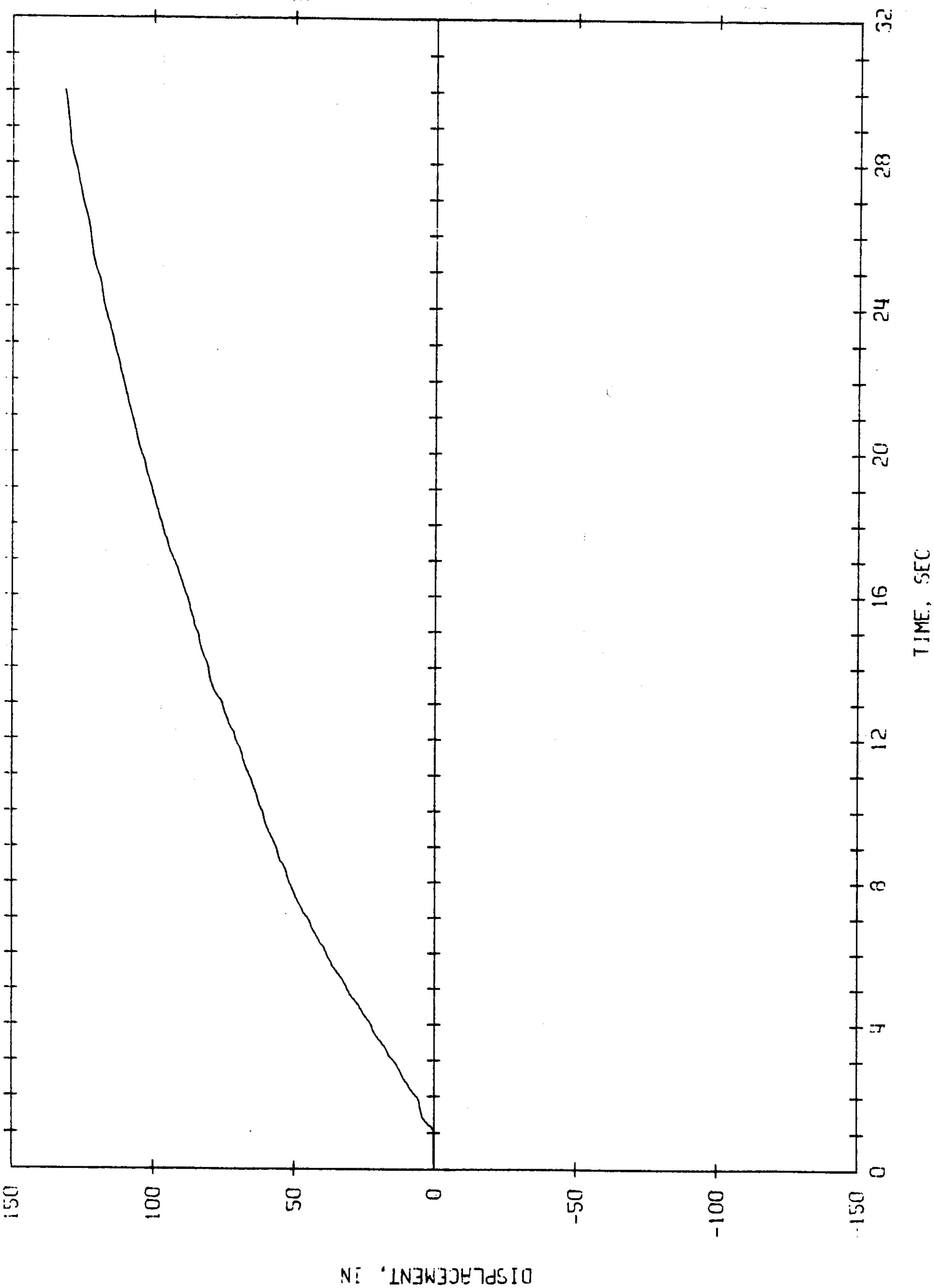


FIG.2.3 DISPLACEMENT - TIME HISTORY, SAN FERNANDO, CALIF., 2/9/1971
CASTAIC N69W - UNADJUSTED RECORD

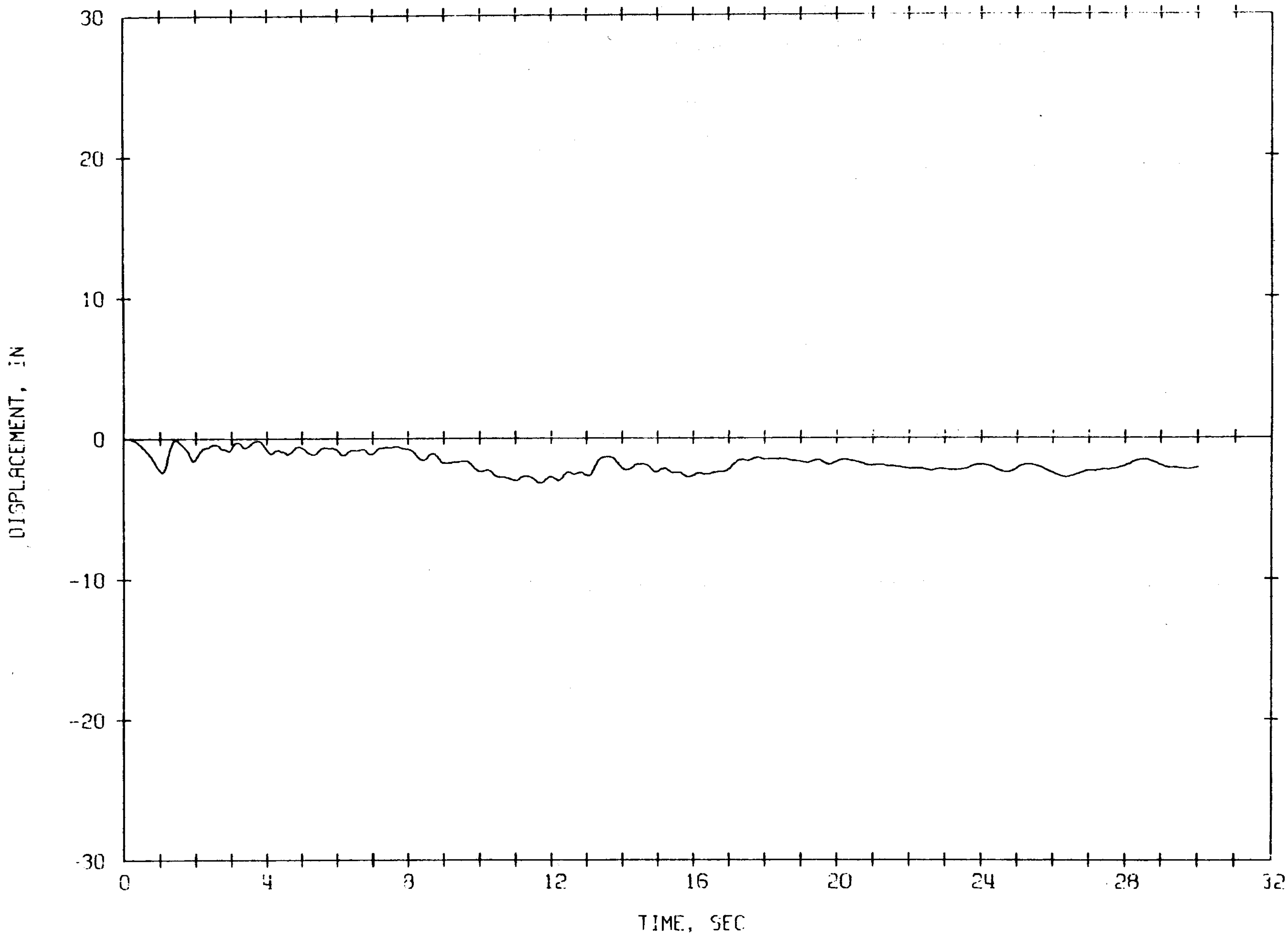


FIG.2.4 DISPLACEMENT - TIME HISTORY, SAN FERNANDO, CALIF., 2/9/1971
CASTAIC N69W - SEGMENTALLY ADJUSTED RECORD

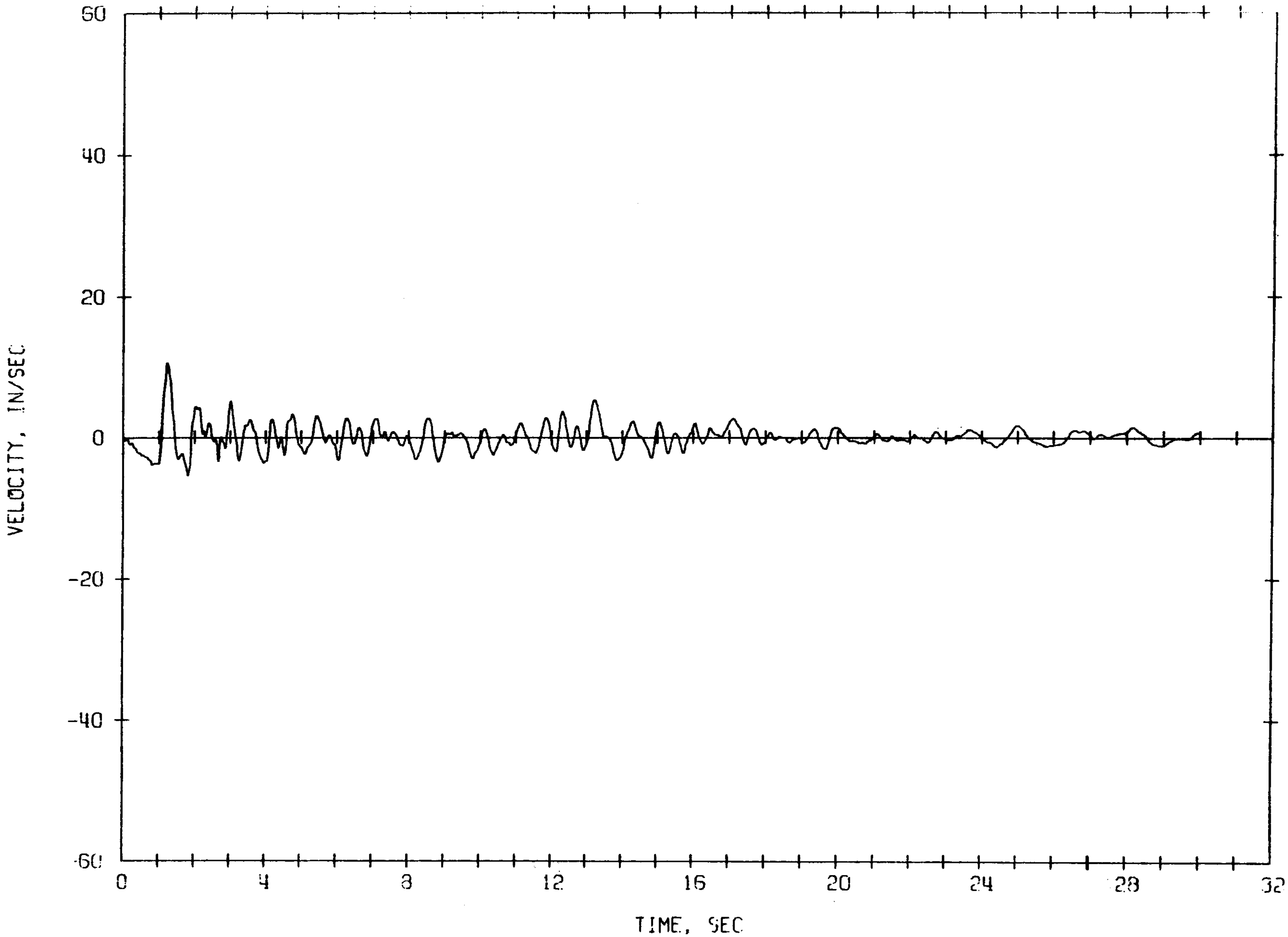


FIG.2.5 VELOCITY - TIME HISTORY, SAN FERNANDO, CALIF., 2/9/1971
CASTAIC N69W - SEGMENTALLY ADJUSTED RECORD

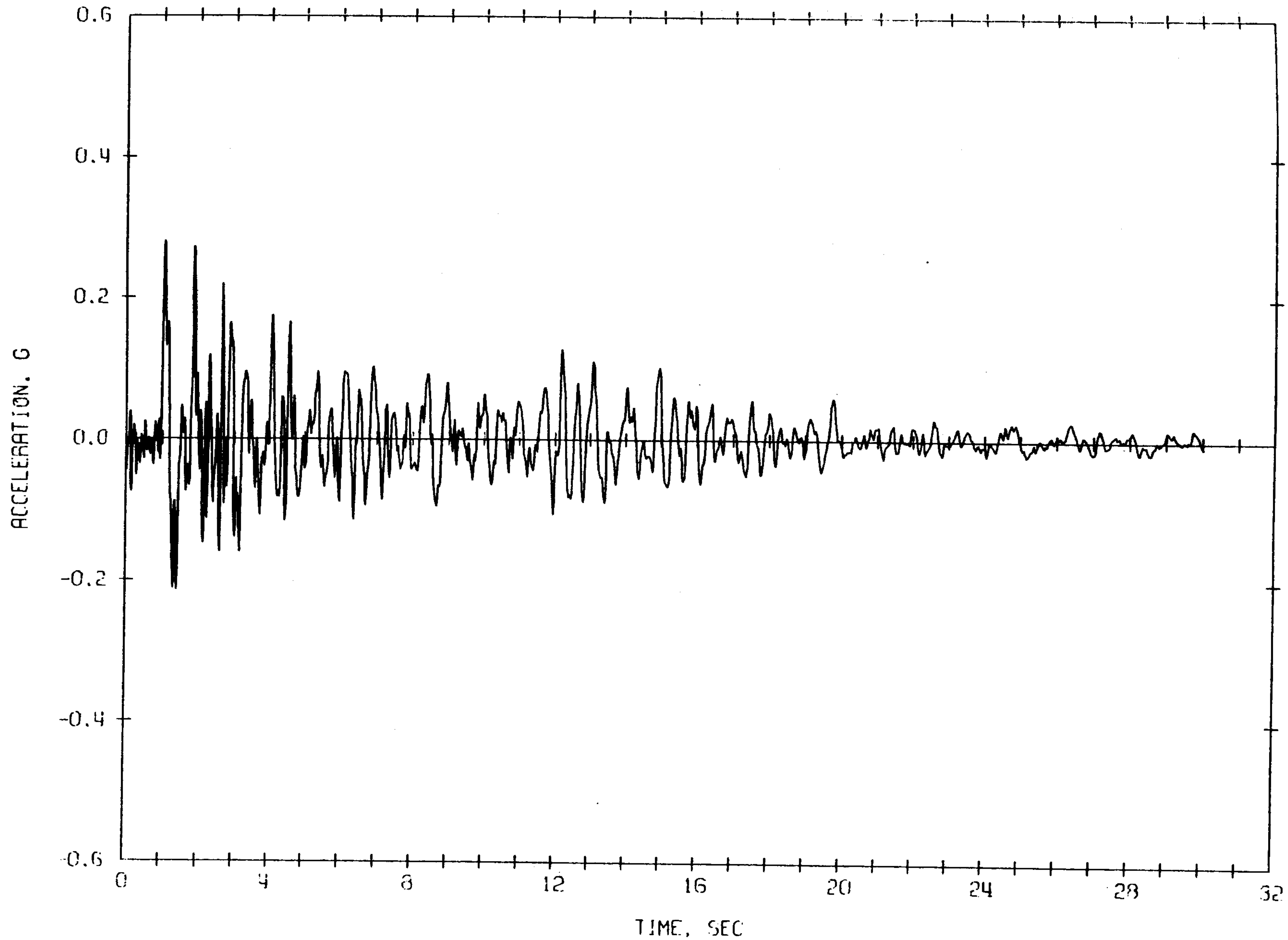


FIG.2.6 ACCELERATION - TIME HISTORY, SAN FERNANDO, CALIF., 2/9/1971
CASTAIC N69W - SEGMENTALLY ADJUSTED RECORD

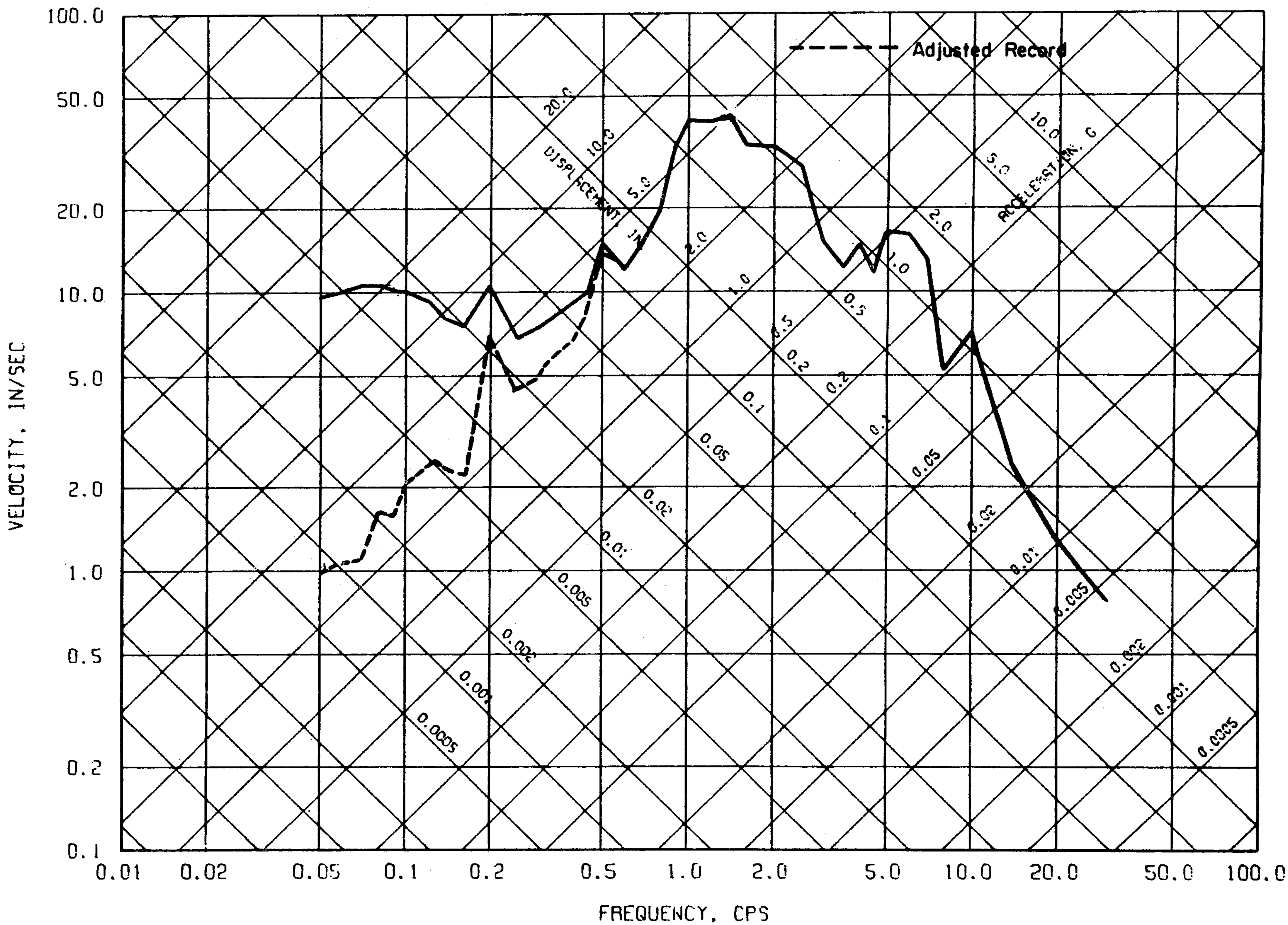


FIG. 2.7 RESPONSE SPECTRA FOR SAN FERNANDO, CALIF., 2/9/1971 - CASTAIC N69W UNADJUSTED RECORD - 0.5 PERCENT OF CRITICAL DAMPING

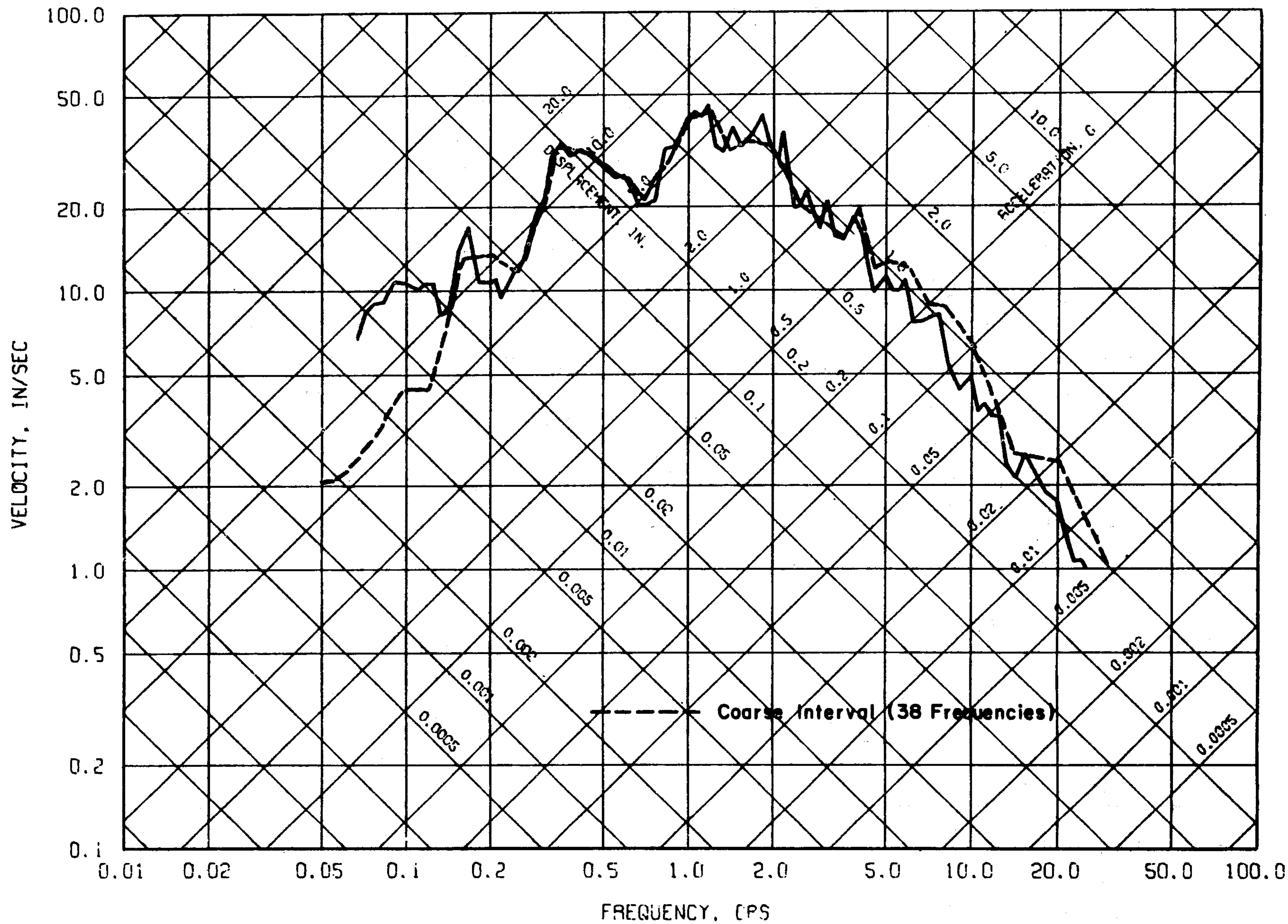


FIG. 2.8 RESPONSE SPECTRA FOR EL CENTRO, CALIF., 5/18/1940 - NS
2.0 PERCENT OF CRITICAL DAMPING - CALTECH SPECTRA

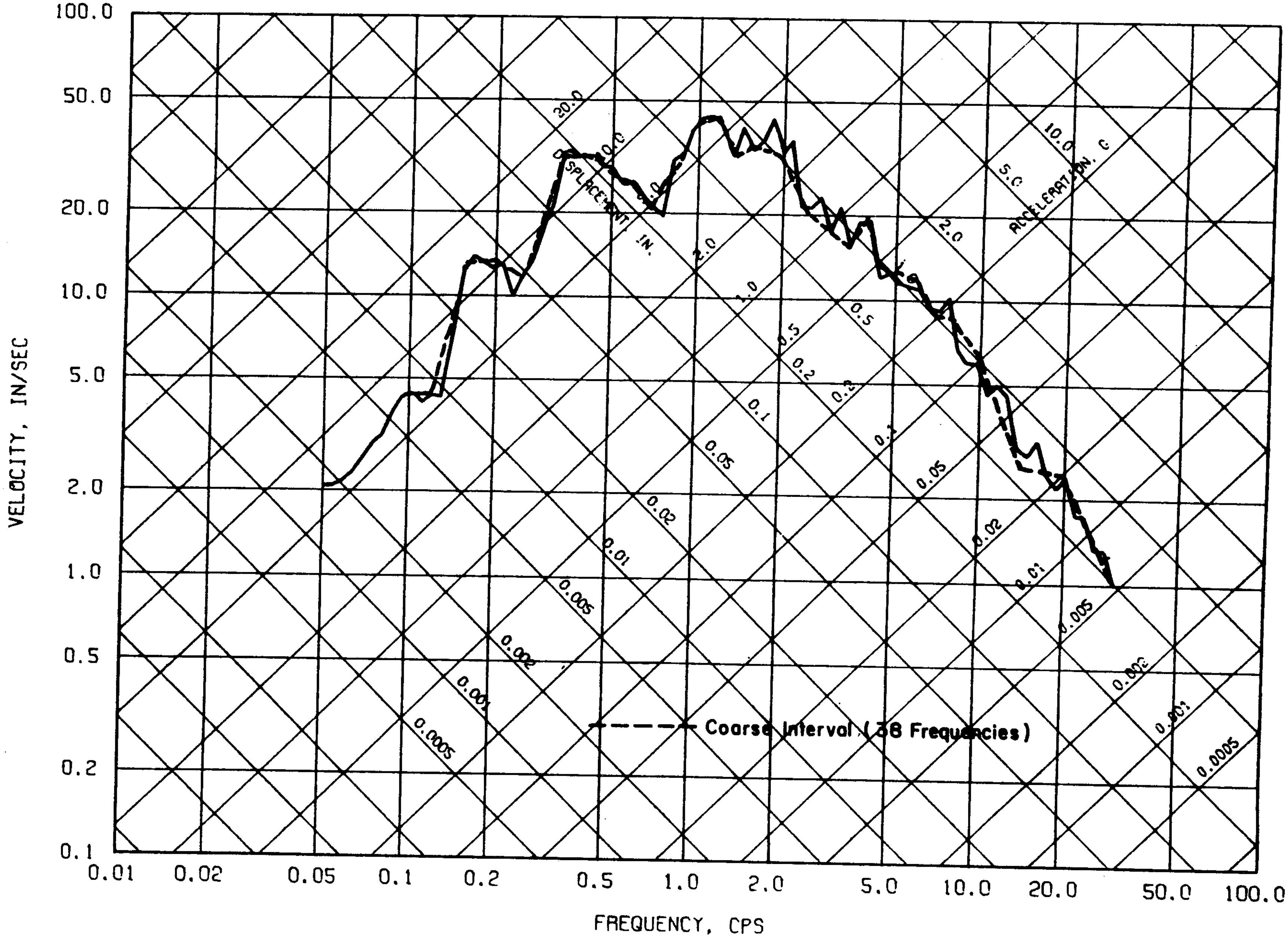


FIG. 2.9 RESPONSE SPECTRA FOR EL CENTRO 1940 - NS - 2.0 PER CENT OF CRITICAL DAMPING, USING 81 EQUALLY SPACED FREQUENCIES ON THE PLOT

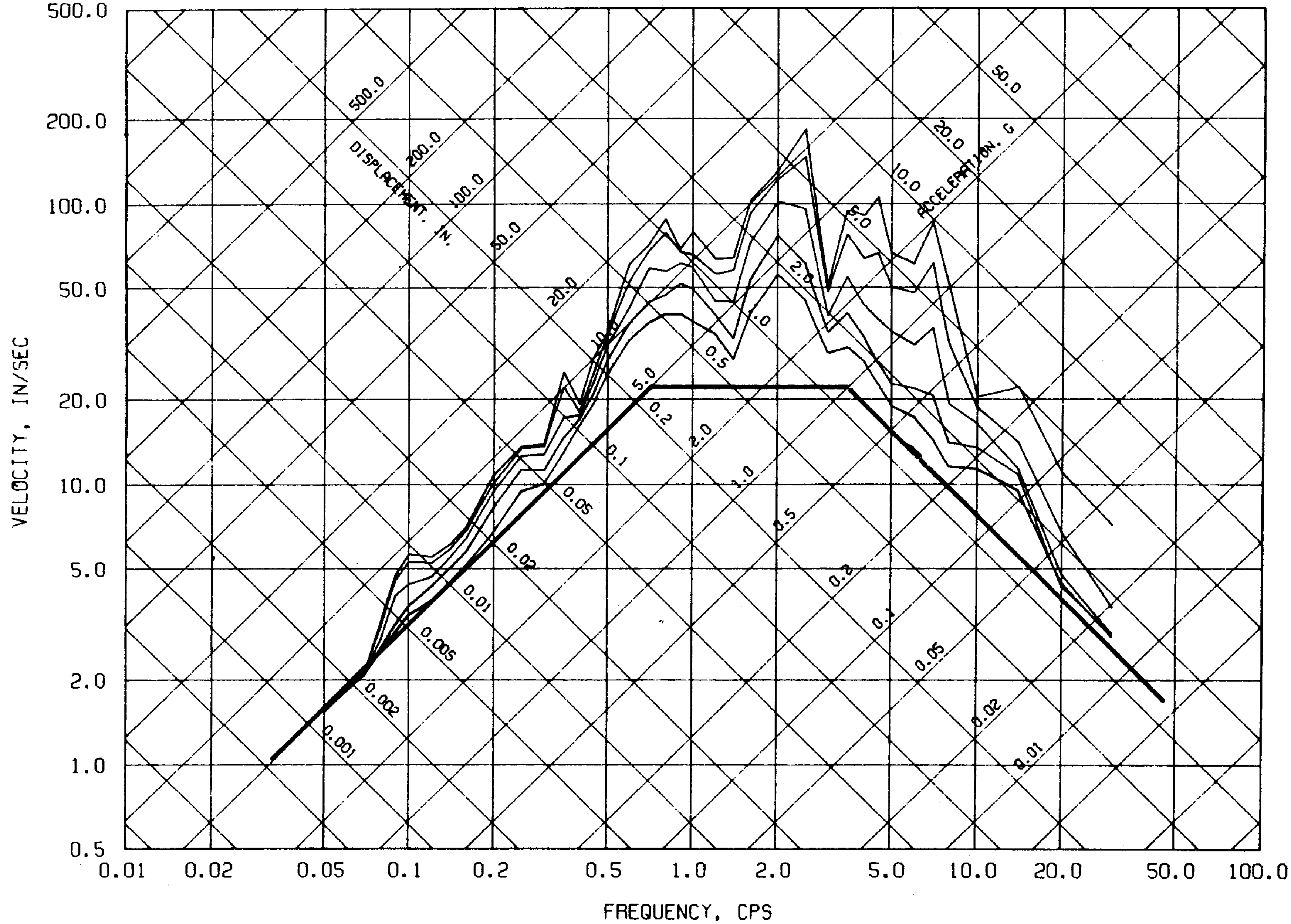


FIG.2.10 RESPONSE SPECTRA - SAN FERNANDO, CALIF., 2/9/1971 - PACOIMA S74W
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

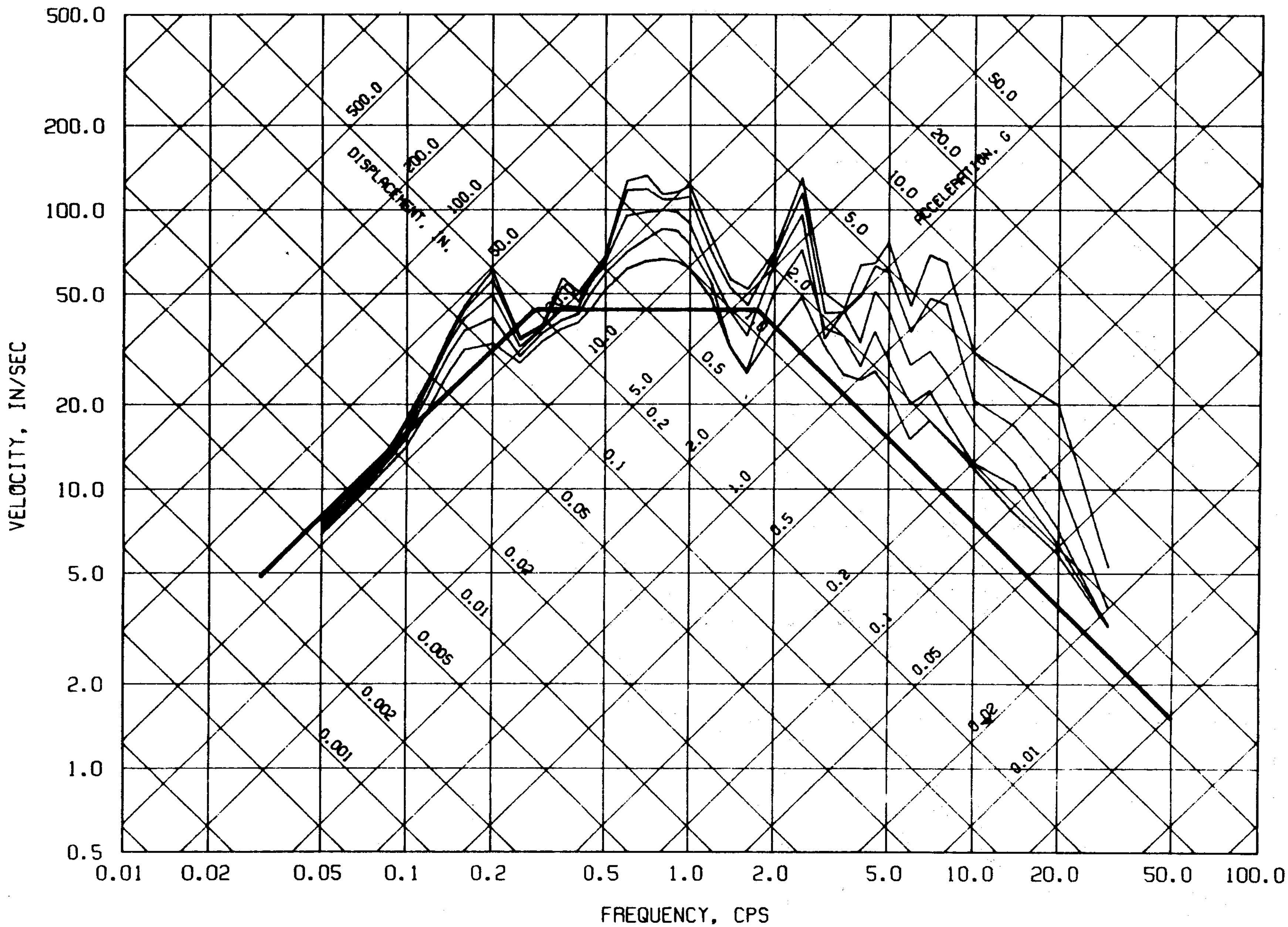


FIG.2.11 RESPONSE SPECTRA - SAN FERNANDO, CALIF., 2/9/1971 - PACOIMA S16E
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

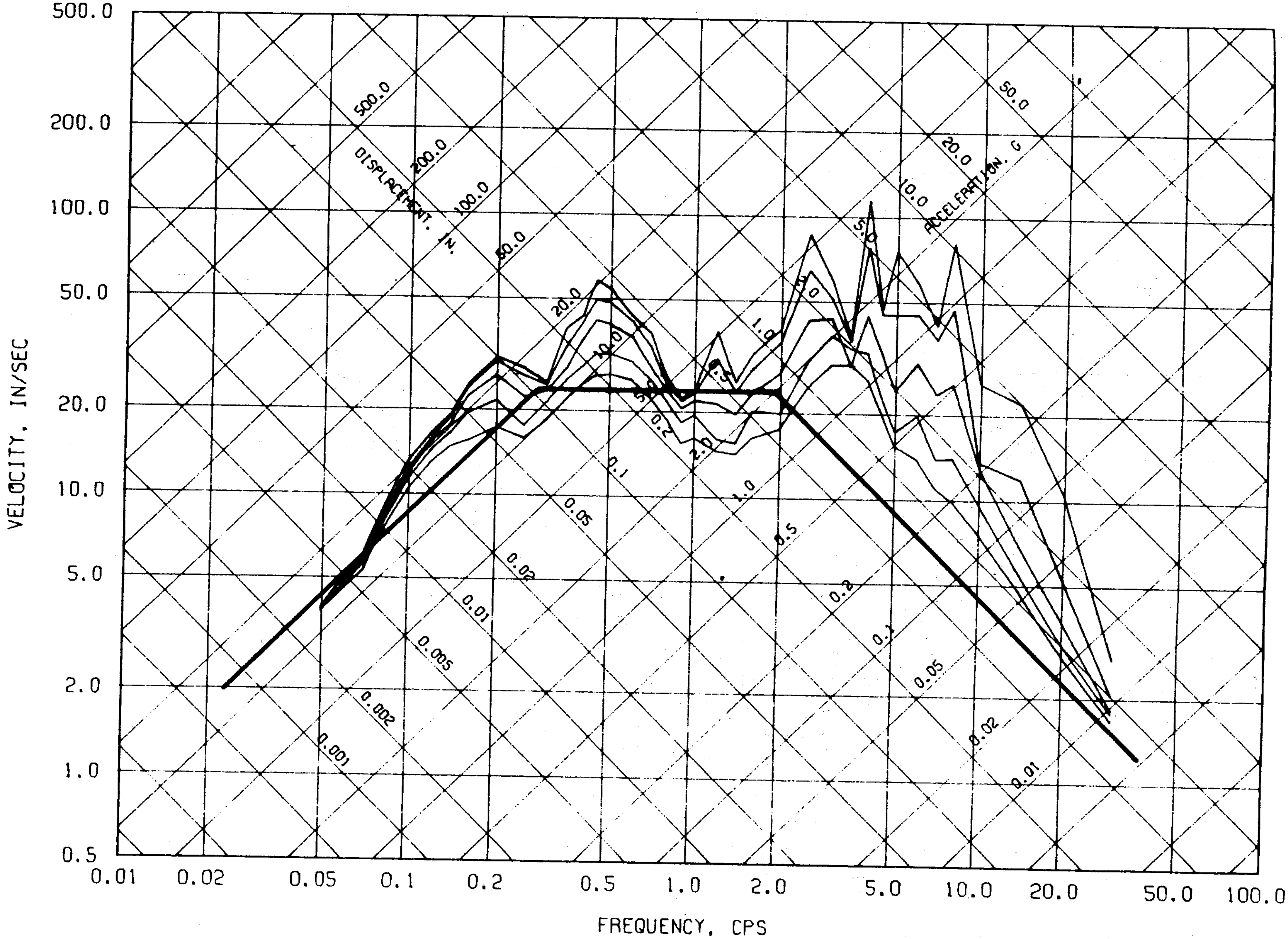


FIG.2.12 RESPONSE SPECTRA - SAN FERNANDO, CALIF., 2/9/1971 - PACOIMA VERTICAL
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

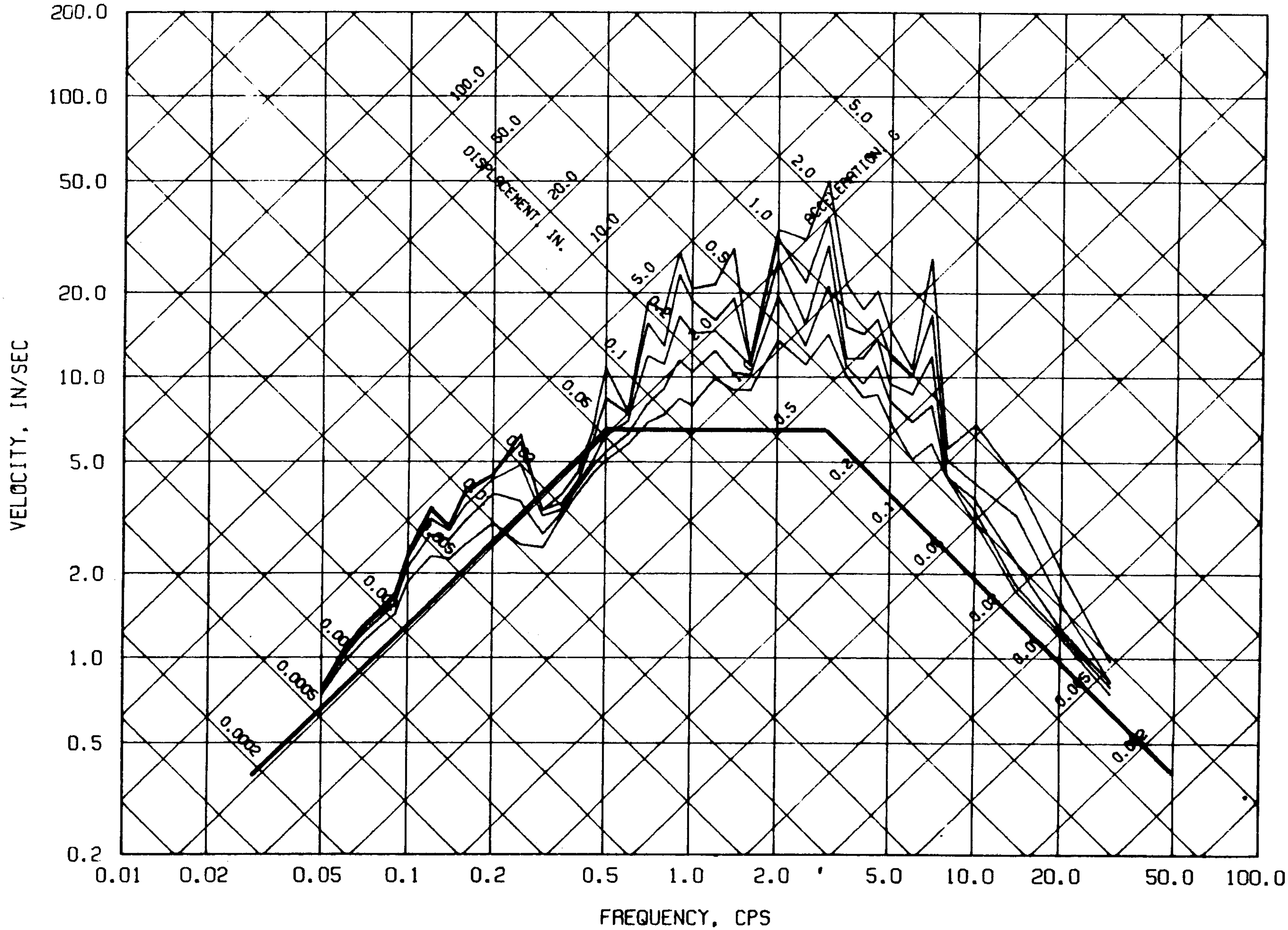


FIG.2.13 RESPONSE SPECTRA - SAN FERNANDO, CALIF., 2/9/1971 - CASTAIC N21E
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

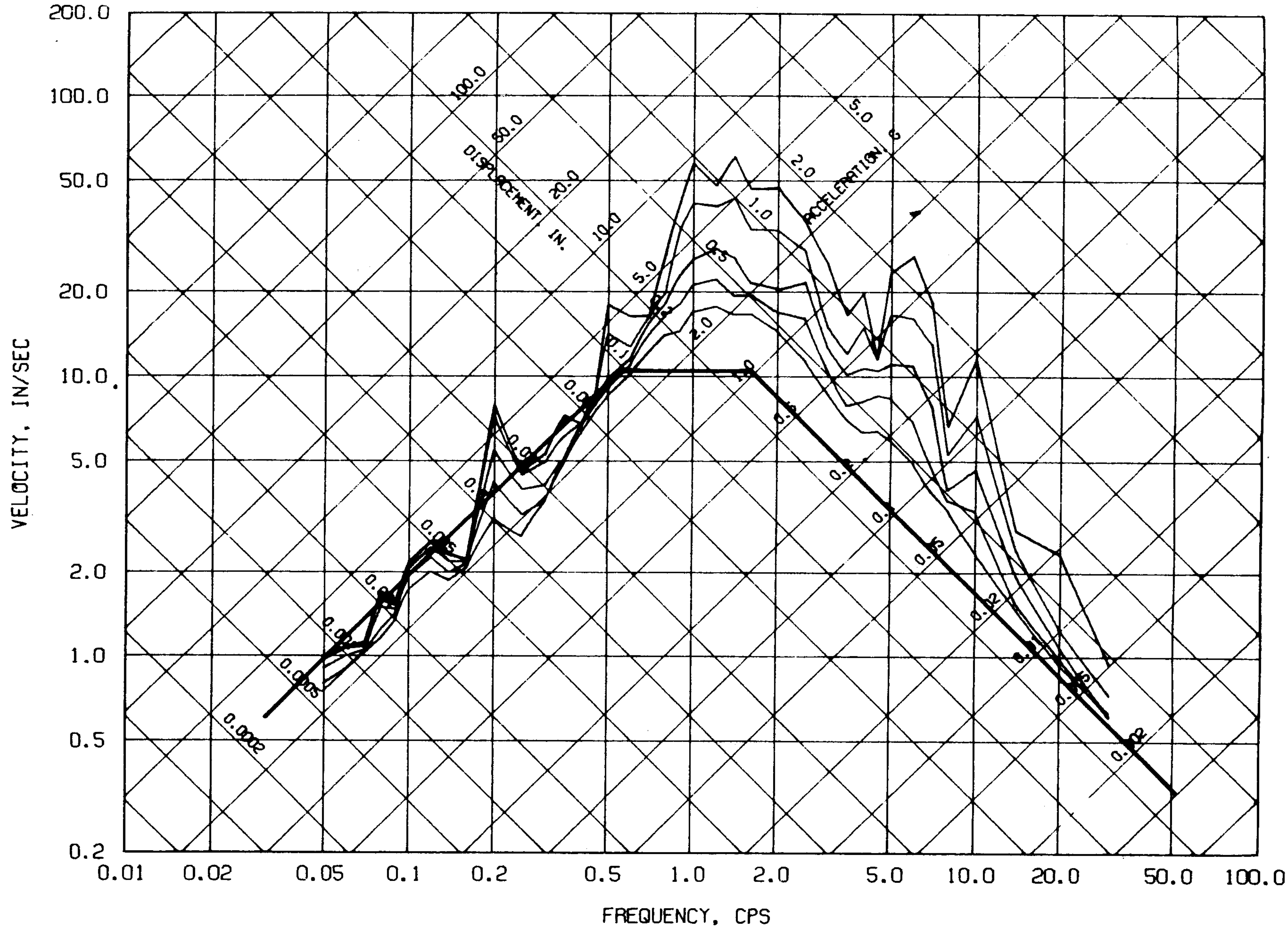


FIG.2.14 RESPONSE SPECTRA - SAN FERNANDO, CALIF., 2/9/1971 - CASTAIC N69W
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

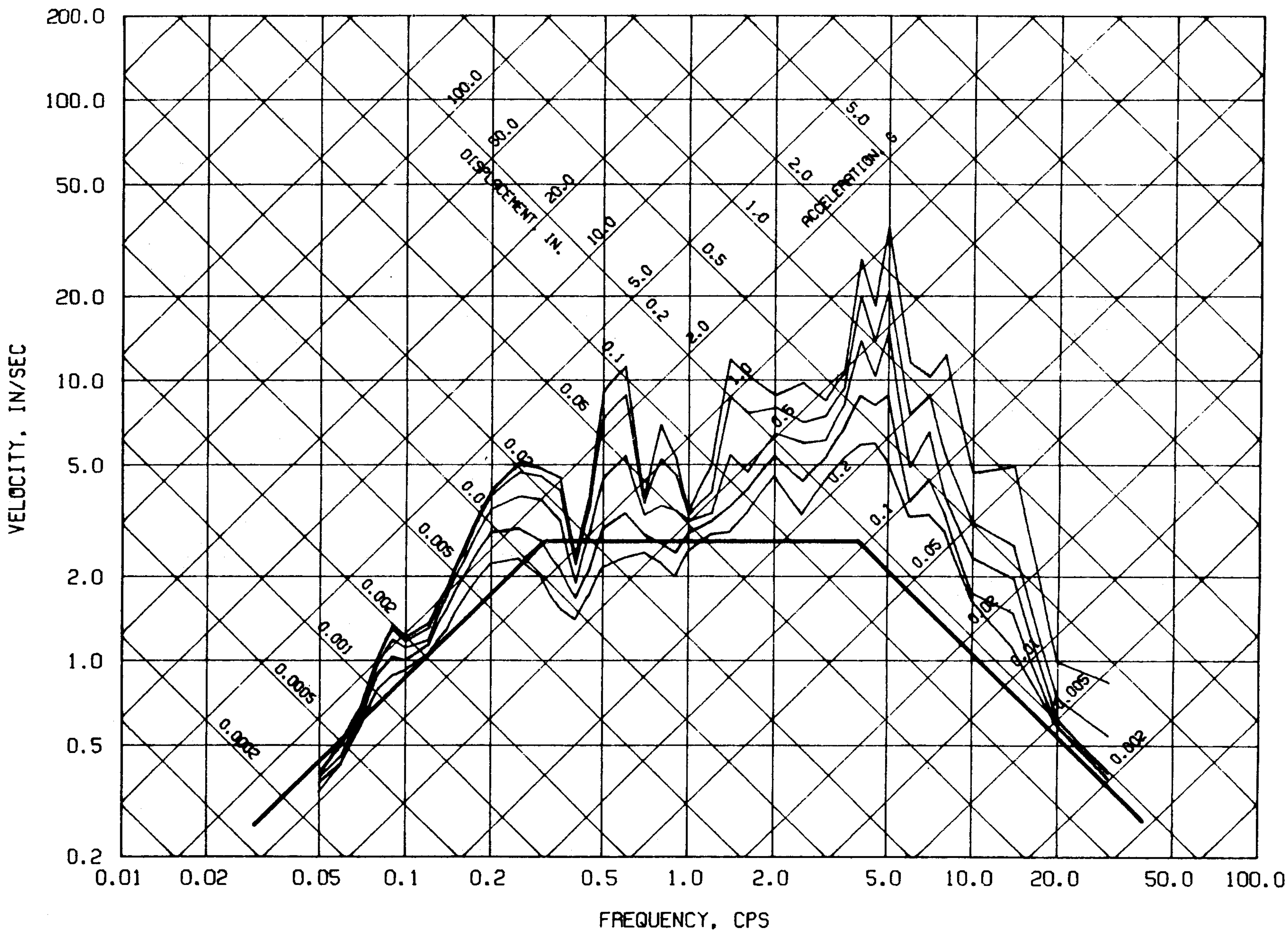


FIG.2.15 RESPONSE SPECTRA - SAN FERNANDO, CALIF., 2/9/1971 - CASTAIC VERTICAL
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

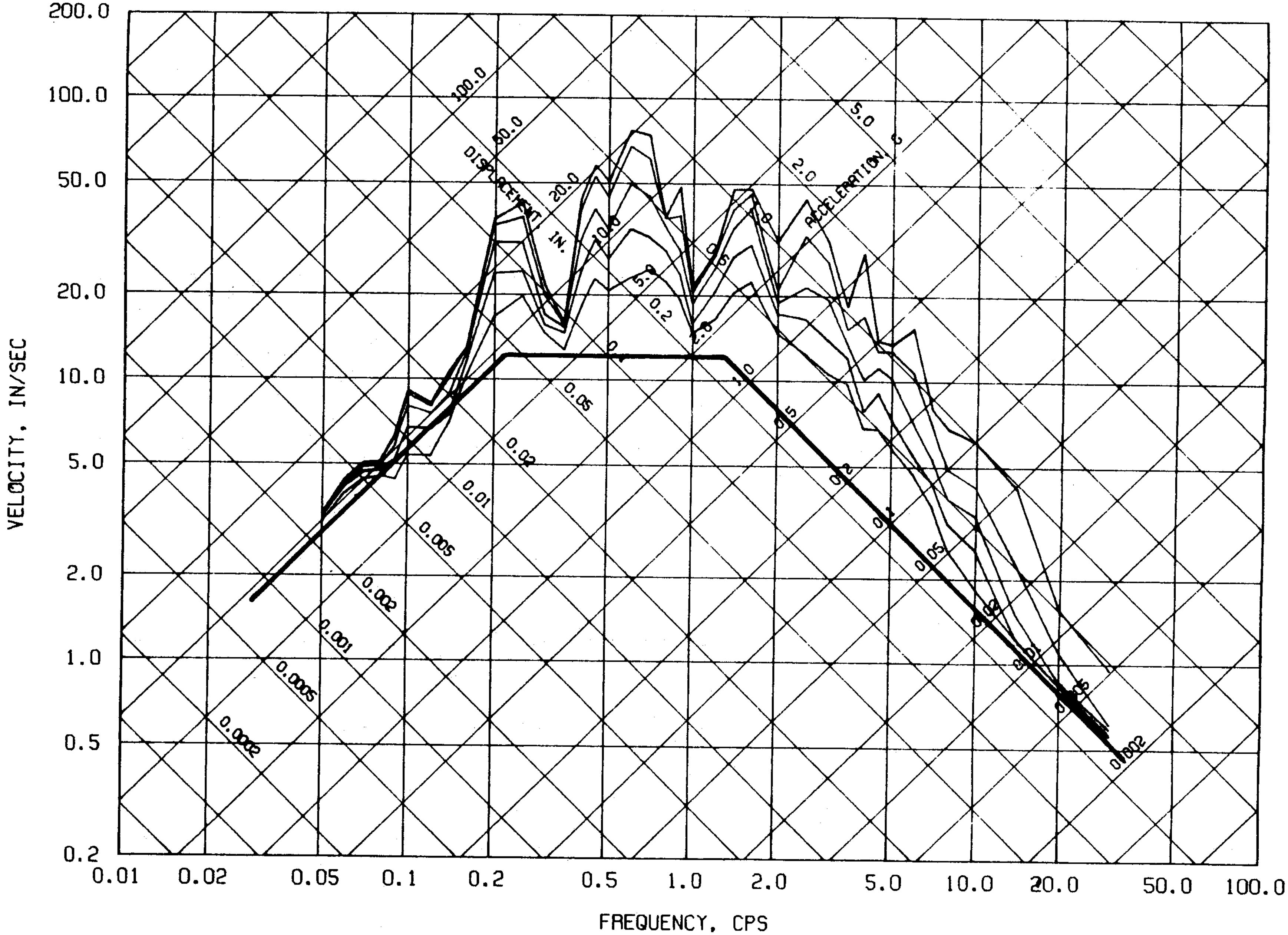


FIG.2.16 RESPONSE SPECTRA - SAN FERNANDO, CALIF., 2/9/1971 - HOLIDAY INN NS
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

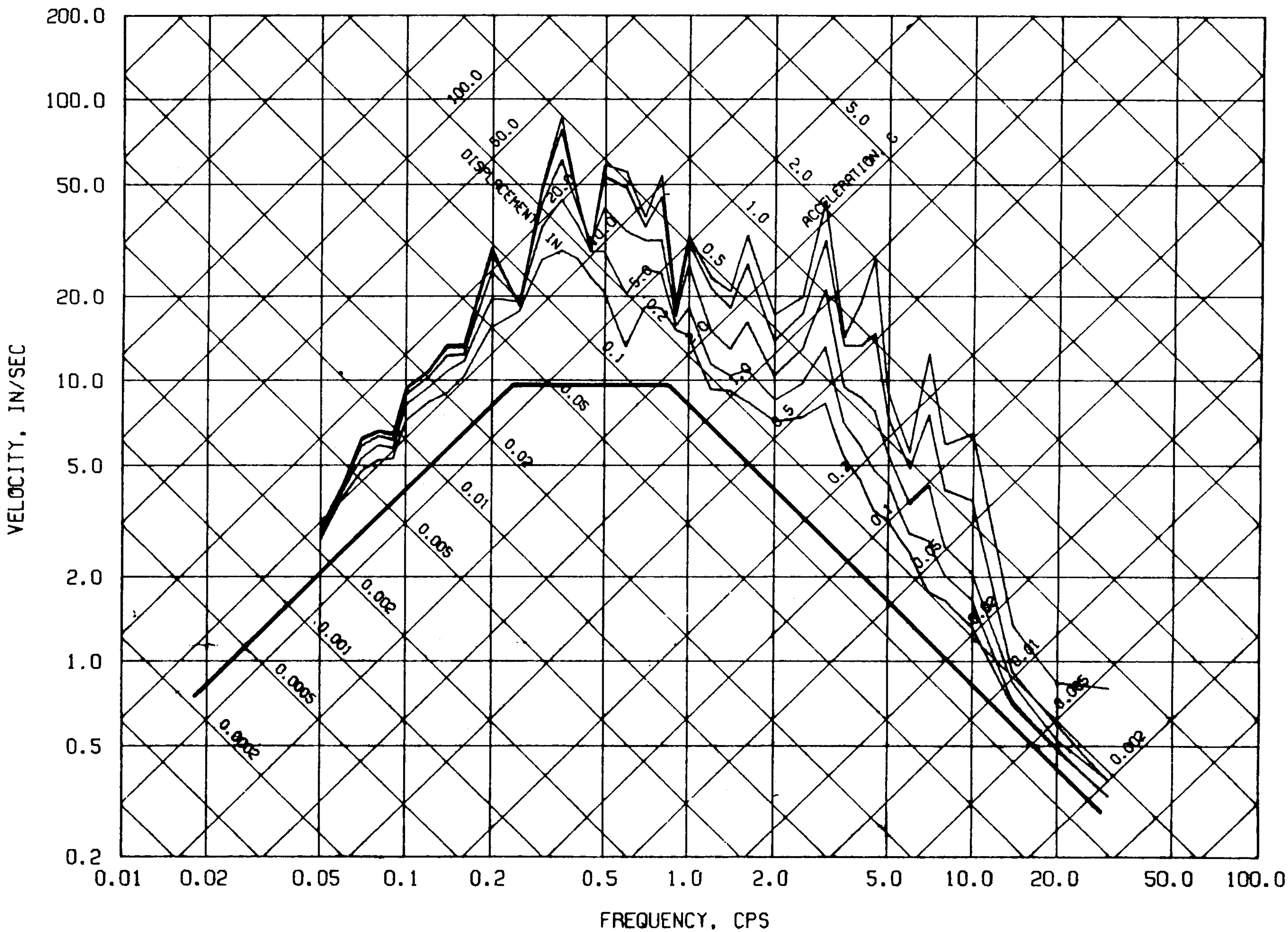


FIG.2.17 RESPONSE SPECTRA - SAN FERNANDO, CALIF., 2/9/1971 - HOLIDAY INN EW
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

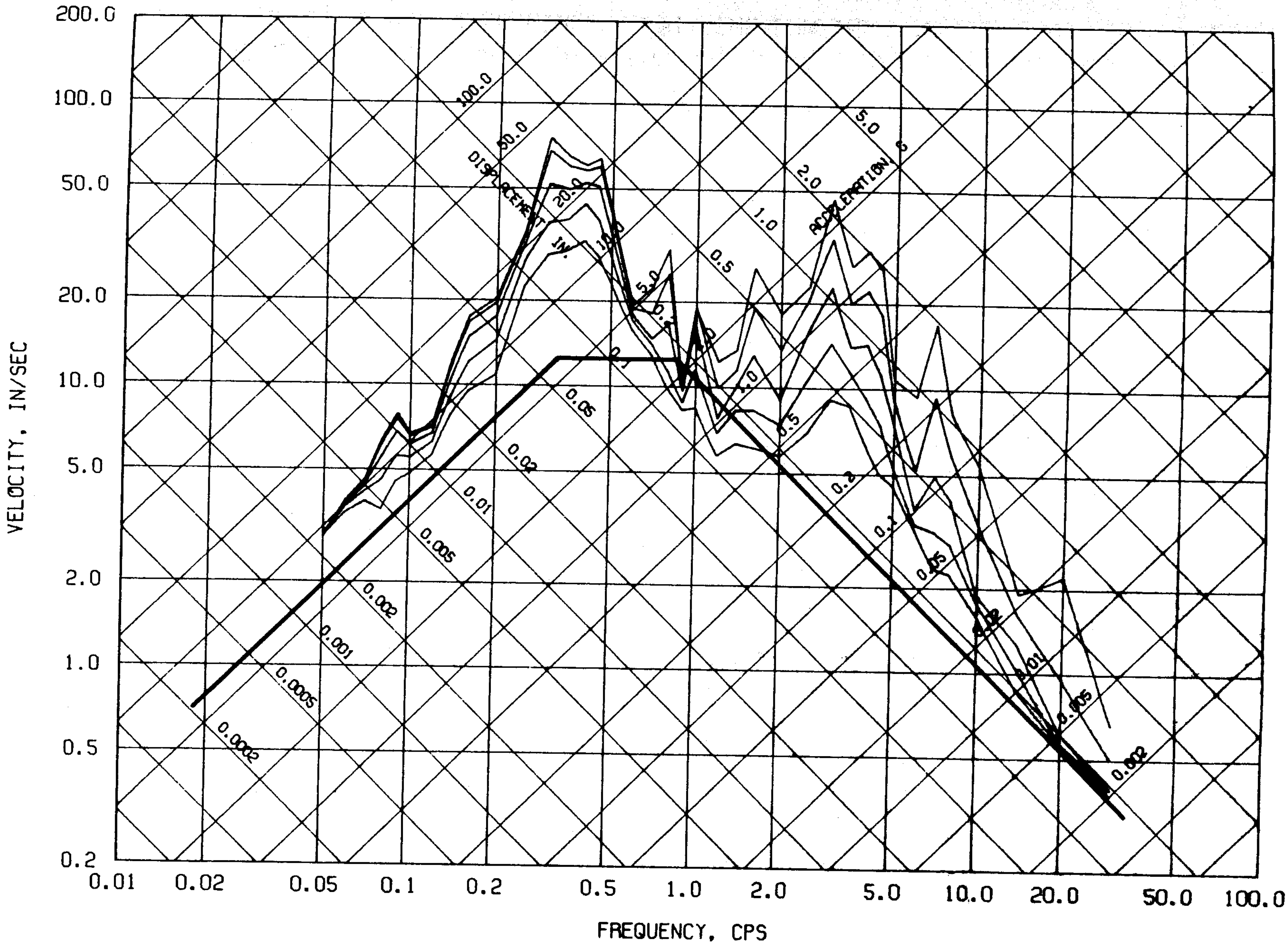


FIG.2.18 RESPONSE SPECTRA - SAN FERNANDO, CALIF., 2/9/1971 - HOLIDAY INN VERTICAL
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

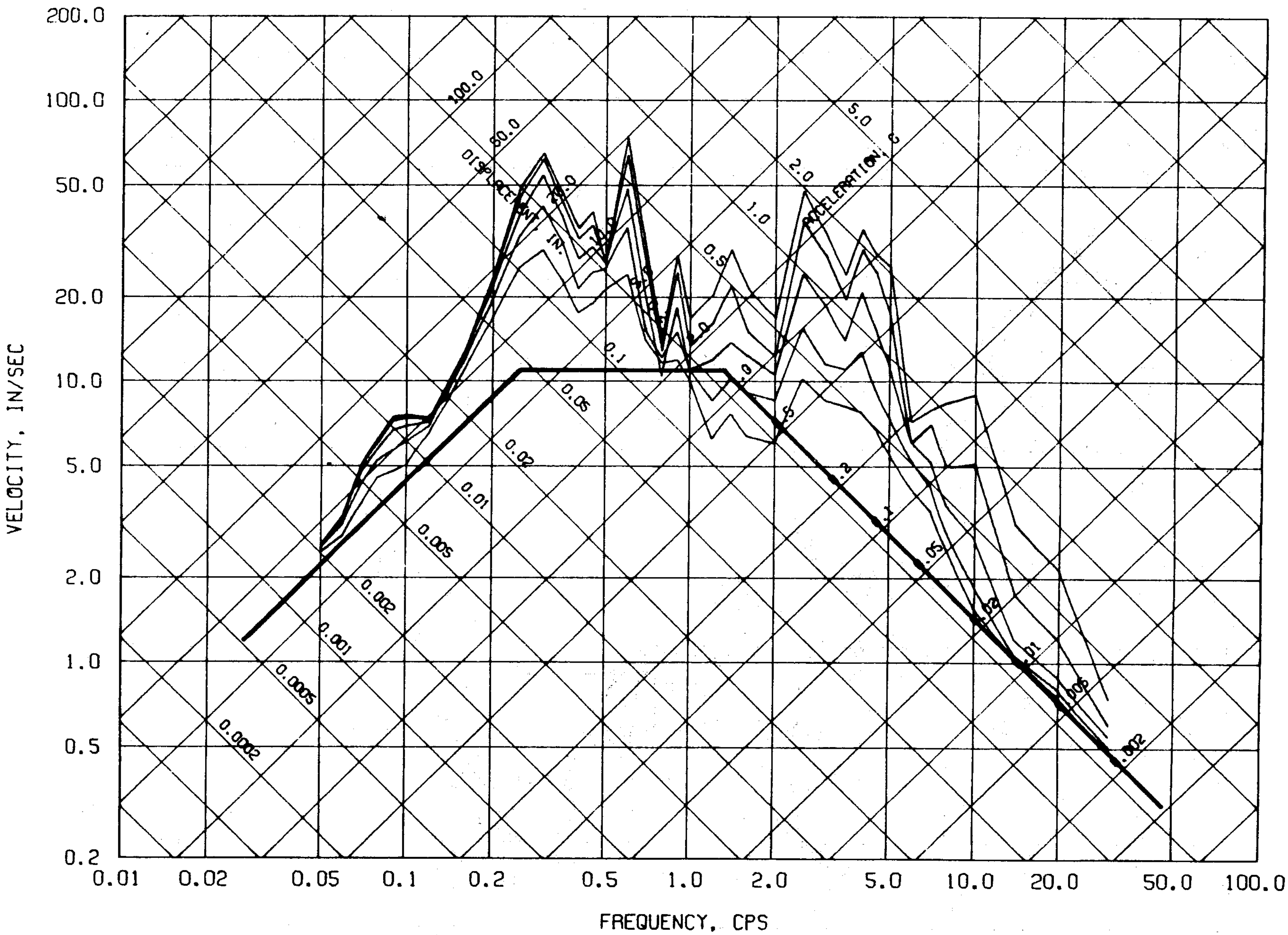


FIG.2.19 RESPONSE SPECTRA - SAN FERNANDO, CALIF., 2/9/1971 - VENTURA BLVD N11E
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

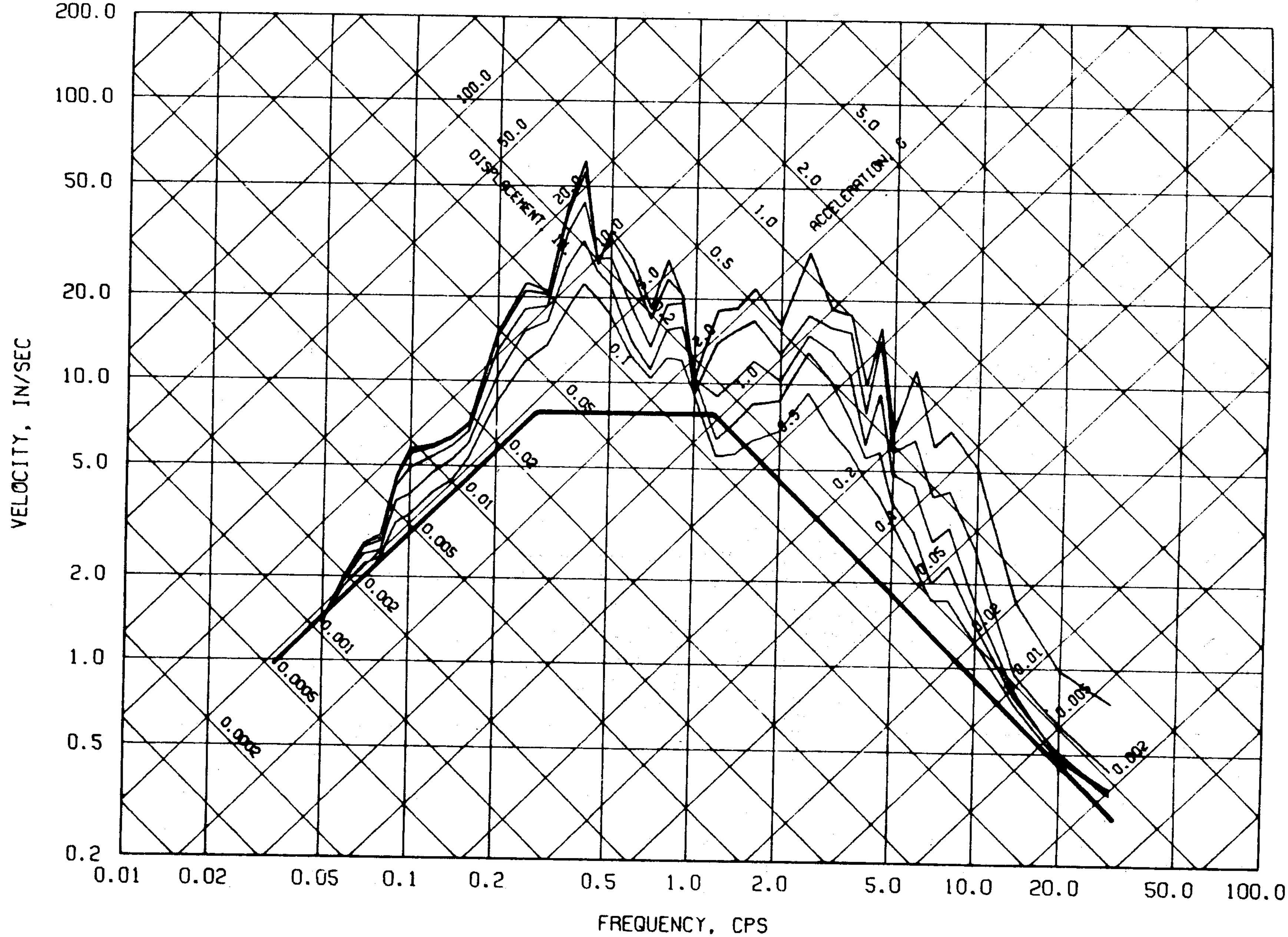


FIG.2.20RESPONSE SPECTRA - SAN FERNANDO, CALIF., 2/9/1971 - VENTURA BLVD N79W
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

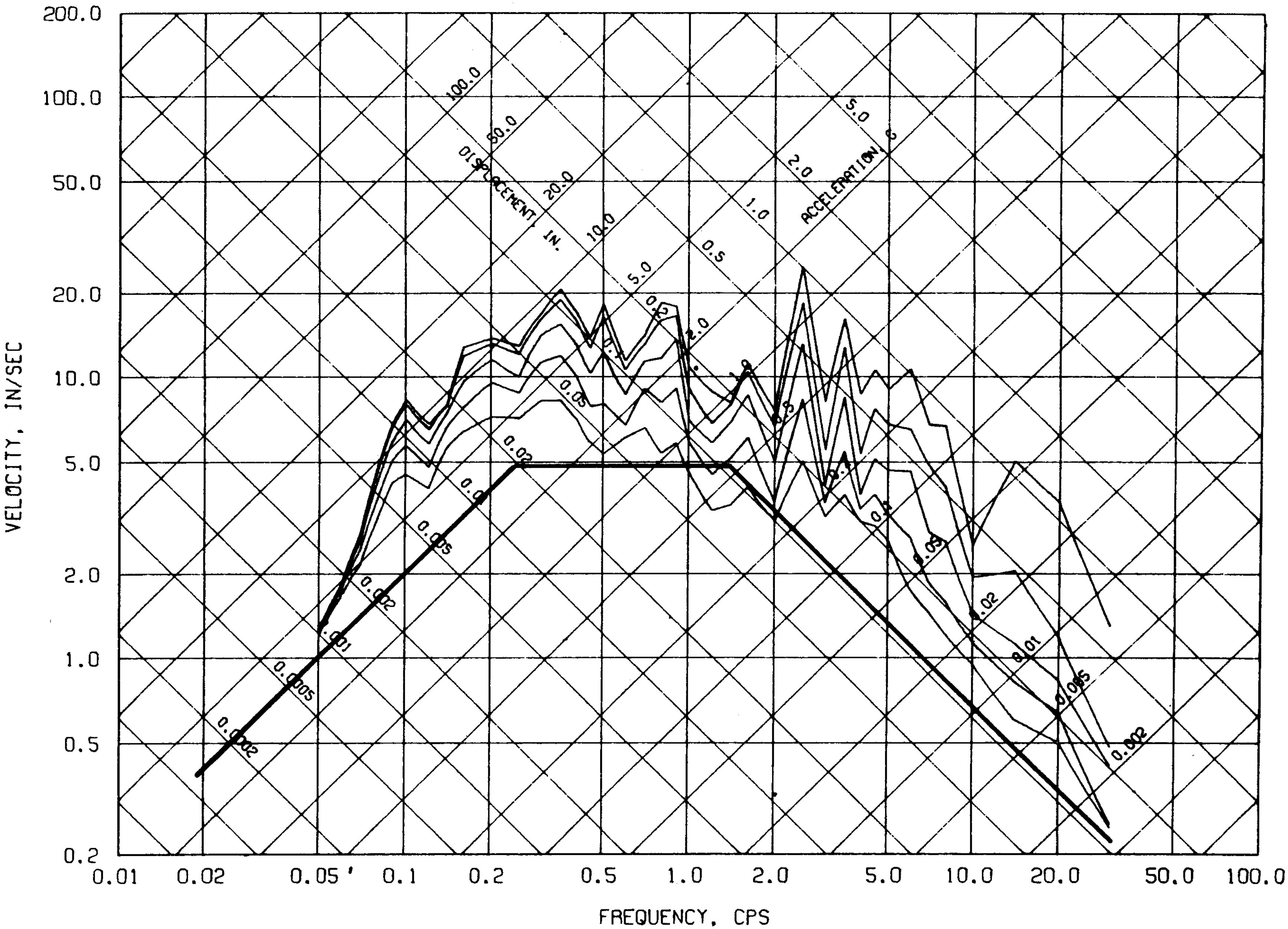


FIG.2.21 RESPONSE SPECTRA - SAN FERNANDO, CALIF., 2/9/1971 - VENTURA BLVD VERTICAL
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

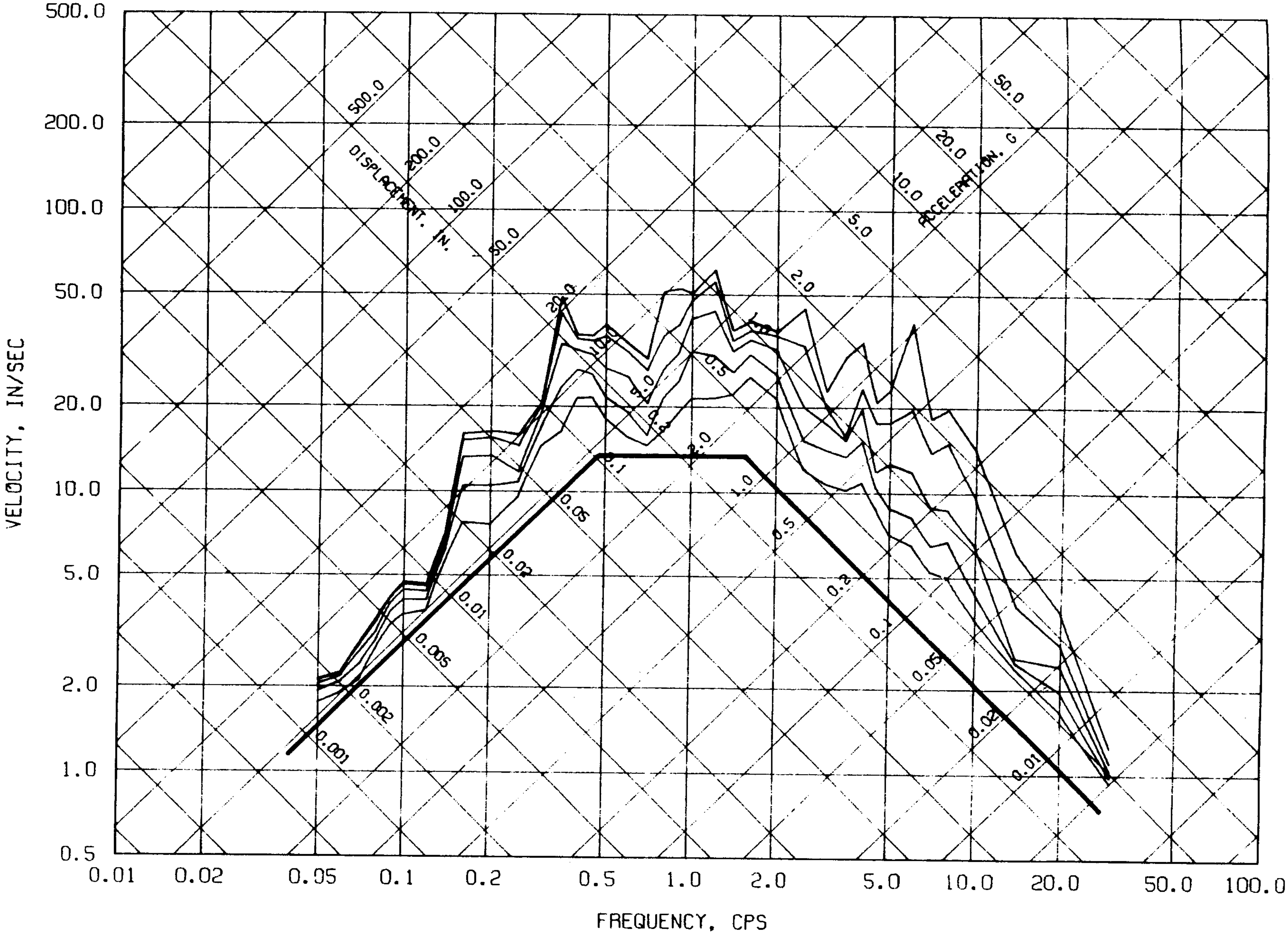


FIG.2.22 RESPONSE SPECTRA - EL CENTRO, CALIF., 5/18/1940 - NS
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

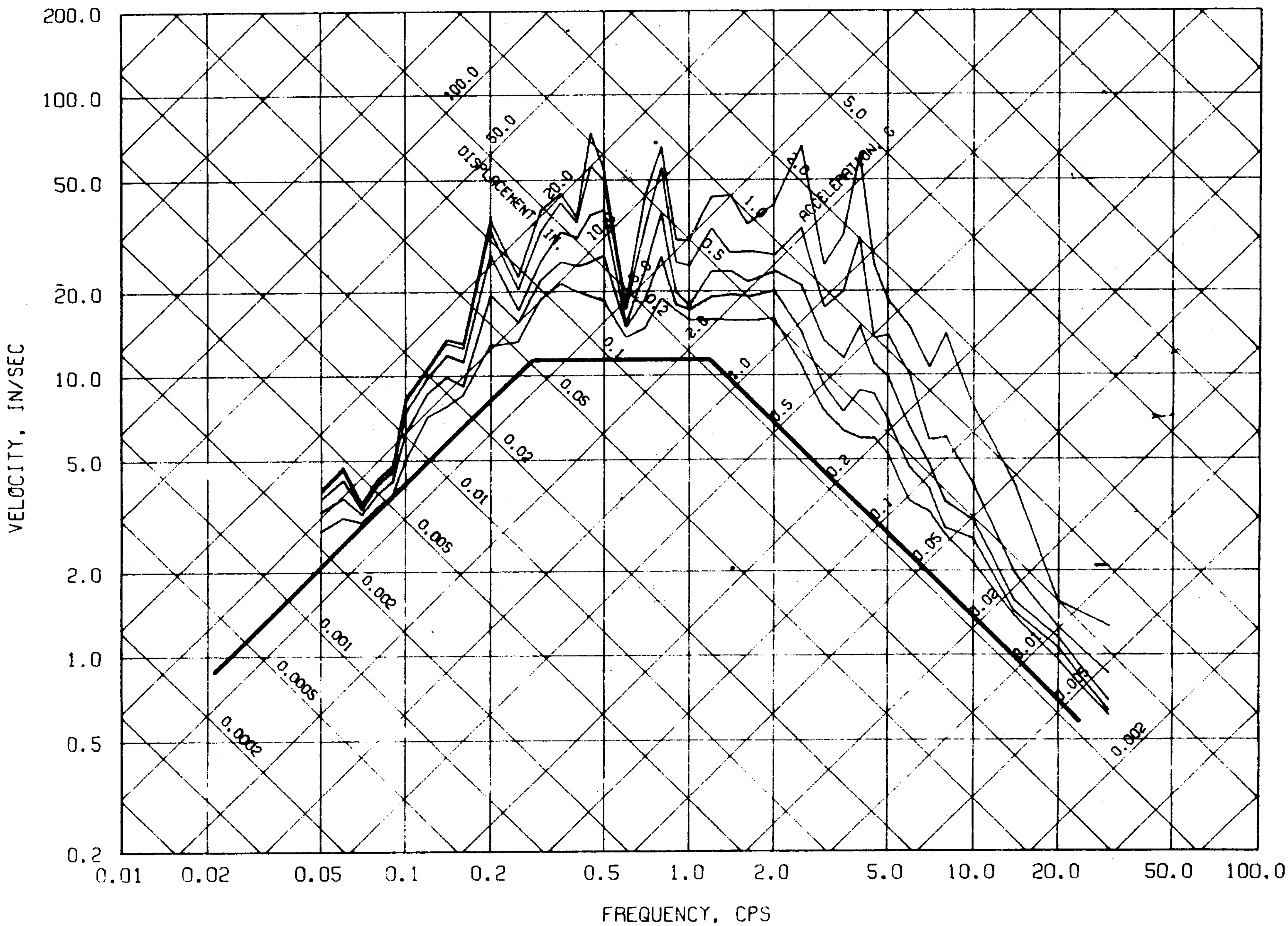


FIG.2.23 RESPONSE SPECTRA - EL CENTRO, CALIF., 5/18/1940 - EW
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

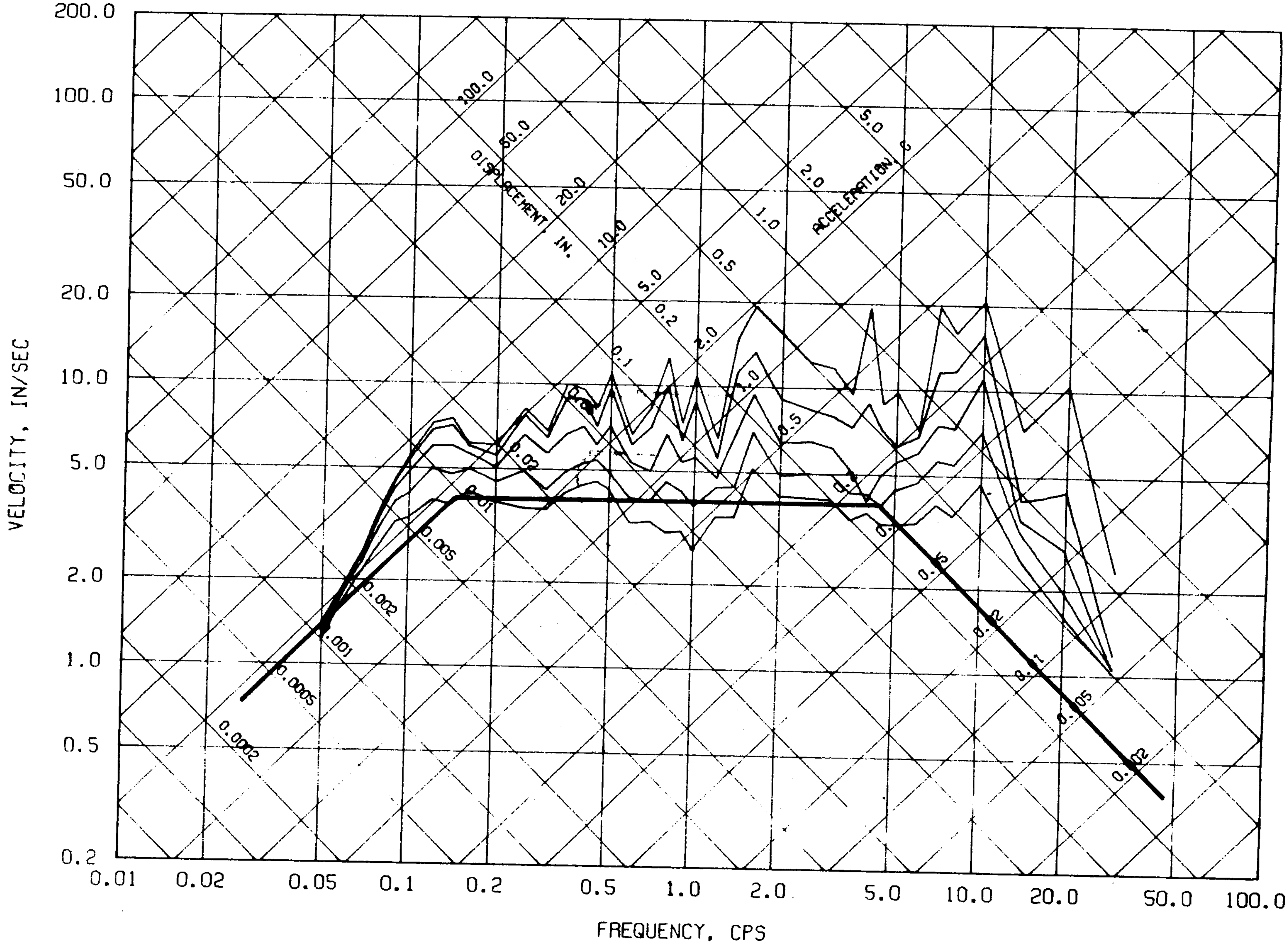


FIG.2.24 RESPONSE SPECTRA - EL CENTRO, CALIF., 5/18/1940 - VERTICAL
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

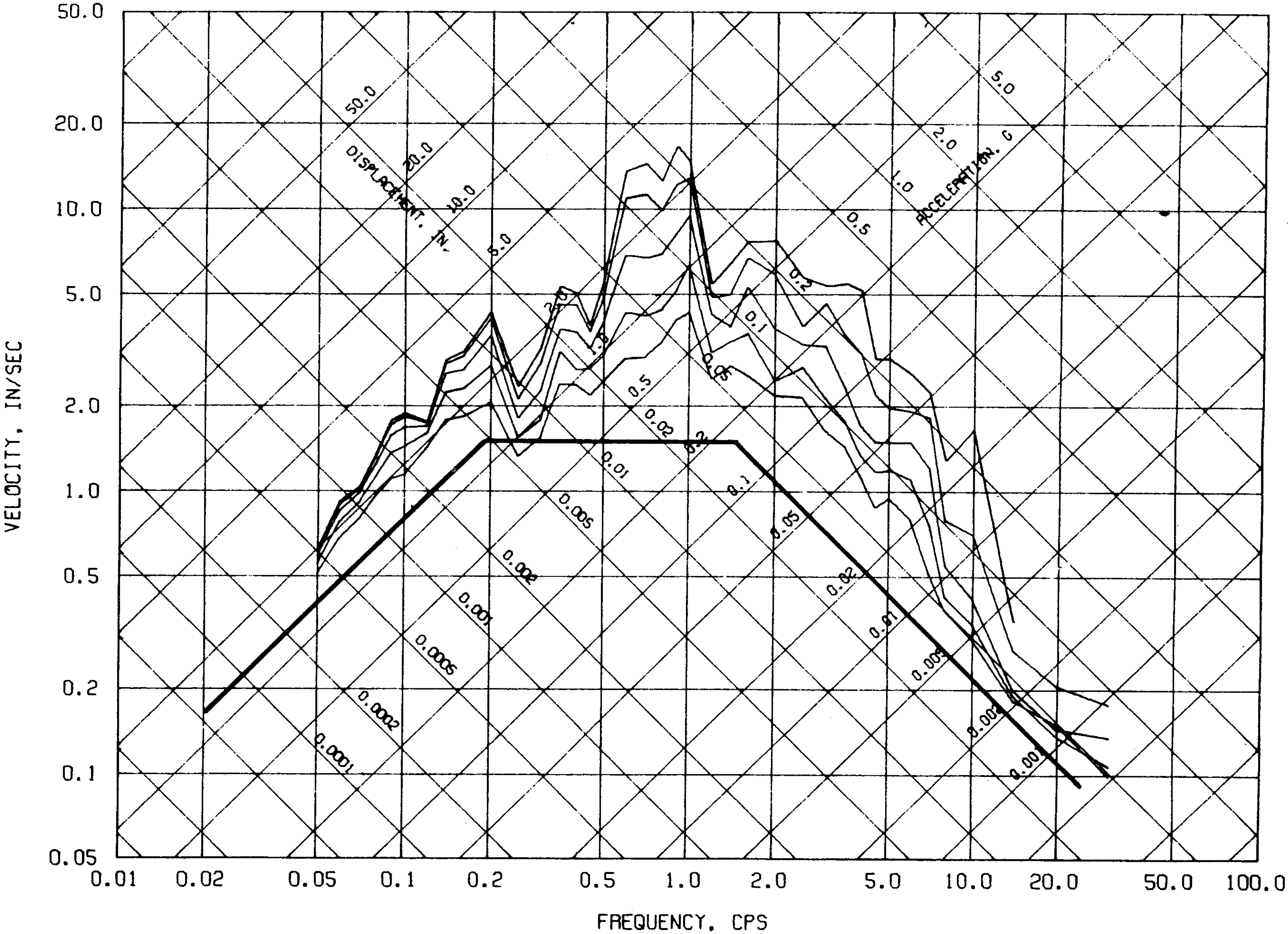


FIG.2.25 RESPONSE SPECTRA - EL CENTRO, CALIF., 2/9/1956 - NS
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

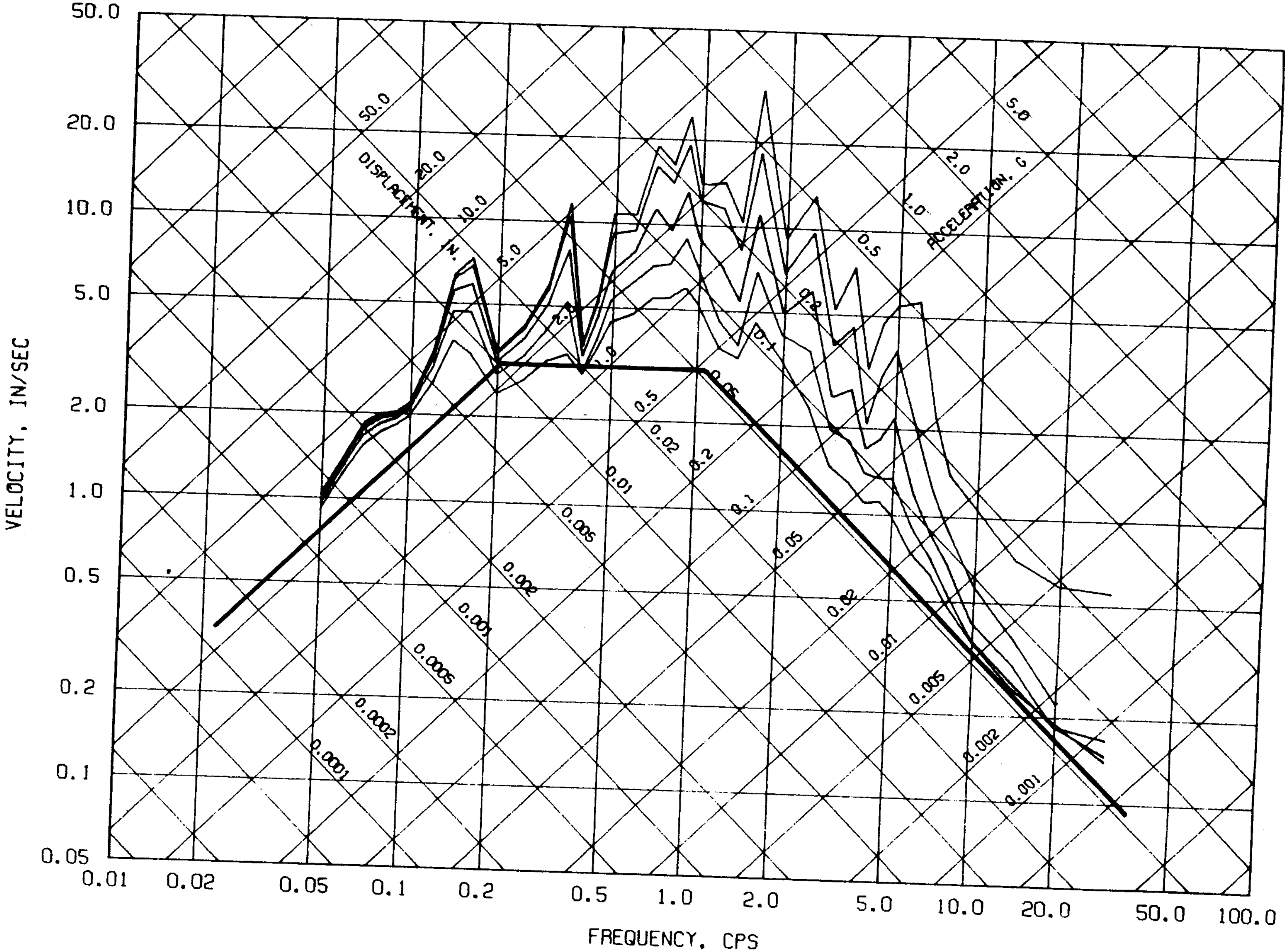


FIG.2.26RESPONSE SPECTRA - EL CENTRO, CALIF., 2/9/1956 - EW
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

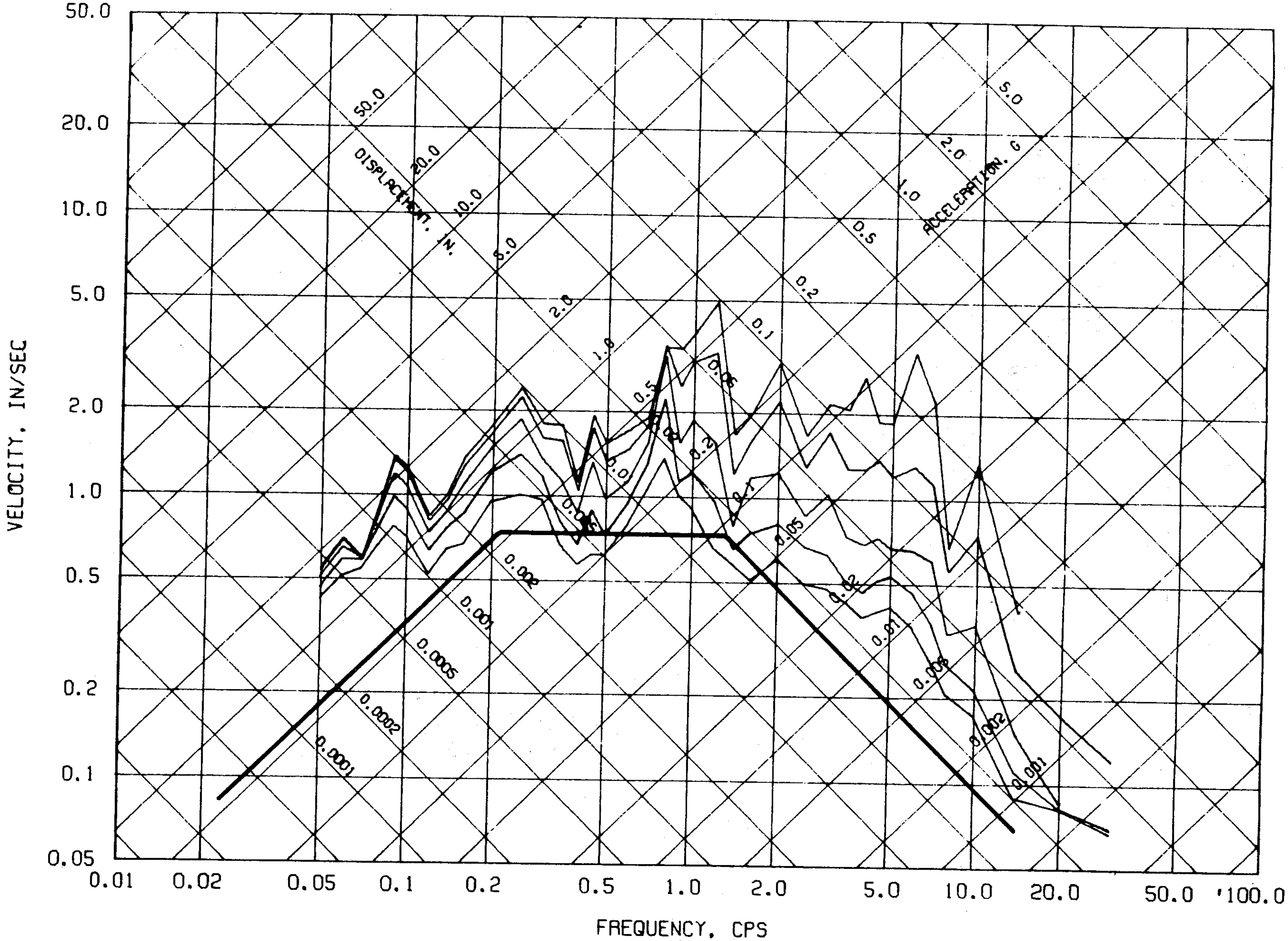


FIG.2.27 RESPONSE SPECTRA - EL CENTRO, CALIF., 2/9/1956 - VERTICAL
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

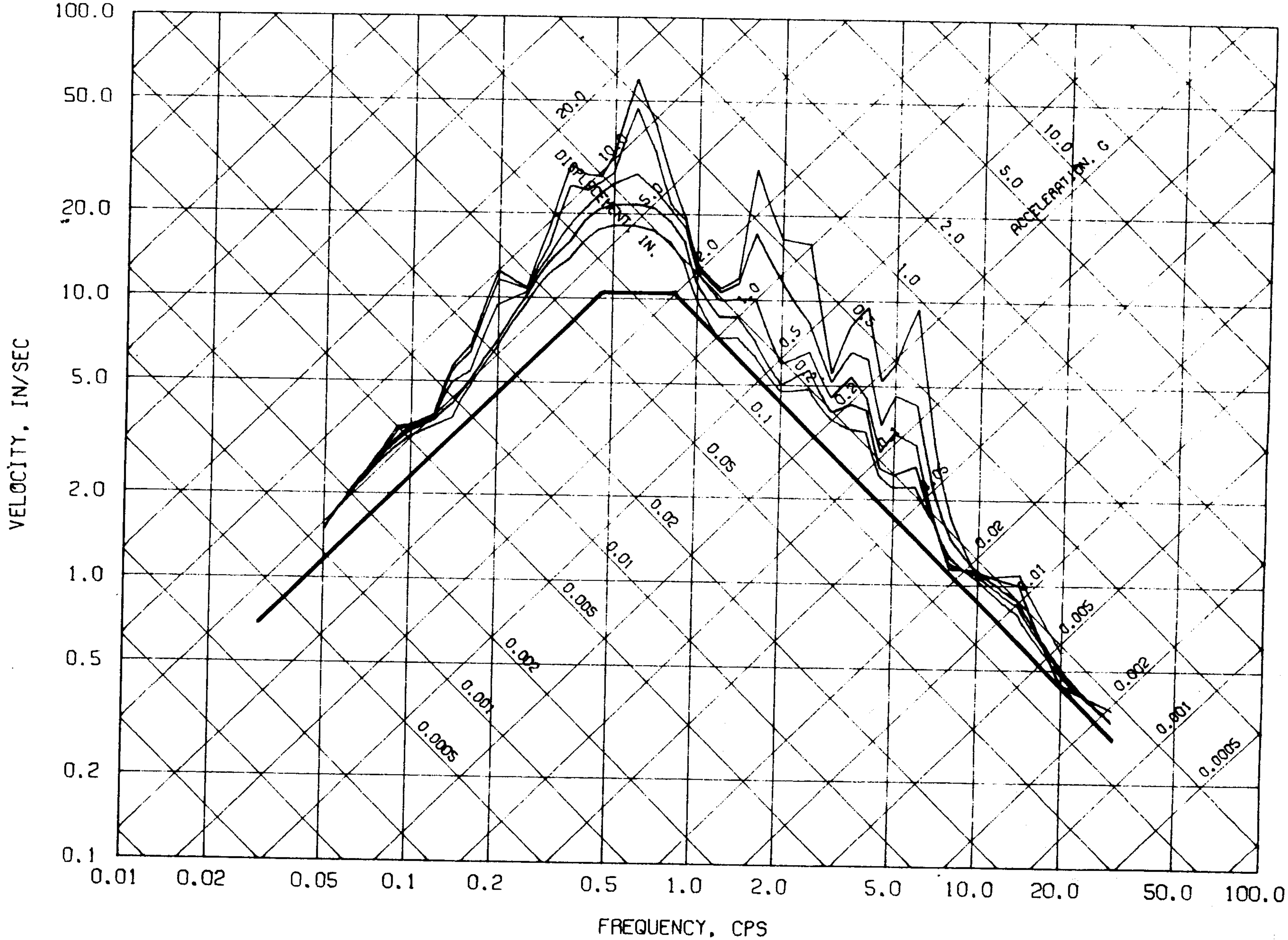


FIG.2.28 RESPONSE SPECTRA - EL CENTRO, CALIF., 4/8/1968 - NS
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

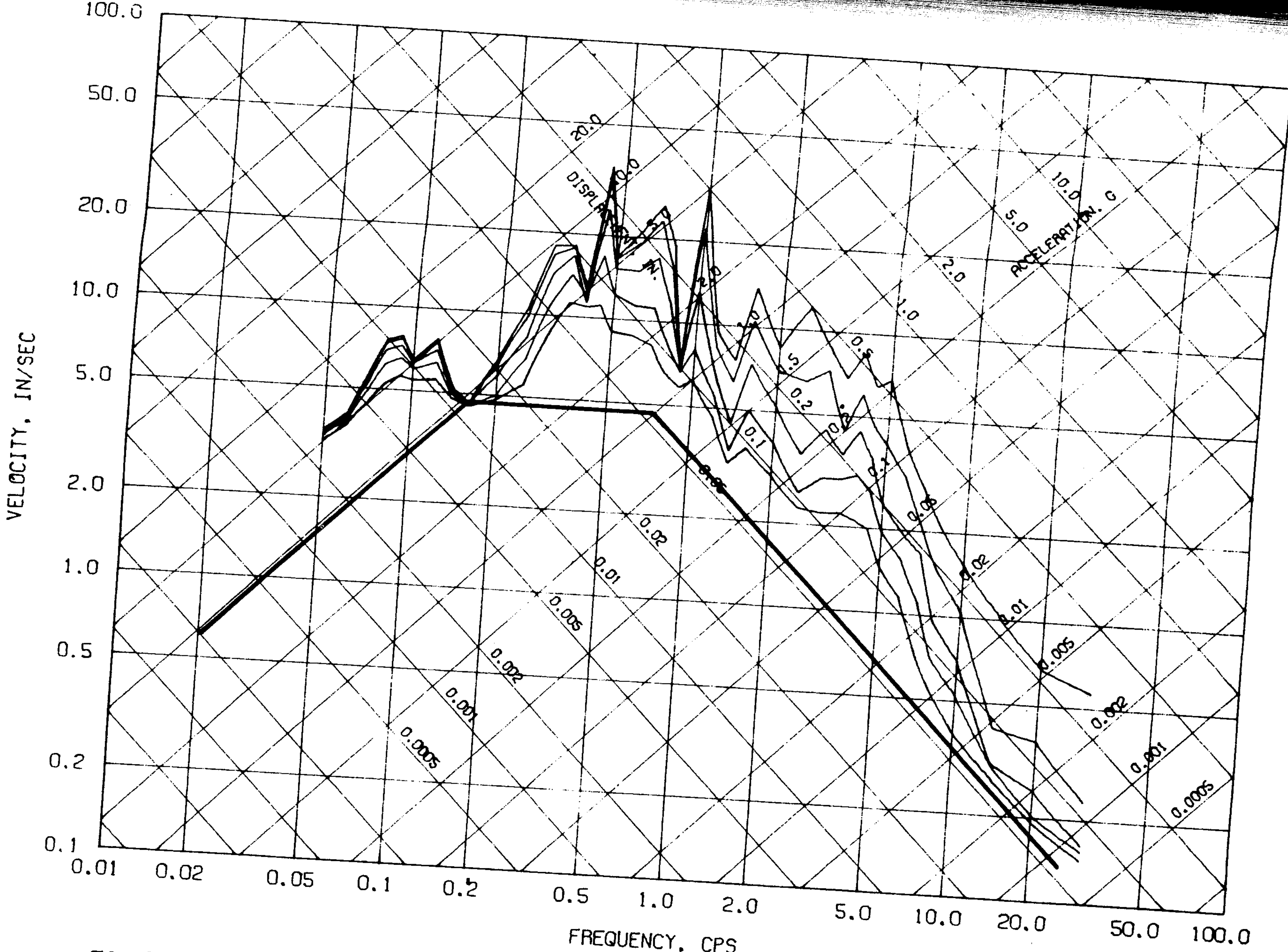


FIG.229 RESPONSE SPECTRA - EL CENTRO, CALIF., 4/8/1968 - EW
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

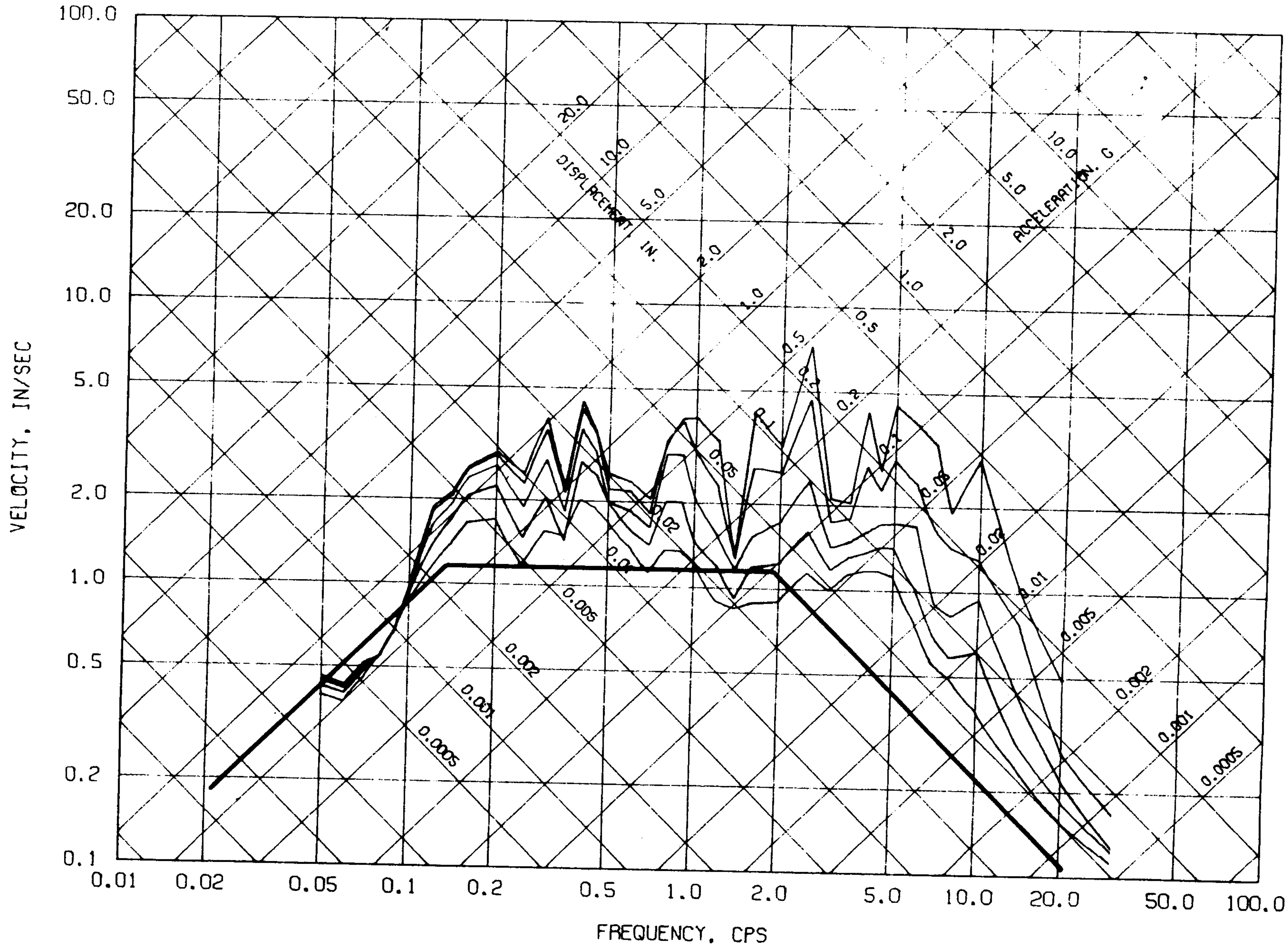


FIG.2.30 RESPONSE SPECTRA - EL CENTRO, CALIF., 4/8/1968 - VERTICAL
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

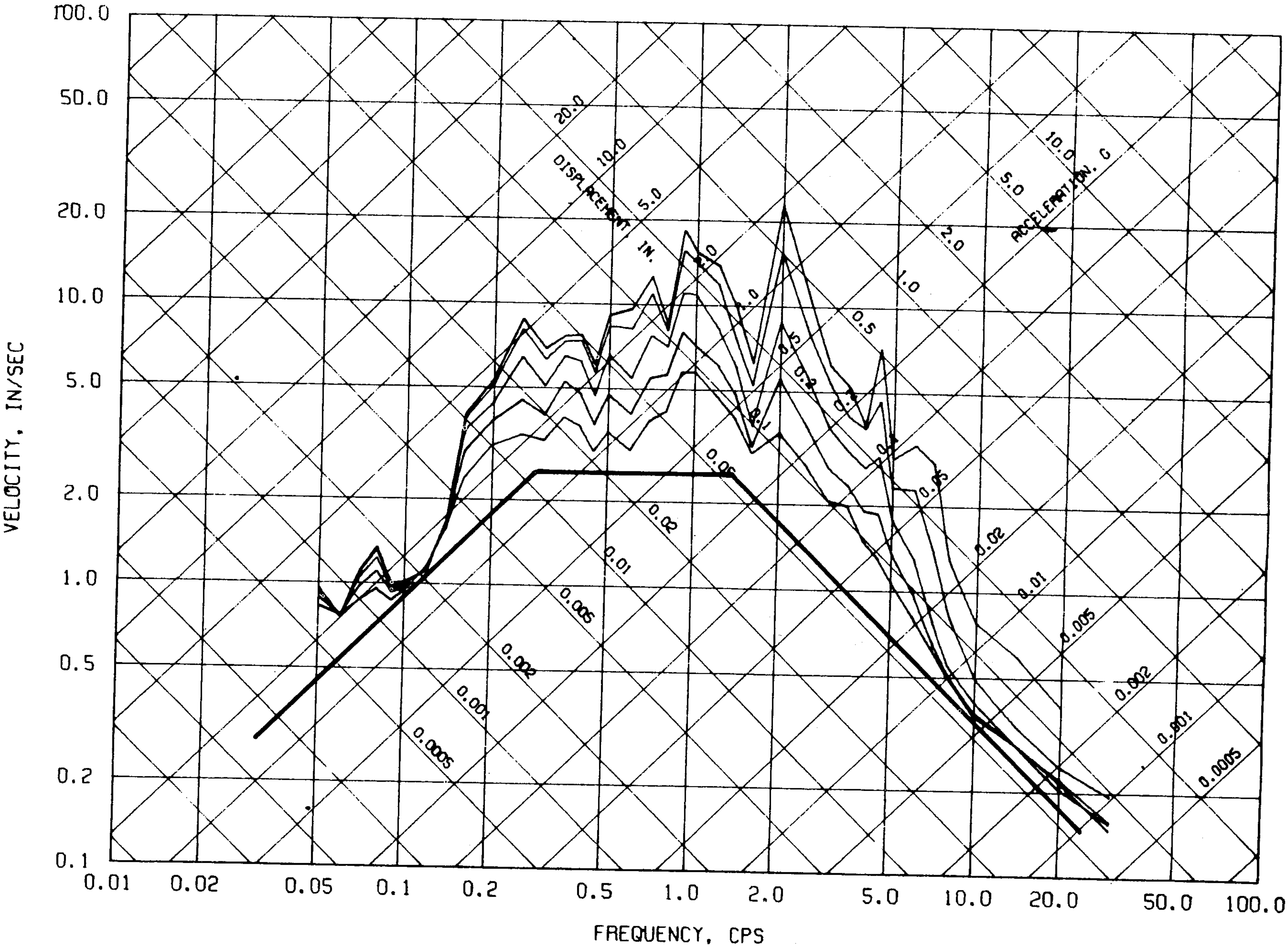


FIG.2.31 RESPONSE SPECTRA - HOLLYWOOD, CALIF., 7/21/1952 - HLWD STG BSMT NS
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

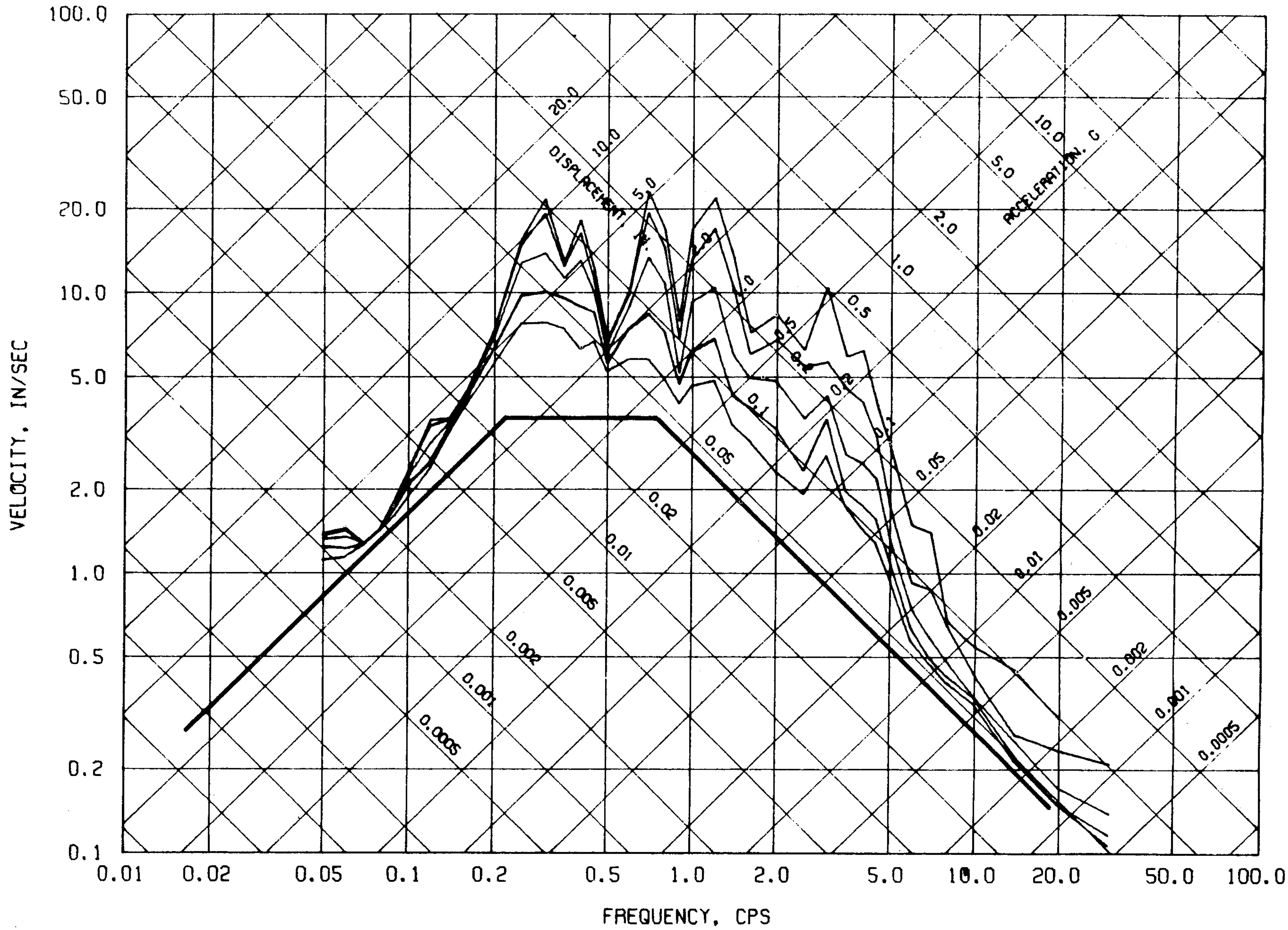


FIG.2.32RESPONSE SPECTRA - HOLLYWOOD, CALIF., 7/21/1952 - HLWD STG BSMT EW
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

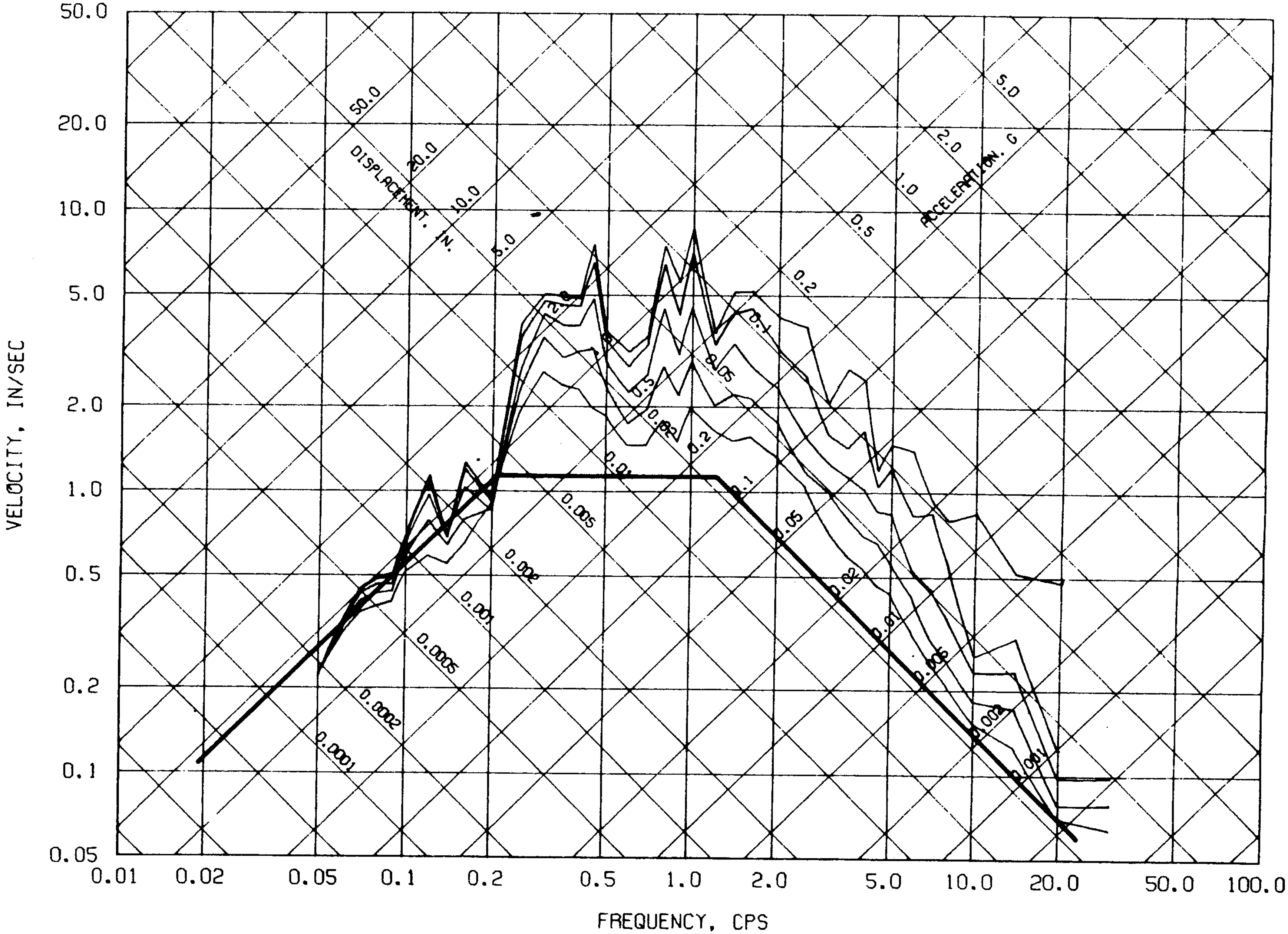


FIG.2.33 RESPONSE SPECTRA - HOLLYWOOD, CALIF., 7/21/1952 - HLWD STG BSMT VERTICAL
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

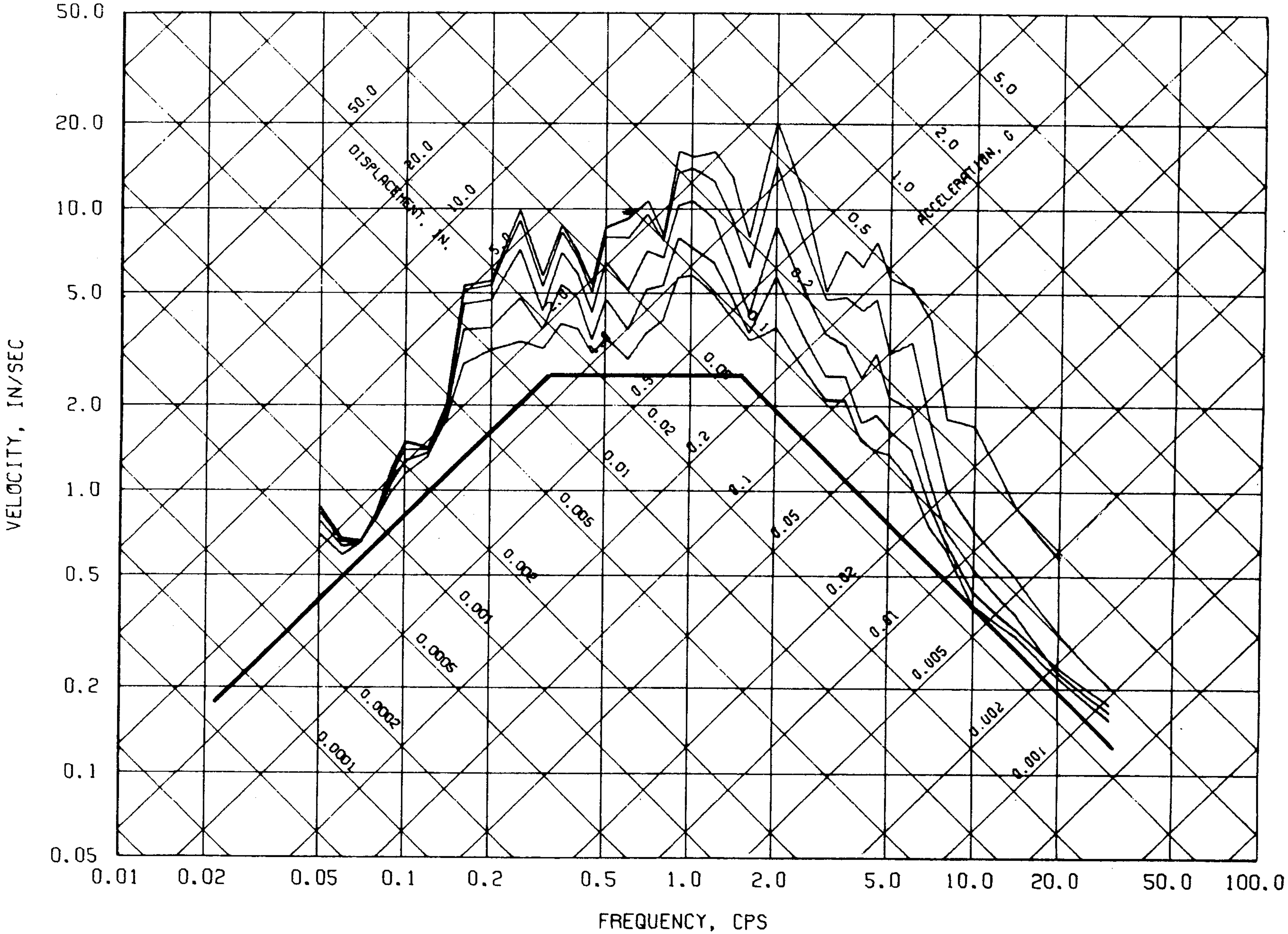


FIG.2.34 RESPONSE SPECTRA - HOLLYWOOD, CALIF., 7/21/1952 - HLWD STG PE LOT NS
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

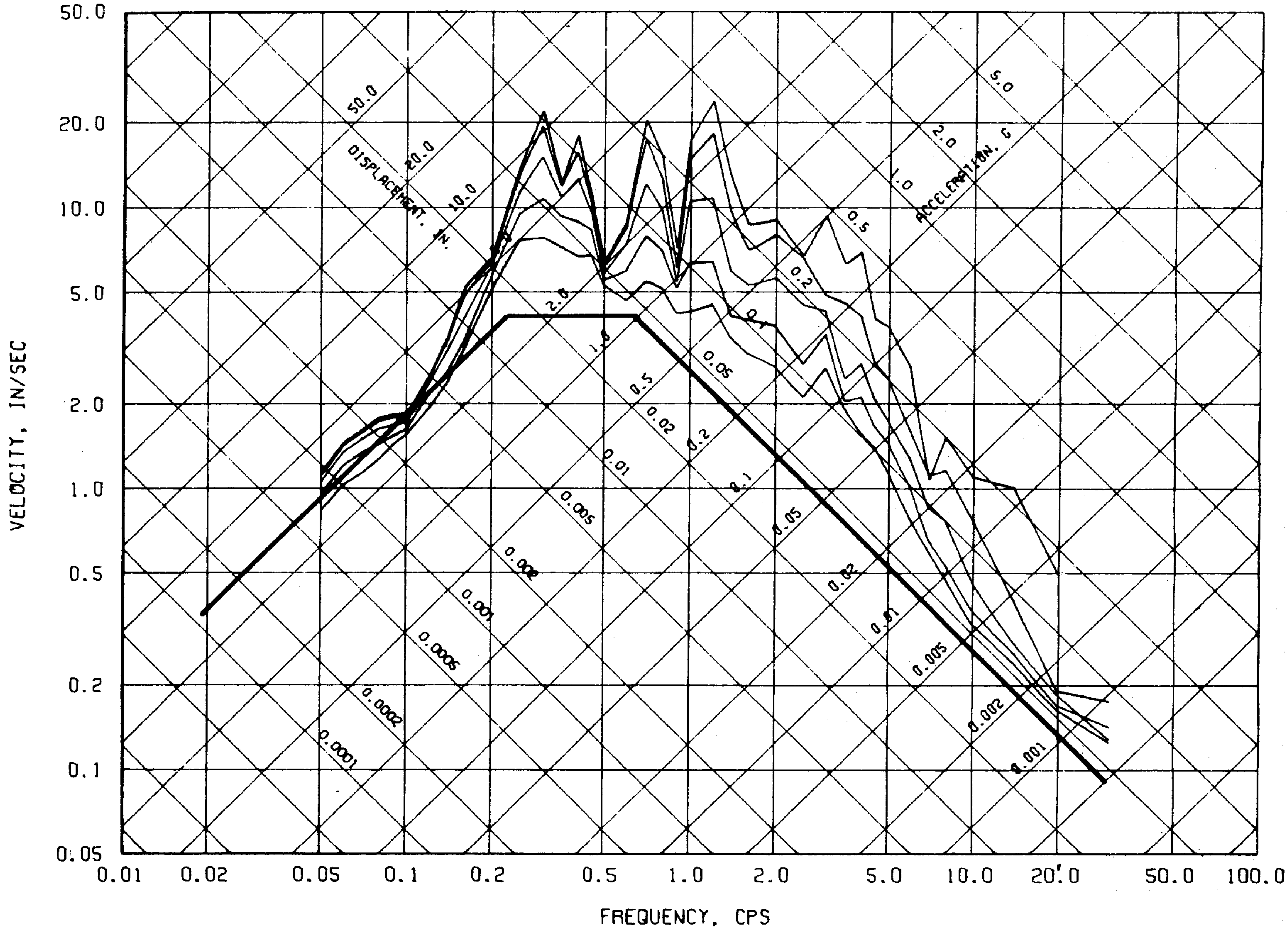


FIG.2.35 RESPONSE SPECTRA - HOLLYWOOD, CALIF., 7/21/1952 - HLWD STG PE LOT EW
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

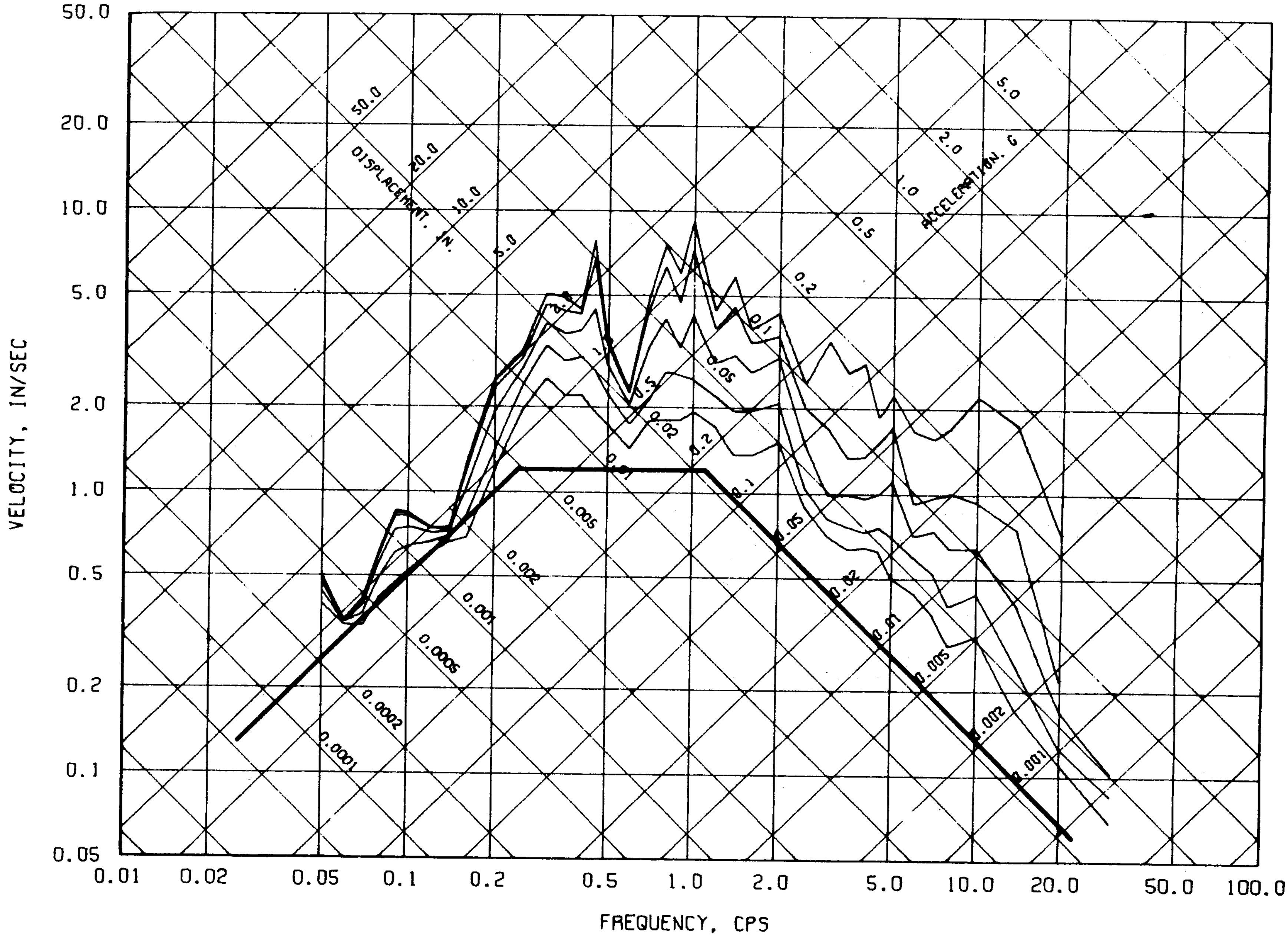


FIG.2.36RESPONSE SPECTRA - HOLLYWOOD, CALIF., 7/21/1952 - HLWD STG PE LOT VERT.
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

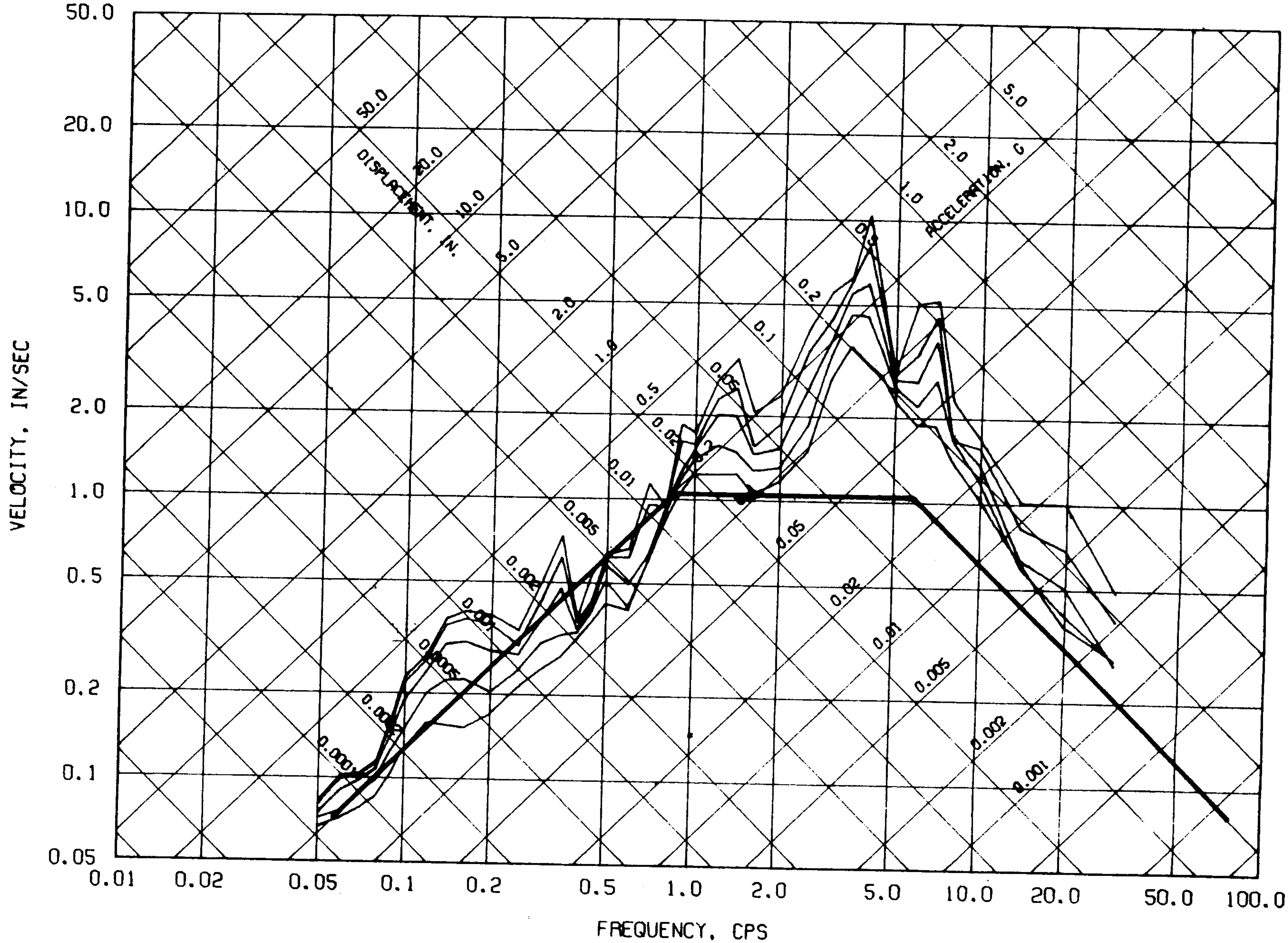


FIG.2.37 RESPONSE SPECTRA - SAN FRANCISCO, CALIF., 3/22/1957 - GLDN GATE PK N10E
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

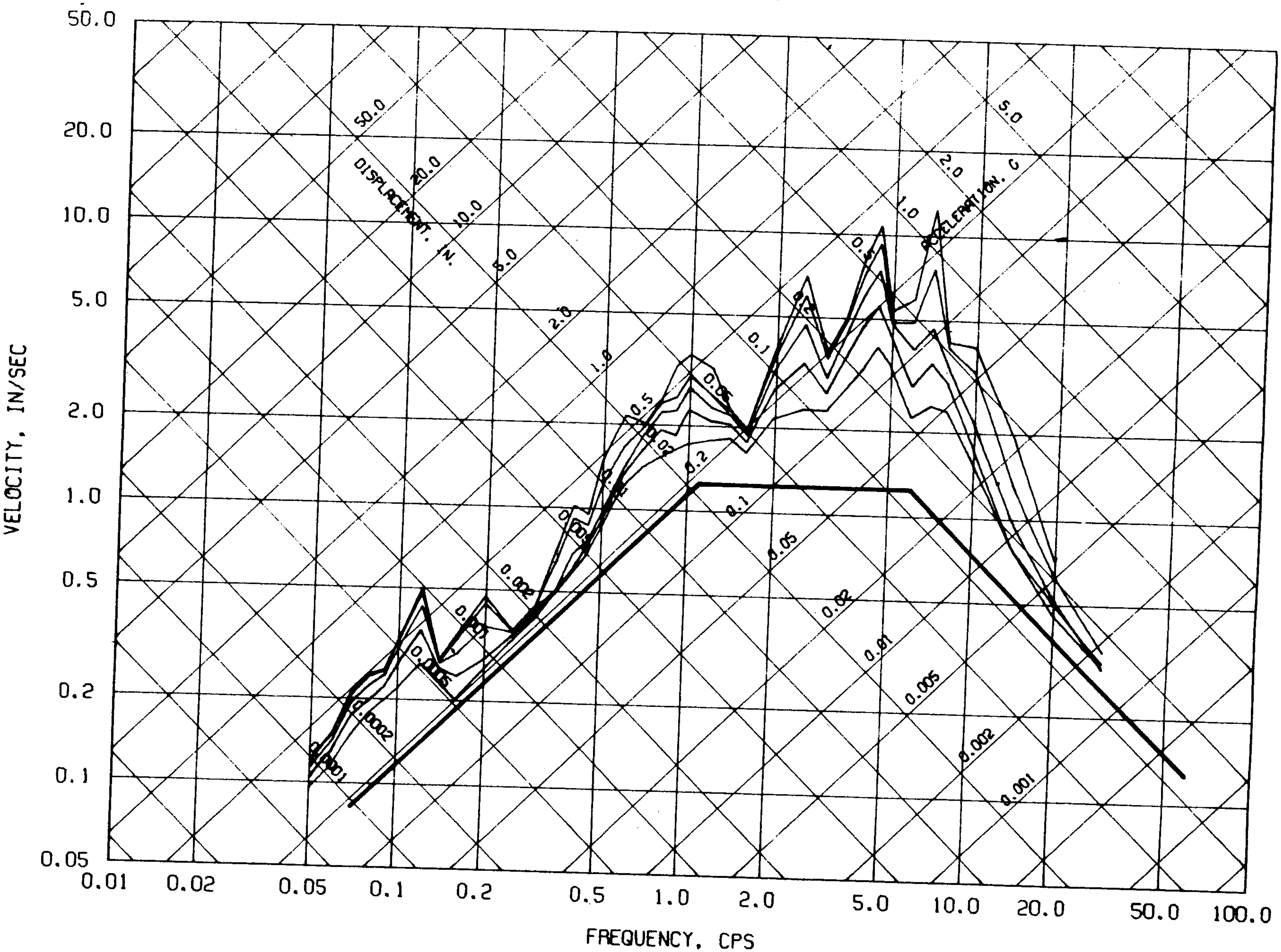


FIG.2.38RESPONSE SPECTRA - SAN FRANCISCO, CALIF., 3/22/1957 - GLDN GATE PK S80E
0. .5. 2. 5. & 10 PERCENT CRITICAL DAMPING

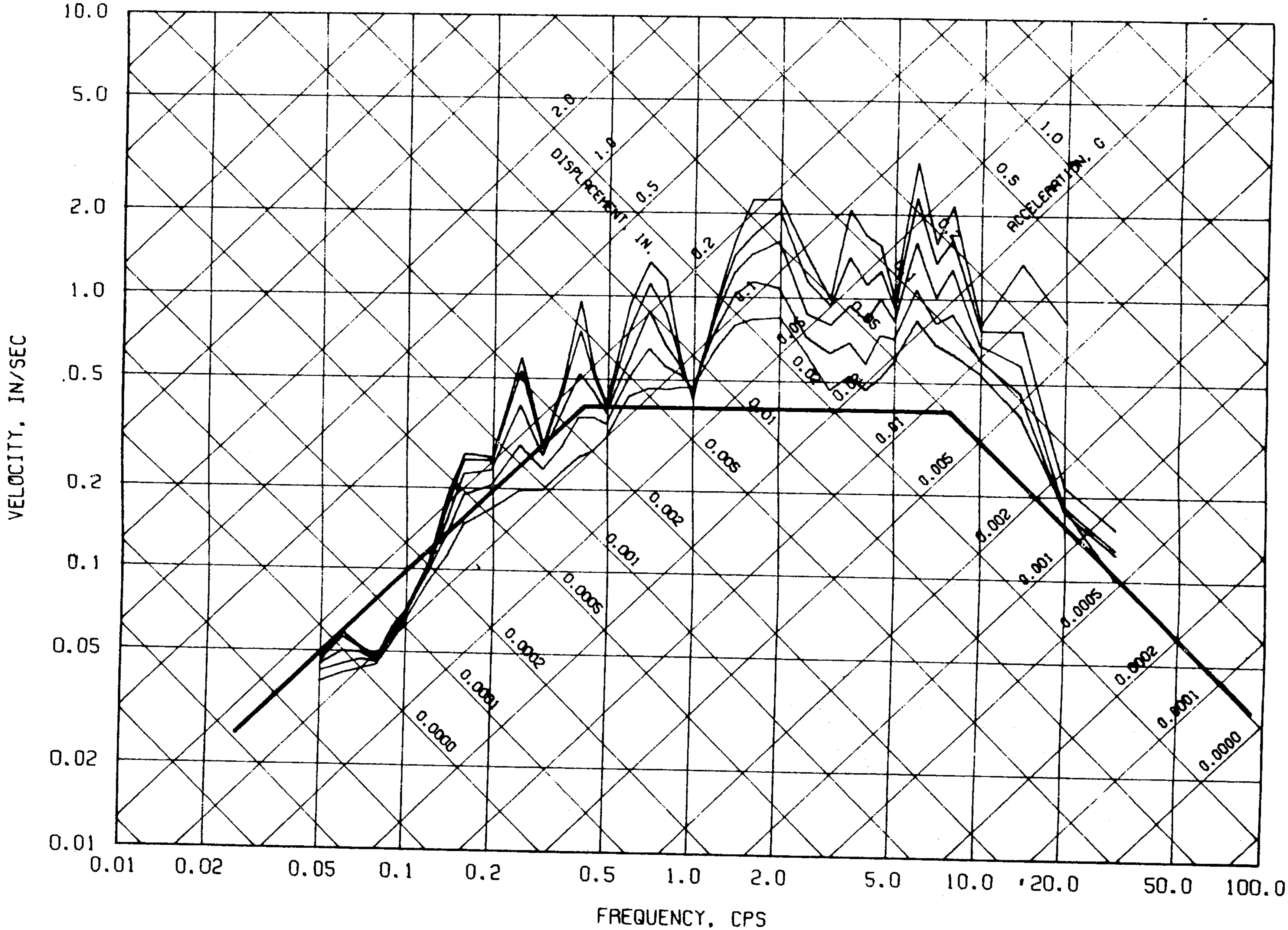


FIG.2.39RESPONSE SPECTRA - SAN FRANCISCO, CALIF., 3/22/1957 - GLDN GATE PK VERT.
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

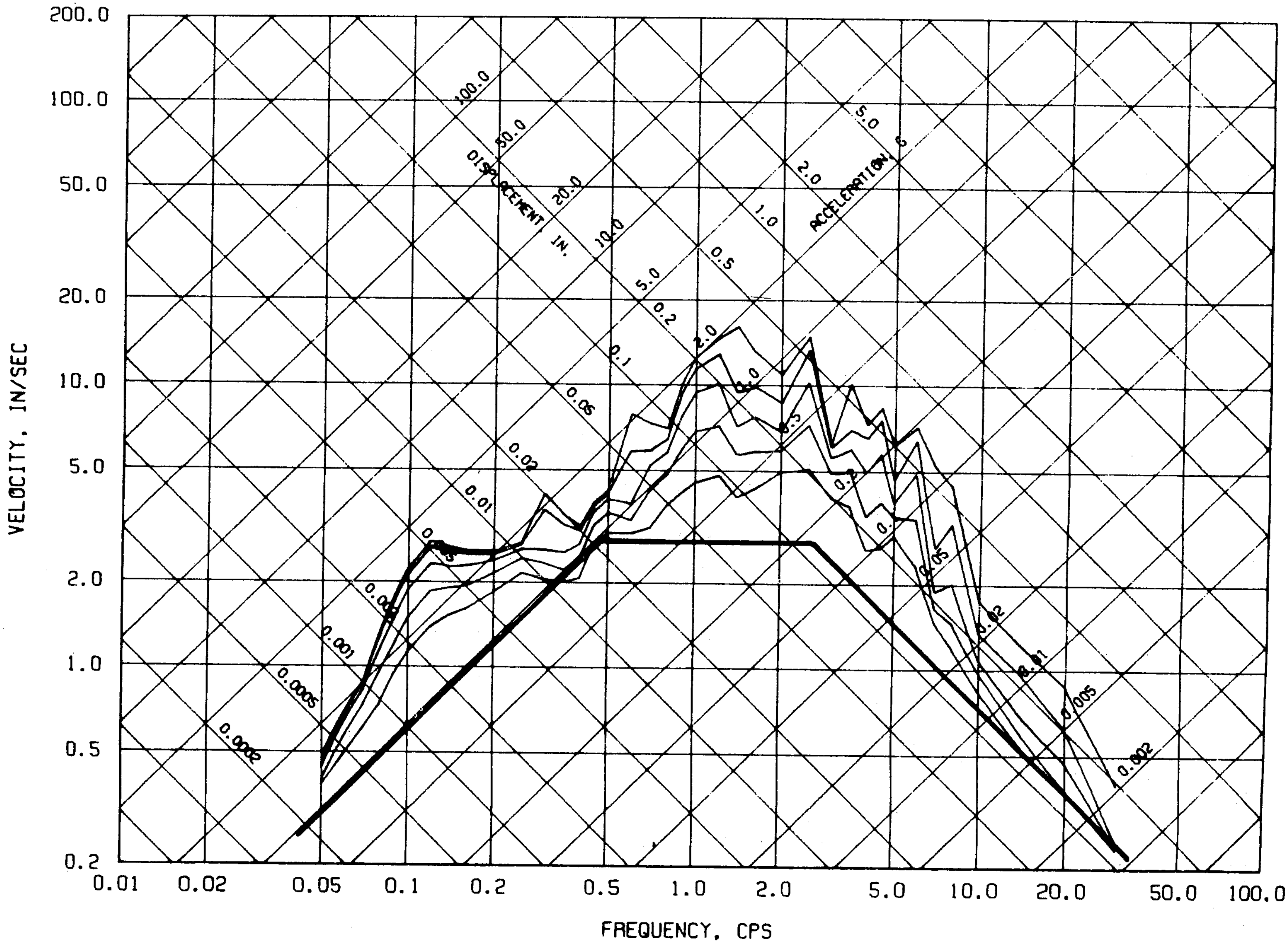


FIG.2.40 RESPONSE SPECTRA - FERNDALE, CALIF., 10/7/1951 - N46W
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

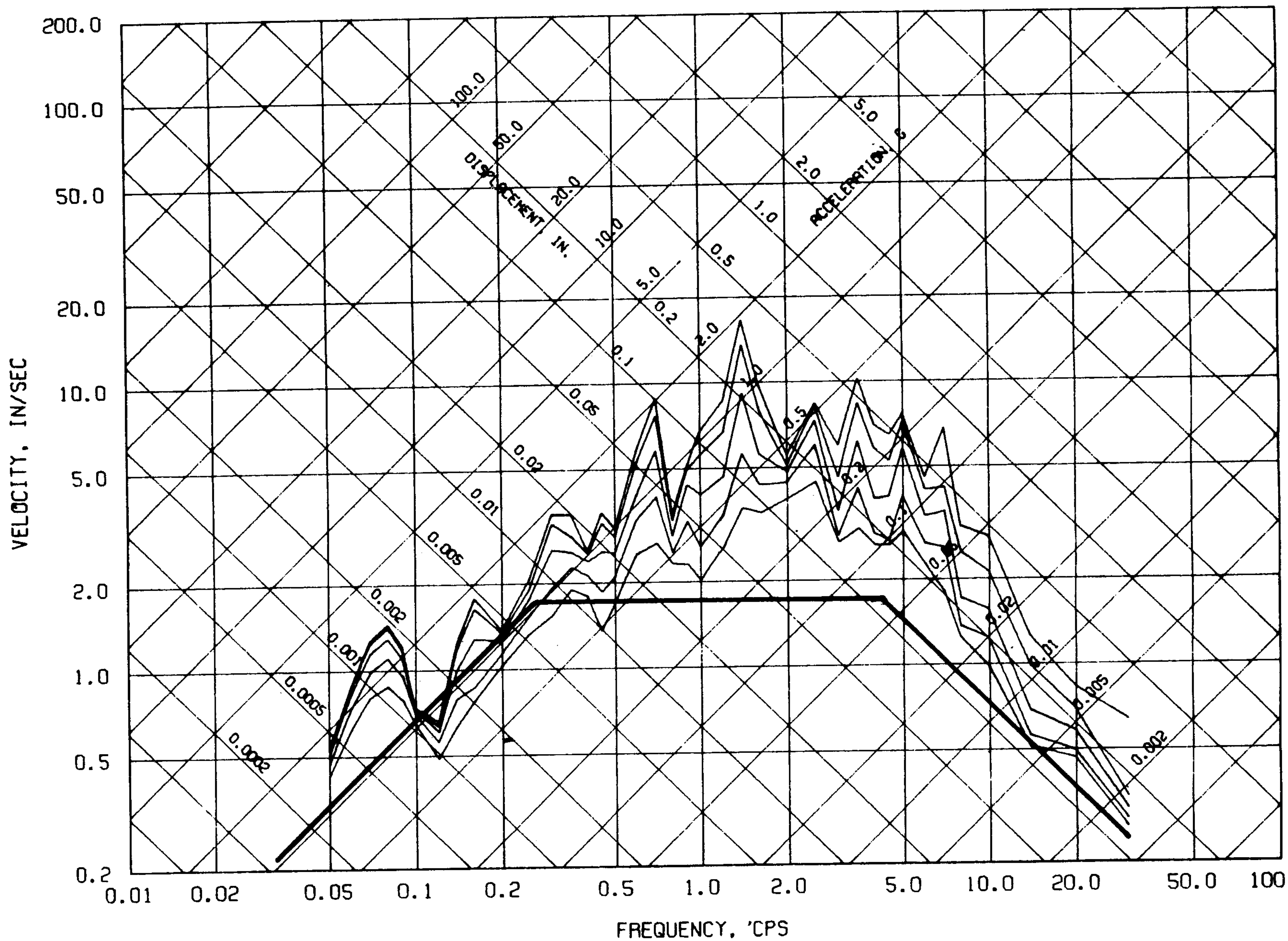


FIG.2.41 RESPONSE SPECTRA - FERNDALE, CALIF., 10/7/1951 - S44W
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

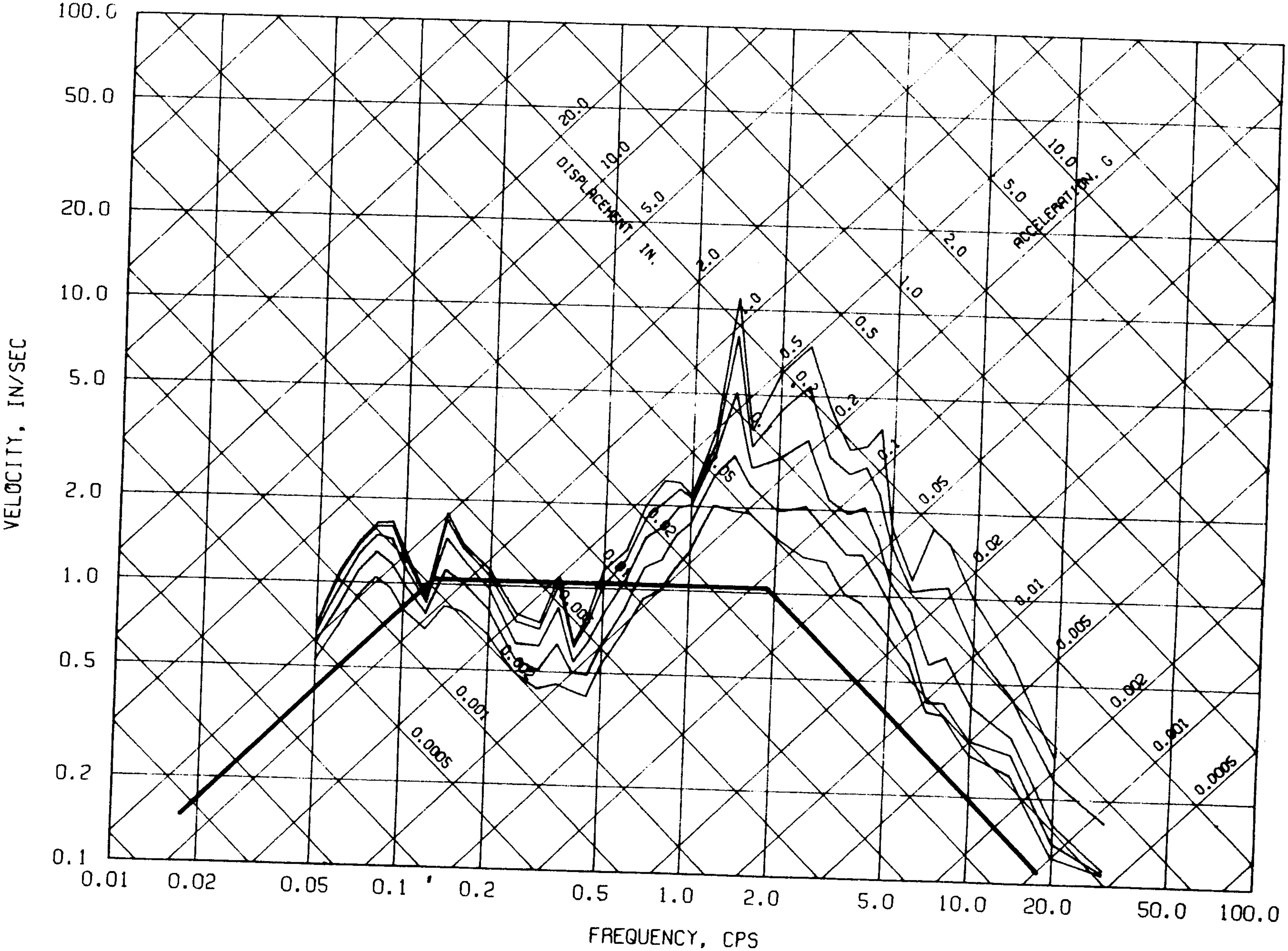


FIG.2.42RESPONSE SPECTRA - FERNDALE, CALIF., 10/7/1951 - VERTICAL
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

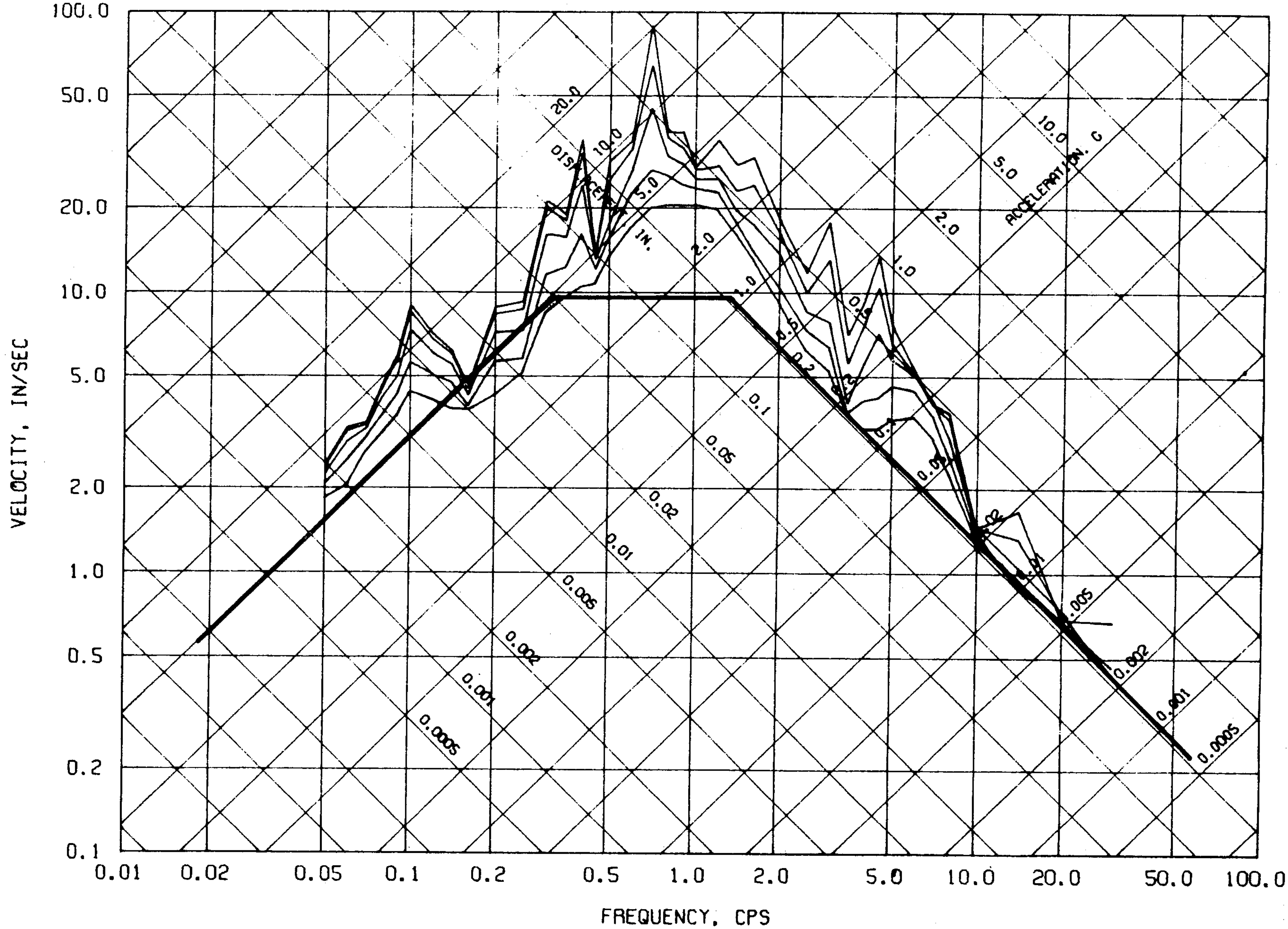


FIG.2.43RESPONSE SPECTRA - FERNDALE, CALIF., 12/21/1954 - N46W
0. .5. 2. 5. & 10 PERCENT CRITICAL DAMPING

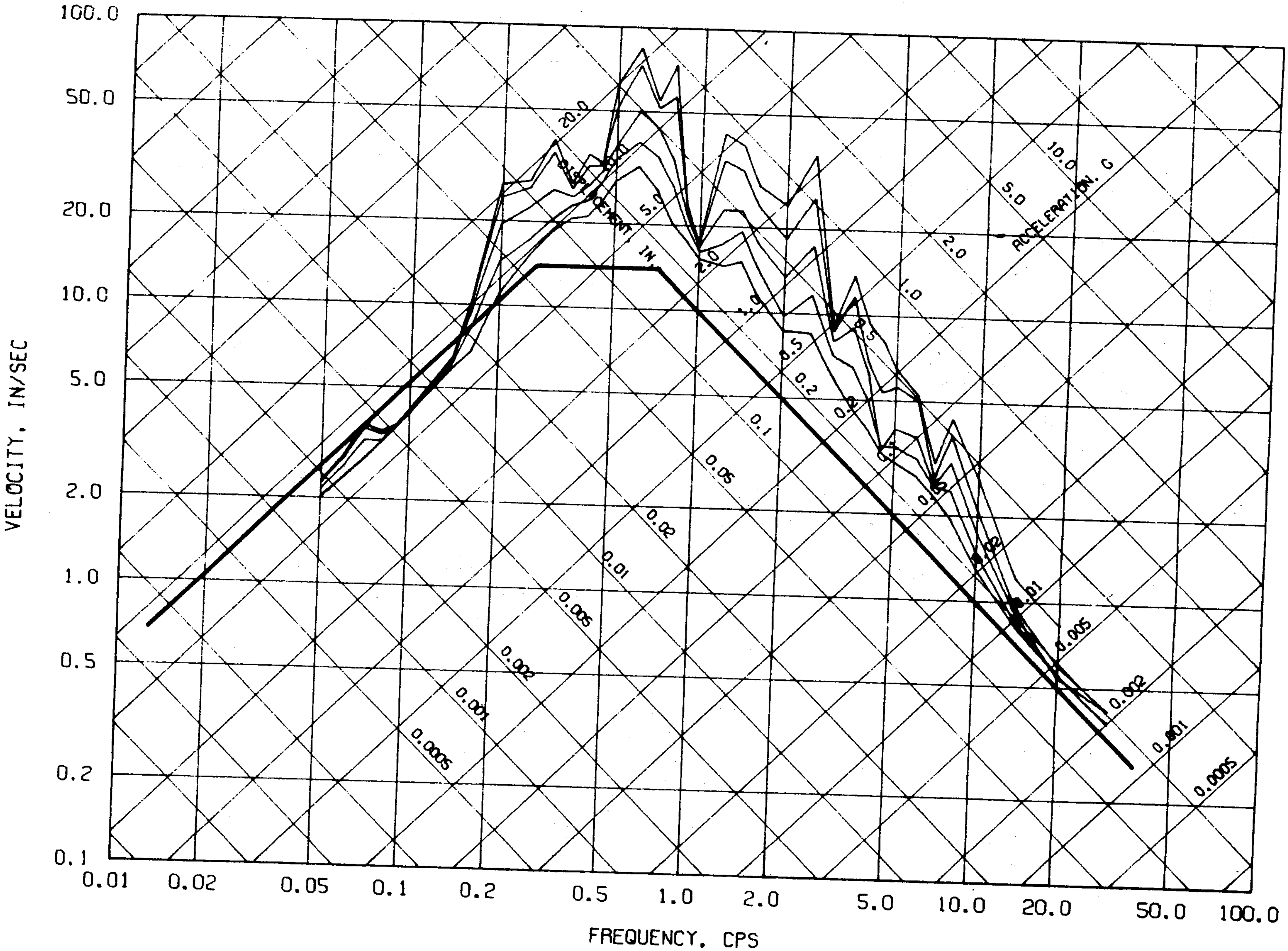


FIG.2.44 RESPONSE SPECTRA - FERNDALE, CALIF., 12/21/1954 - N44E
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

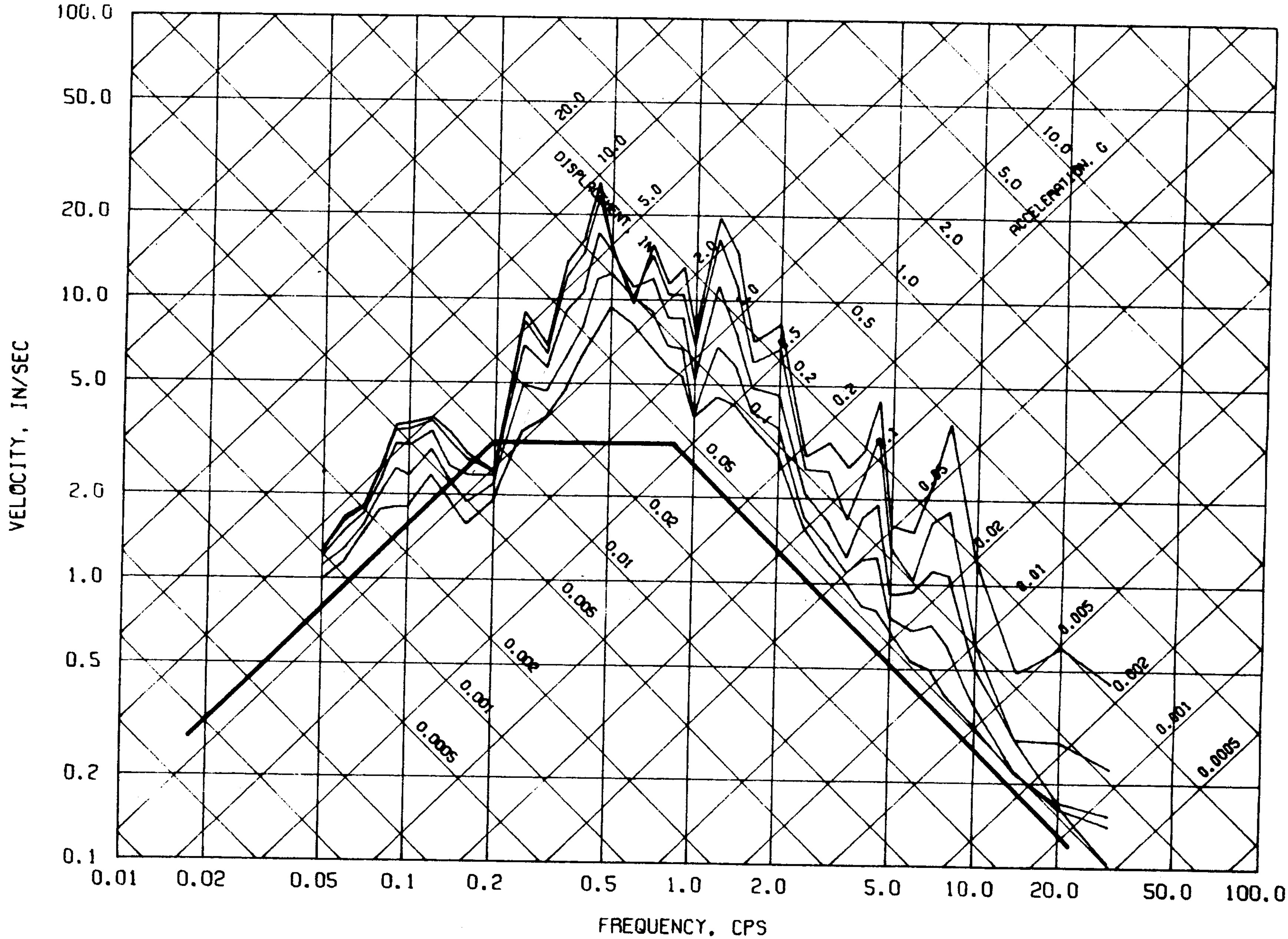


FIG.2.45 RESPONSE SPECTRA - FERNDALE, CALIF., 12/21/1954 - VERTICAL
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

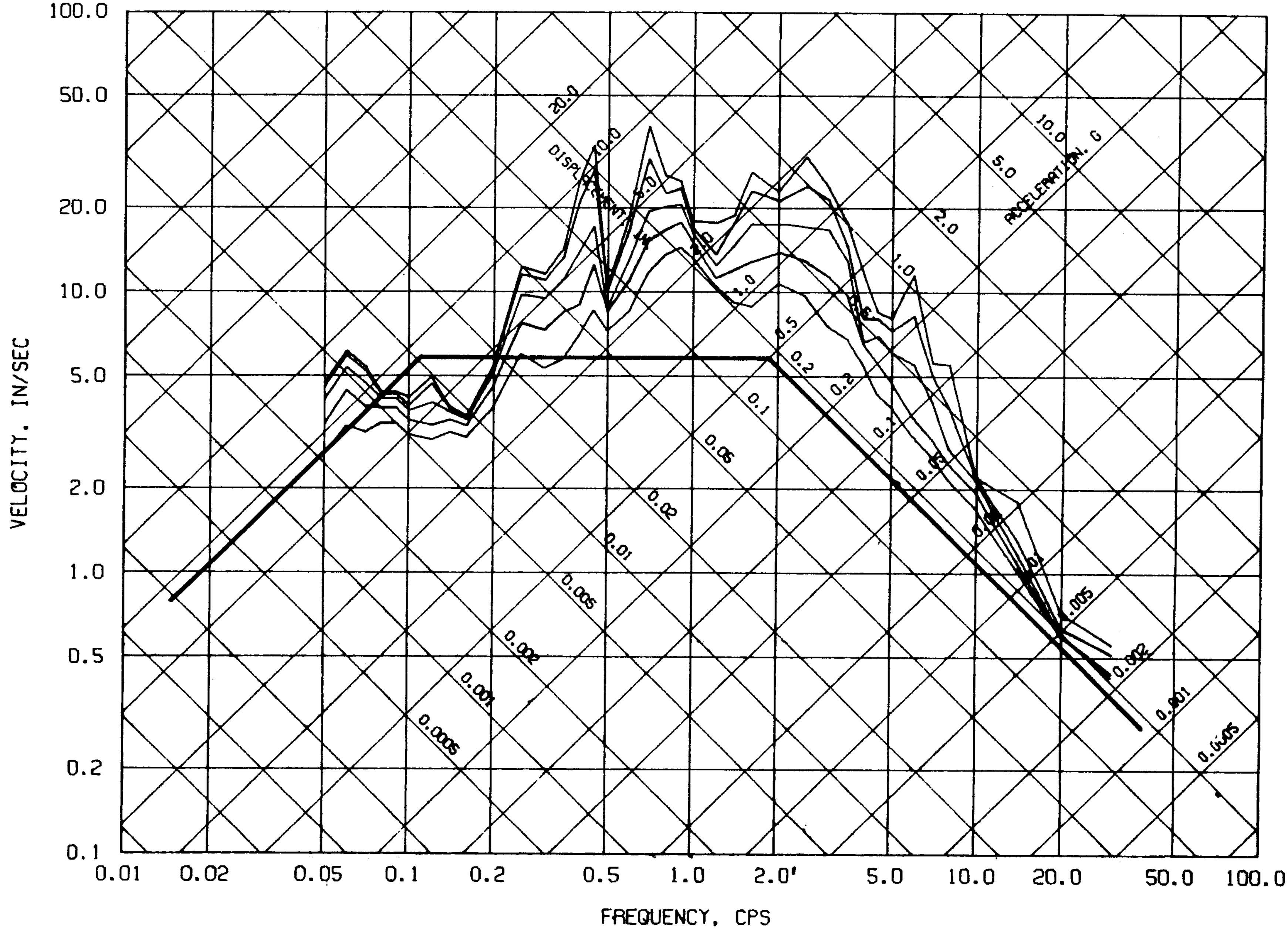


FIG.2.46 RESPONSE SPECTRA - EUREKA, CALIF., 12/21/1954 - N11W
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

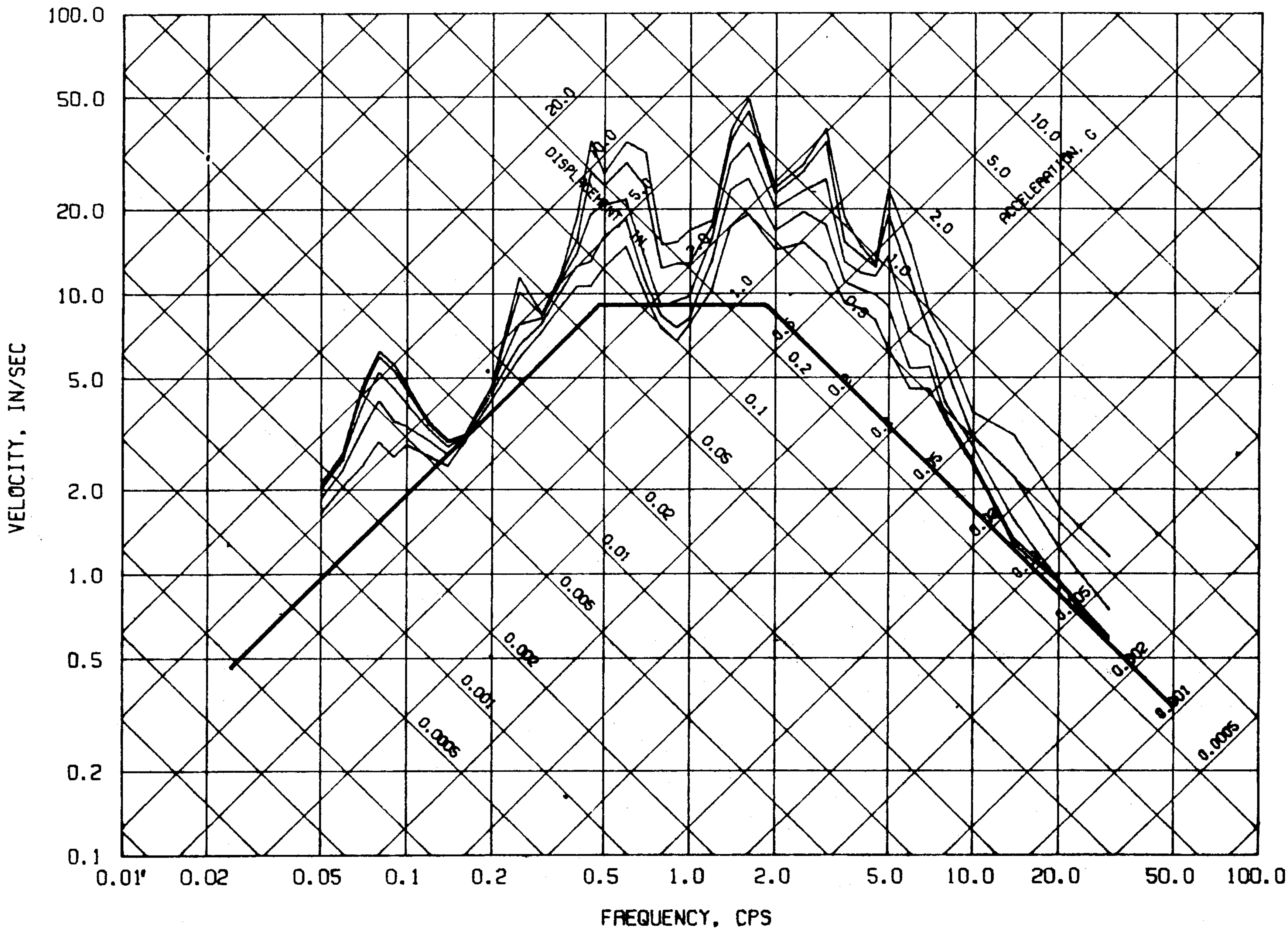


FIG.2.47 RESPONSE SPECTRA - EUREKA, CALIF., 12/21/1954 - N79E
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

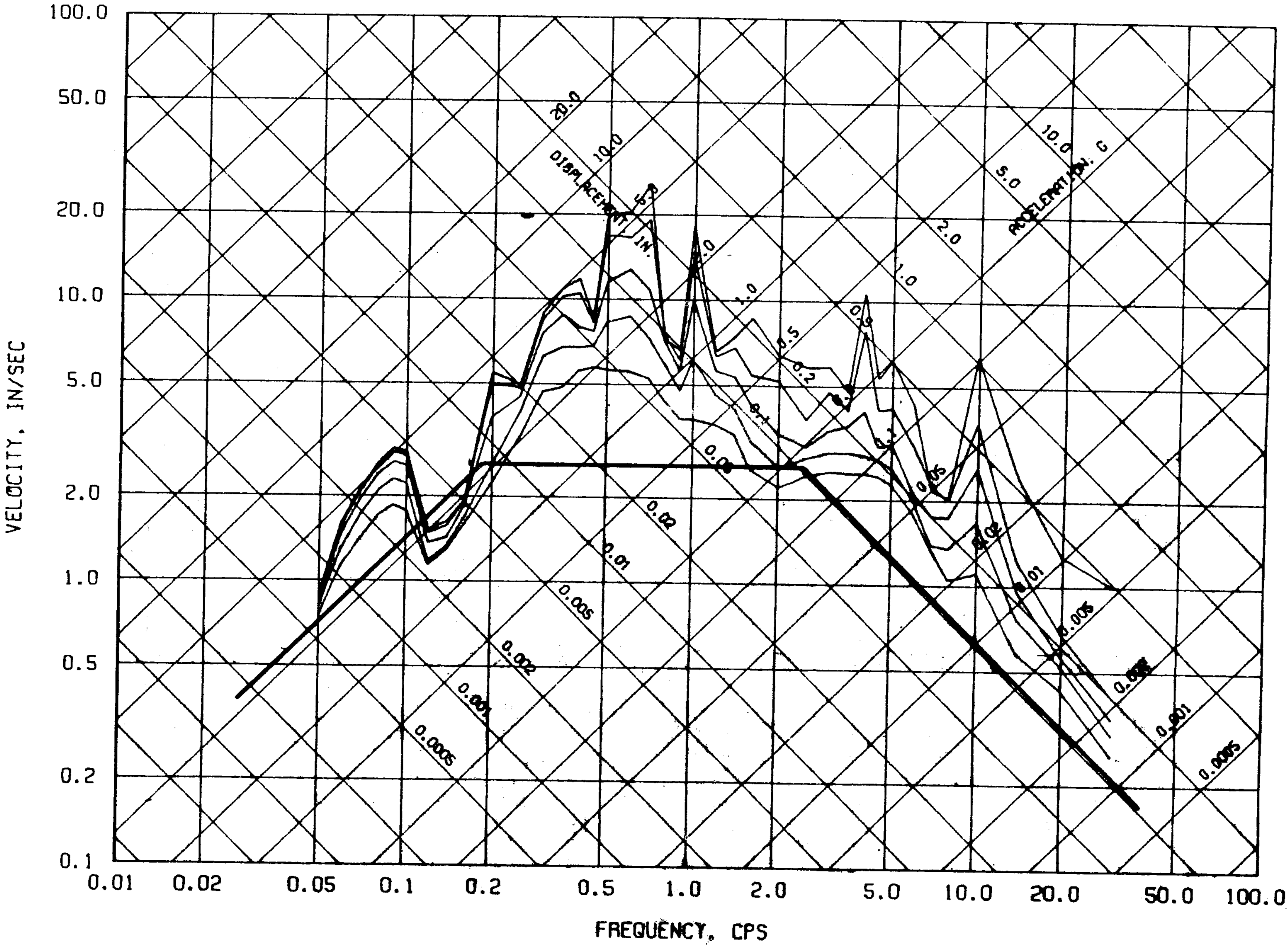


FIG.248RESPONSE SPECTRA - EUREKA, CALIF., 12/21/1954 - VERTICAL
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

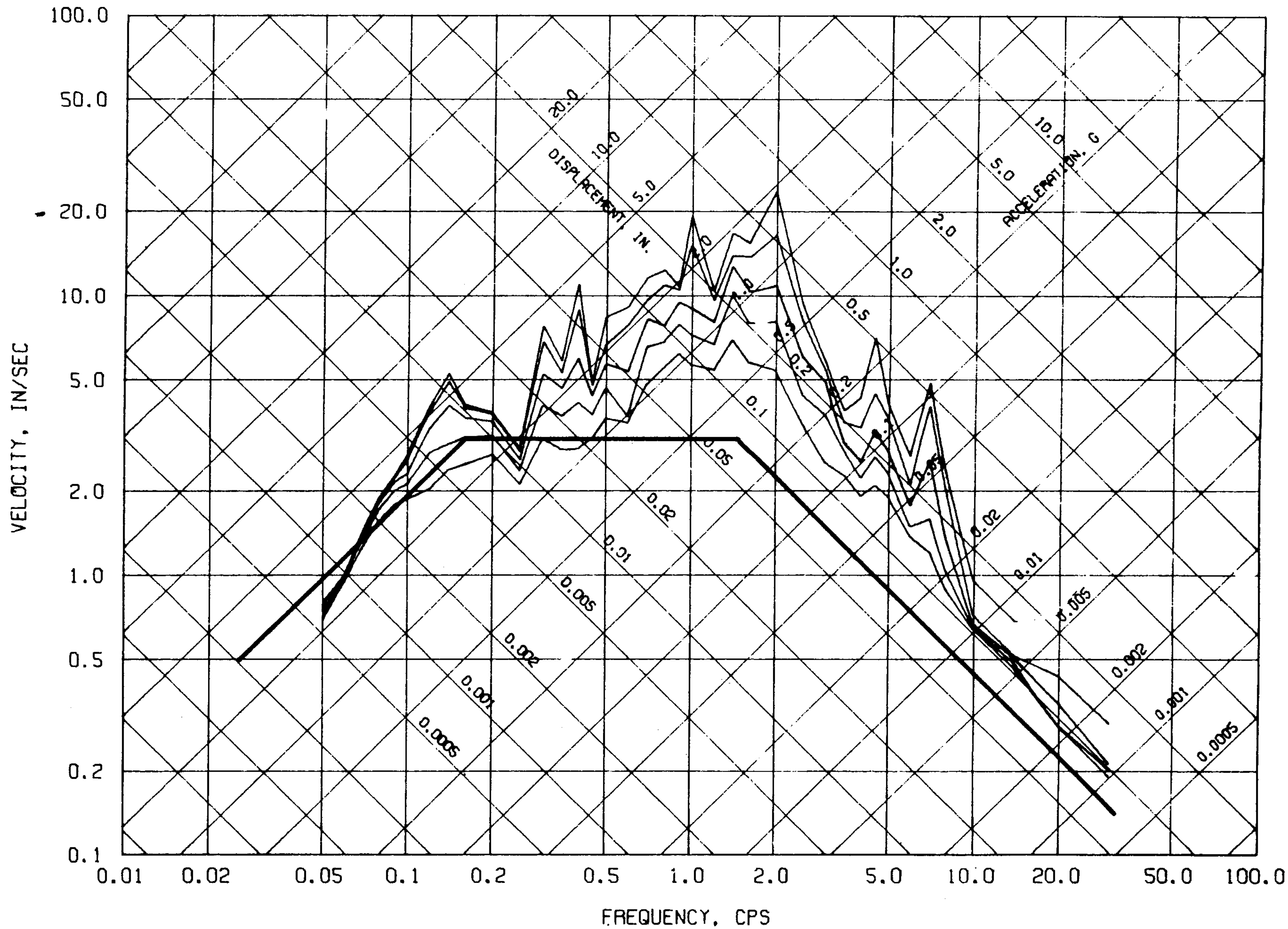


FIG.2.49 RESPONSE SPECTRA - HOLLISTER, CALIF., 4/8/1961 - S01W
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

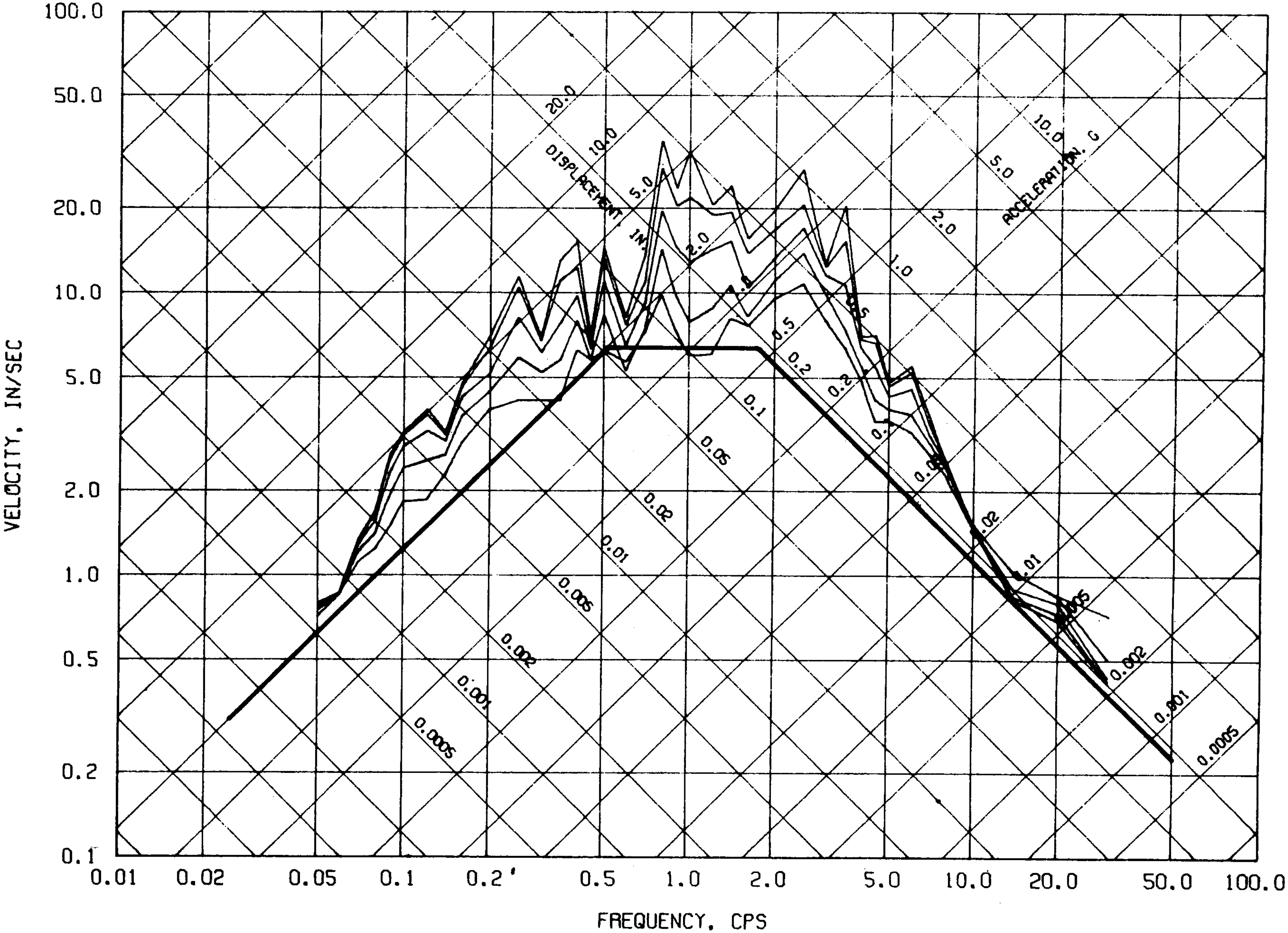


FIG.2.50 RESPONSE SPECTRA - HOLLISTER, CALIF., 4/8/1961 - N89W
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

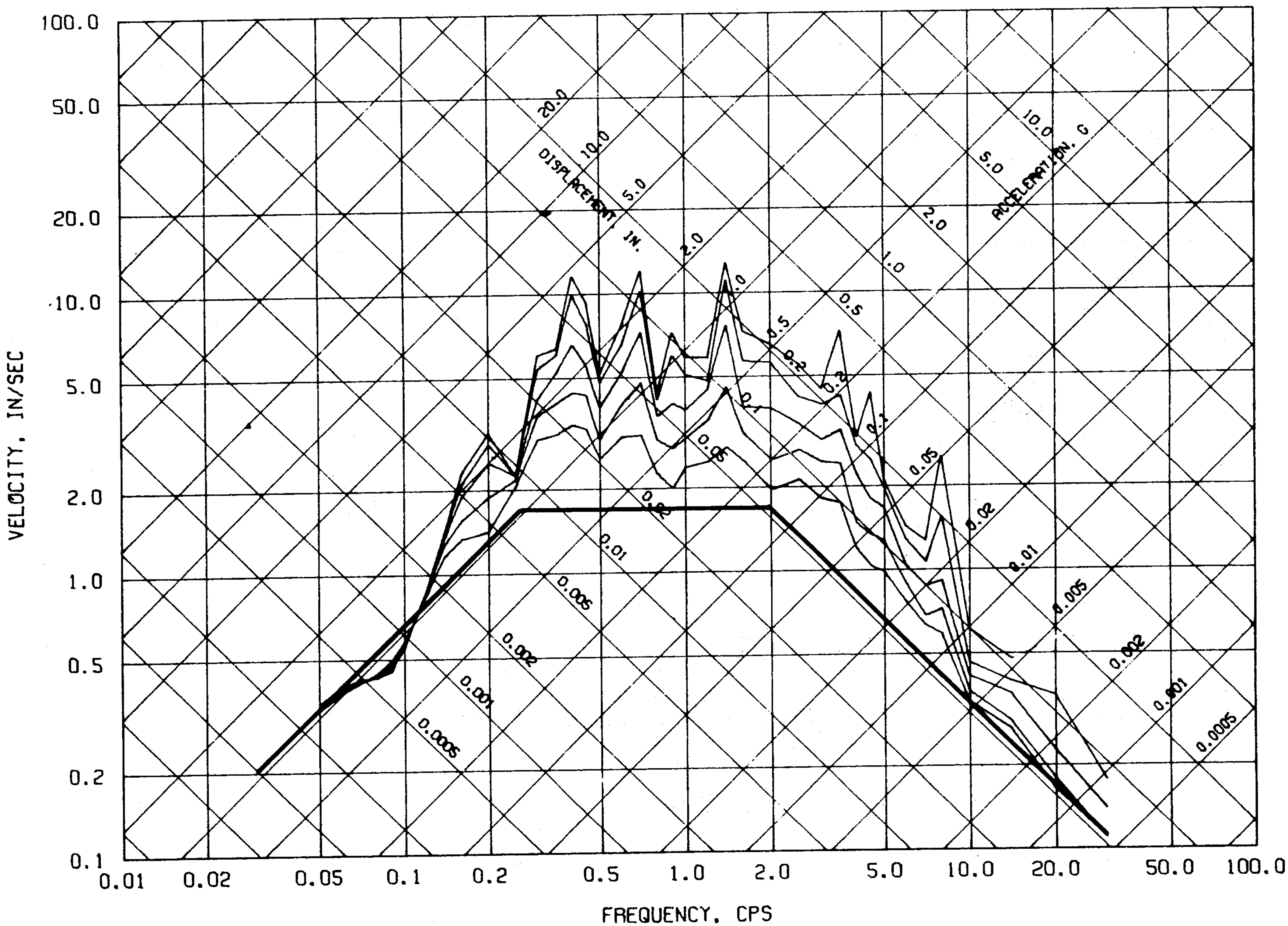


FIG.2.51 RESPONSE SPECTRA - HOLLISTER, CALIF., 4/8/1961 - VERTICAL
0, .5, 2, 5, & 10 PERCENT CRITICAL DAMPING

3. PRESENTATION AND DISCUSSION OF RESULTS

3.1 Ground Motion

The maximum values of ground motion obtained from the adjusted acceleration, velocity, and displacement time-histories for the 3 components of the 14 earthquake records considered are given in Table 3.1 along with a brief site description. It should be recognized that although an attempt was made to characterize the site descriptions as rock, alluvium, or otherwise, these descriptions are not completely dependable and accurate owing to a lack of satisfactory information about the geologic conditions at most of the sites where strong motion instruments have been located. The nondimensional ratio ad/v^2, where a, v, and d are the maximum ground acceleration, velocity, and displacement, respectively, is also given in Table 3.1. The ratio ad/v^2 is at least in part a function of the focal distance of the earthquake and the attenuation of motion in the ground.(6) For very large focal distances, where the ground motion approaches a harmonic motion, ad/v^2 approaches 1.0. The ratio increases as the focal distance decreases. The range of ad/v^2 for the earthquake records considered in this study is 1.84 to 17.61 for the horizontal and 2.66 to 30.58 for the vertical components, respectively. The average ad/v^2 for the 28 horizontal components and the 14 vertical components are 5.6 and 10.6, respectively. Among the 42 component records considered in this study, only one component (vertical component of El Centro, 5-18-40, 2037 PST) has an ad/v^2 which is extremely high. The ad/v^2 for this component is 63 percent higher than the next highest value of the vertical components. If this highest ad/v^2 value is not included, the average ad/v^2 for the remaining 13 vertical components reduces to 9.1. A summary of the average ad/v^2 values for horizontal and vertical components for alluvium and rock is presented in Table 3.2. Further discussion of the data presented in Table 3.2 and particularly with reference to classification by acceleration level appears in the next section.

Since the three components of the ground motion in a given record for a given site have the same focal distance, the difference in ad/v^2 values probably arises from attenuation of the ground motion and local geological effects on transmission of the ground motions.

The ratio ad/v^2 provides some bound on the relative magnitude of ground motion. For most earthquake records, the ratio ad/v^2 is between 5 to 15.[(6)] This ratio is important in selection of ground motions for use in constructing the design spectra as discussed next and later in Chapter 4. However, a knowledge of only the applicable or chosen ad/v^2 value is not in itself sufficient for constructing the basic ground motion bounds which are required in the construction of design spectra. In addition to the characteristic ad/v^2 values, one needs to know the absolute values of two of the three ground motion quantities (acceleration, velocity, displacement). Knowing two of these three quantities, plus the ad/v^2 value, the remaining quantity can be calculated.

It is convenient for scaling purposes to base the acceleration value on an acceleration of 1.0g. The construction could proceed for any other desired value. Moreover, because of the way in which the data are obtained and knowledge arising from a number of years of experience with the construction of spectra from earthquake and other shock-type loadings, it is normally customary to work with the quantities of velocity and acceleration, and the relationship between them. One reason for this is that very few good measurements of displacement have been recorded, and the least is known about this quantity. In an effort to arrive at the interrelationship between values of velocity and acceleration, a number of studies were made of the data. The salient features of these studies are recorded in the tables which are described briefly in the following.

In Table 3.3 there is presented a summary of the ratio of the velocity to the acceleration for the horizontal and vertical components of the records. These values can be obtained directly from the data in Table 3.1. Among the 14 earthquake records considered in this study, the v/a ratios for one record (San Francisco Golden Gate Park, 3-22-57, 1144 PST), both for the horizontal and vertical components, are about 47 percent lower than for the next lowest record's horizontal and vertical components. By not including the three v/a ratios for this record, the average v/a ratios for both alluvium and rock, and rock alone, increase slightly. The summary of the average v/a ratios, based on the data presented in Table 3.3, is presented in Table 3.4. Shown in that table are the various ratios, including: (1) all of the 28 horizontal components for alluvium and rock; (2) 26 horizontal components on alluvium and rock with two components not included, as just discussed; (3) alluvium alone; (4) rock alone; and (5) rock alone with two values not included. Other comparisons are presented for alluvium and rock for all horizontal traces where the maximum ground acceleration is greater than 0.1g, etc. Similar comparisons are presented in Table 3.4 for vertical components.

In Table 3.5 is shown a summary of the vertical to horizontal v/a ratios. Considerable study indicated that the most representative values could not be obtained by averaging numbers of the type shown in Table 3.4, but instead individual trace data, as shown in Table 3.3, were averaged. On this basis, as noted in Table 3.5, the ratio of the velocity to the acceleration for the vertical traces compared with that of the horizontal traces is on the order of 0.90, and ranges from 0.81 to 0.99.

Similarly, in Table 3.3 is shown the ratio of the peak ground acceleration from the vertical traces to that for the horizontal traces; these values are shown in the right-hand two columns of Table 3.3. In order to obtain a measure of these ratios, which are needed for scaling purposes for the vertical spectra, studies of the data for various classes of traces based on site characteristics are presented in Table 3.6. It will be noted that the values range from 0.40 to 0.72, depending on the acceleration level included and the type of site, etc. On the basis of these data, and realizing that only a few samples existed for the rock sites, we selected for use later a value of 2/3 as a ratio of vertical to horizontal acceleration.

3.2 Response Amplifications

Studies of the response amplification in the various ranges of frequencies were made by studying plots on the four-way logarithmic plot, with the input ground motion normalized to the following values for all of the earthquake motions studied:

(1) A maximum ground displacement of 1.0 inch

(2) A maximum ground velocity of 10 in/sec

(3) A maximum ground acceleration of 1.0g

The amplified values for the various frequencies for which calculations were made are shown in Figs. 3.1 to 3.16. Separate plots are drawn for vertical and for horizontal components for values of damping of 0.5, 2, 5, and 10 percent of critical. The figures are given for the mean (normal distribution) response and the 75 percent level (ranking) of response. For other probability levels the plots would have generally the same characteristics.

It can be seen that the amplifications for displacement are for all practical purposes constant over the range of frequencies from about 0.10 hertz to some upper limit of the order of 0.4 or 0.5 hertz. It is also clear from the figures that the amplification factors for acceleration are virtually constant for the range of frequencies from about 2 hertz to about 6 hertz in the horizontal responses and from about 3 hertz to about 10 hertz in the vertical responses, and then decrease fairly uniformly to intersect the ground motion accelerations at frequencies of the order of 30 to 50 hertz, varying with the direction and the damping factors.

For the intermediate range of velocities, the horizontal amplifications appear in general to be statistically practically constant in the range of frequencies from about 0.5 to 2 hertz or more, although there are occasional slight roundings with a higher value in the central portion, but there is no basis for using other than a simple constant amplification level in this range. For the vertical component, there is evidence of a slight drop in amplification factor as the frequency increases in the intermediate range, but the drop is only of the order of about 10 percent over the frequency range for which "velocity amplification" is valid, and it therefore appears reasonable for practical purposes to use also a constant amplification for the velocity range, as well as for the displacement and acceleration ranges.

An examination of the response spectra shown in Figs. 2.10-2.51 indicates that for most cases the response spectra for vertical ground motion are flatter (broader) than those for horizontal motions. Careful examination will reveal that the response spectra for ground motion in the vertical direction approach the ground acceleration at higher frequencies than is the case for the horizontal direction. This phenomenon is due mainly to presence of higher frequencies in vertical components of ground motion.[7] Therefore, in constructing a design spectrum, it seems reasonable to amplify the vertical ground acceleration over a larger frequency domain than for the horizontal ground acceleration.

An examination of response amplifications, especially the amplifications for velocity and acceleration, indicated that earthquakes with low ground acceleration have greater amplifications than those with a high ground acceleration. The presence of sharp peaks in an accelerogram reduces the response amplification for high frequencies. This is demonstrated in Figs. 3.17 and 3.18. Figure 3.17 shows the adjusted acceleration-time history for El Centro, 5-18-1940, NS component with the first and the second peaks scaled such that the maximum ground acceleration is 1.0g. The response spectrum for 2.0 percent of critical damping normalized to ground acceleration for this accelerogram is compared with the one without fictitious high peaks, Fig. 3.18. It is seen that for high frequencies the amplification for acceleration is lower for accelerogram with high peaks. The difference between the two curves for intermediate and low frequencies arises from normalizing the response spectra to only the ground acceleration over the entire range of frequencies (see Appendix B for further discussion of this point).

For this reason, the statistical values of response amplification were computed for two groups of data. One group included all data, whereas the other group included records with peak accelerations greater than 0.1g and 0.05g for the horizontal and vertical components, respectively. The records which were included in the latter group are as follows (see Table 3.1):

Pacoima Dam, 2-9-71, 0600 PST (all components)

Castaic, 2-9-71, 0600 PST (all components)

Holiday Inn (First Floor), 2-9-71, 0600 PST (all components)

15250 Ventura Boulevard (Basement), 2-9-71, 0600 PST (all components)

El Centro, 5-18-40, 2037 PST (all components)

El Centro, 4-8-68, 1830 PST (NS component only)

San Francisco Golden Gate Park, 3-22-57, 1144 PST (all components)

Ferndale, 10-7-51, 2011 PST (N46W and S44W components only)

Ferndale, 12-21-54, 1156 PST (N46W and N44E components only)

Eureka, 12-21-54, 1156 PST (all components)

Hollister, 4-8-61, 2323 PST (N89W and vertical components only)

The statistical values of response amplifications corresponding to 50, 75, 90 and 95 percentile levels obtained from a normal distribution curve for 0.5, 2.0, 5.0 and 10.0 percent of critical damping are presented in Tables 3.7 and 3.8 for all 28 (horizontal) or 14 (vertical) components along with corresponding amplification values for those horizontal and vertical components with peak ground accelerations greater than 0.1g and 0.05g, respectively. These amplifications were obtained by first computing the mean and the standard deviation of amplifications for displacement, velocity and acceleration at each frequency for which response computations had been performed. From the mean and the standard deviation at each frequency, amplifications corresponding to various percentile levels were determined. The displacement, velocity and acceleration amplifications for a number of frequencies (within a frequency band) were then averaged and are presented in the tables. The frequency bands used for averaging the amplifications, which were established, through examination of the spectra, are as follows:

Horizontal displacement	0.2 to 0.4 hertz
Horizontal velocity	0.4 to 2.0 hertz
Horizontal acceleration	2.0 to 6.0 hertz
Vertical displacement	0.1 to 0.3 hertz
Vertical velocity	0.3 to 3.0 hertz
Vertical acceleration	3.0 to 10.0 hertz

Amplification values similar to those just described but obtained from ranking the data are presented in Tables 3.9 and 3.10.

The amplifications given in Tables 3.7 to 3.10 indicate that for records with horizontal and vertical ground acceleration greater than 0.1g and 0.05g, respectively, the velocity and acceleration amplifications are lower than the corresponding values obtained by including all data. In other words, the strong motion data clearly indicate a decrease in amplification, especially for the velocity and acceleration regions, as compared to the case where low intensity excitation is included.

Table 3.1 Maximum Ground Motions and Site Description

Record description	Maximum ground acc. a, g	Maximum ground vel. v, in/sec	Maximum ground displ. d, in	$\frac{ad}{v^2}$	Site description (See Sec. 3.1)	Remarks
Pacoima Dam, 2-9-71, 0600 PST (Record IC 041)					Highly jointed diorite gneiss 4 km from surface faulting	Small building houses the instrument
S 74 W	1.250	22.49	5.11	4.88		
S 16 E	1.241	43.70	23.18	5.82		
Vertical	0.718	23.06	13.75	7.17		Ref. (8)
Castaic, 2-9-71, 0600 PST (Record ID 056)					Sandstone	Small building houses the instrument
N 21 E	0.333	6.73	2.05	5.82		
N 69 W	0.281	10.55	3.22	3.14		
Vertical	0.181	2.75	1.42	13.13		Ref. (8)
Holiday Inn (First Floor), 2-9-71, 0600 PST (Record IC 048)					Alluvium 8 km from surface faulting	Instrument on the first floor of a 7 story RC building structure
NS	0.258	12.13	8.70	5.90		
EW	0.137	9.68	6.37	3.60		
Vertical	0.177	12.81	6.37	2.66		Ref. (8)
15250 Ventura Boulevard (Basement), 2-9-71, 0600 PST (Record IH 115)					Alluvium water table at 55'	Instrument in the basement of a 12 story RC building structure
N 11 E	0.234	10.96	7.07	5.32		
N 79 W	0.154	7.88	4.48	4.29		
Vertical	0.108	4.77	3.09	5.67		Ref. (8)
El Centro, 5-18-40, 2037 PST (Record IA 1)					Alluvium to about 5000 ft	Instrument on the first floor of a 2 story massive concrete, heavily reinforced structure
NS	0.352	13.88	4.74	3.35		
EW	0.223	11.72	6.58	4.13		
Vertical	0.280	3.95	4.41	30.58		Ref. (8)

Record description	Maximum ground acc. a, g	Maximum ground vel. v, in/sec	Maximum ground displ. d, in	$\frac{ad}{v^2}$	Site description (See Sec. 3.1)	Remarks
El Centro, 2-9-56, 0633 PST (Record IA 11)					Alluvium to about 5000 ft	Instrument on the first floor of a 2 story massive concrete, heavily reinforced structure Ref. (9)
NS	0.036	1.52	1.27	7.65		
EW	0.055	3.11	2.48	5.45		
Vertical	0.016	0.75	0.55	6.05		
El Centro, 4-8-68, 1830 PST (Record IA 19)					Alluvium to about 5000 ft	Instrument on the first floor of a 2 story massive concrete, heavily reinforced structure Ref. (9)
NS	0.142	10.49	3.68	1.84		
EW	0.058	4.72	4.68	4.71		
Vertical	0.036	1.16	1.36	14.06		
Hollywood Storage Basement, 7-21-52, 0453 PDT (Record IA 6)					700' ± of alluvium	Instrument in the basement of a 14 story RC building Ref. (8)
NS	0.059	2.58	1.41	4.83		
EW	0.046	3.74	2.73	3.47		
Vertical	0.023	1.12	0.85	6.02		
Hollywood Storage PE Lot, 7-21-52, 0453 PDT (Record IA 7)					700' ± of alluvium	Ref. (8)
NS	0.063	2.60	1.26	4.54		
EW	0.043	4.11	2.89	2.84		
Vertical	0.023	1.22	0.81	4.84		
San Francisco Golden Gate Park, 3-22-57, 1144 PST (Record IA 15)					Siliceous sandstone 1-2 miles from San Andreas Fault	Instrument in a small shack used to house electrical equipment Ref. (9)
N 10 E	0.106	1.09	0.20	6.90		
S 80 E	0.127	1.26	0.18	5.56		
Vertical	0.051	0.41	0.16	18.76		

Record description	Maximum ground acc. a, g	Maximum ground vel. v, in/sec	Maximum ground displ. d, in	$\frac{ad}{v^2}$	Site description (See Sec. 3.1)	Remarks
Ferndale, 10-7-51, 2011 PST (Record IA 2)					40-80 ft of alluvium over 100 ft of sandstone over siltstone	Instrument on the ground floor of a 2 story frame structure Ref. (9)
N 46 W	0.120	2.86	0.95	5.39		
S 44 W	0.123	1.73	1.07	16.99		
Vertical	0.032	1.02	1.24	14.74		
Ferndale, 12-21-54, 1156 PST (Record IA 9)					40-80 ft of alluvium over 100 ft of sandstone over siltstone	Instrument on the ground floor of a 2 story frame structure Ref. (9)
N 46 W	0.209	9.79	4.92	4.15		
N 44 E	0.166	14.10	8.09	2.61		
Vertical	0.045	3.13	2.49	4.42		
Eureka, 12-21-54, 1156 PST (Record IA 8)					100' sandstone (poorly consolidated) over 360 ft of siltstone over sandstone	Instrument in the basement of a brick and stone building Ref. (9)
N 11 W	0.189	5.92	8.45	17.61		
N 79 E	0.271	9.23	3.14	3.86		
Vertical	0.110	2.64	2.22	13.54		
Hollister, 4-8-61, 2323 PST (Record IA 18)					500 ft of alluvium over cenozoic rock water table at 50 ft	Instrument on the first floor of the public library, a 2 story structure Ref. (9)
S 01 W	0.076	3.10	3.03	9.26		
N 89 W	0.189	6.45	1.97	3.46		
Vertical	0.056	1.73	1.03	7.45		

Table 3.2 Summary of Average ad/v^2 Values

Site	Direction	No. of Records	ad/v^2
alluvium & rock	horizontal	28	5.6
alluvium	horizontal	22	5.7
rock	horizontal	6	5.4
alluvium & rock, $a>0.1g$	horizontal	20	5.7
alluvium, $a>0.1g$	horizontal	14	5.9
rock, $a>0.1g$ (same as above)	horizontal	6	5.4
alluvium, $a<0.1g$	horizontal	8	5.3
alluvium & rock	vertical	14	10.7
alluvium & rock*	vertical	13	9.1
alluvium	vertical	11	10.0
alluvium*	vertical	10	7.9
rock	vertical	3	13.0
alluvium & rock, $a>0.05g$	vertical	8	12.4
alluvium, $a>0.05g$	vertical	5	12.0
alluvium, $a>0.05g$*	vertical	4	7.3
rock, $a>0.05g$ (same as above)	vertical	3	13.0
alluvium, $a<0.05g$	vertical	6	8.4

* Not including the one extreme value, El Centro, 5-18-40, 2037 PST, vertical component $ad/v^2 = 30.58$

Table 3.3 Ratios of Maximum Ground Motions

Record description	v/a horizontal		v/a vertical	v/a - vertical / v/a - horizontal		a - vertical / a - horizontal	
Pacoima Dam 2-9-71, 0600 PST (Record IC 041)	17.99	35.21	32.12	1.78	0.91	0.57	0.58
Castaic 2-9-71, 0600 PST (Record ID 056)	20.21	37.54	15.19	0.75	0.40	0.54	0.64
Holiday Inn (First Floor) 2-9-71, 0600 PST (Record IC 048)	47.02	70.66	72.37	1.53	1.02	0.69	1.29
15250 Ventura Boulevard (Basement) 2-9-71, 0600 PST (Record IH 115)	46.84	51.17	44.17	0.94	0.86	0.46	0.70
El Centro 5-18-40, 2037 PST (Record IA 1)	39.43	52.56	14.11	0.35	0.26	0.80	1.26
El Centro 2-9-56, 0633 PST (Record IA 11)	42.22	56.55	46.88	1.11	0.82	0.29	0.44
El Centro 4-8-68, 1830 PST (Record IA 19)	73.87	81.38	32.22	0.43	0.39	0.25	0.62
Hollywood Storage Basement 7-21-52, 0453 PDT (Record IA 6)	43.73	81.30	48.69	1.11	0.59	0.39	0.50

Record description	v/a horizontal		v/a vertical	v/a - vertical / v/a - horizontal		a - vertical / a - horizontal	
Hollywood Storage PE Lot 7-21-52, 0453 PDT (Record IA 7)	41.27	95.58	53.04	1.28	0.55	0.37	0.54
San Francisco Golden Gate Park 3-22-57, 1144 PST (Record IA 15)	9.92	10.28	8.04	0.81	0.78	0.40	0.48
Ferndale 10-7-51, 2011 PST (Record IA 2)	14.07	23.83	31.87	2.26	1.33	0.26	0.27
Ferndale 12-21-54, 1156 PST (Record IA 9)	46.84	84.94	69.56	1.48	0.81	0.22	0.27
Eureka 12-21-54, 1156 PST (Record IA 8)	31.32	34.06	24.00	0.76	0.70	0.41	0.58
Hollister 4-8-61, 2323 PST (Record IA 18)	34.13	40.79	30.89	0.90	0.75	0.30	0.74

Table 3.4 Summary of Average v/a Ratios

Site	Direction	No. of records	v/a (in/sec/g)
alluvium & rock	horizontal	28	45
alluvium & rock*	horizontal	26	48
alluvium	horizontal	22	52
rock	horizontal	6	22
rock*	horizontal	4	28
alluvium & rock, a>0.1g	horizontal	20	39
alluvium & rock, a>0.1g*	horizontal	18	42
alluvium, a>0.1g	horizontal	14	47
alluvium, a<0.1g	horizontal	8	60
alluvium & rock	vertical	14	37
alluvium & rock*	vertical	13	40
alluvium	vertical	11	43
rock	vertical	3	18
rock*	vertical	2	24
alluvium & rock, a>0.05g	vertical	8	30
alluvium & rock, a>0.05g*	vertical	7	33
alluvium, a>0.05g	vertical	5	37
alluvium, a<0.05g	vertical	6	47

* Not including the extreme ratios, San Francisco Golden Gate Park, 3-22-57, 1144 PST.

Table 3.5 Summary of Vertical to Horizontal v/a Ratios

Site	No. of records	Average $\frac{\text{v/a - vertical}}{\text{v/a - horizontal}}$
alluvium & rock	28	0.92
alluvium	22	0.92
rock	6	0.91
alluvium & rock, a_h>0.1g, a_v>0.05g	15	0.85
alluvium alone, a_h>0.1g, a_v>0.05g	9	0.81
alluvium & rock, a_h<0.1g, a_v<0.05g	13*	0.99

* Actually alluvium values only since all rock components had peak ground accelerations > 0.1g (horizontal) and 0.05g (vertical).

Table 3.6 Summary of Vertical to Horizontal Acceleration Ratios

Site	No. of records	Average $\frac{\text{a - vertical}}{\text{a - horizontal}}$
alluvium & rock	28	0.53
alluvium	22	0.53
rock	6	0.54
alluvium & rock, a_h>0.1g, a_v>0.05g	15	0.65
alluvium, a_h>0.1g, a_v>0.05g	9	0.72
alluvium & rock, a_h<0.1g, a_v<0.05g	13*	0.40

* Actually alluvium values only since all rock components had peak ground accelerations > 0.1g (horizontal) and 0.05g (vertical).

Table 3.7 Statistical Values of Response Amplifications (Normal Distribution - Horizontal Components)

Percentile	Damping	All Records (28)			Records with a > 0.1g (20)		
		D	V	A	D	V	A
50	0.5	1.98	2.86	4.00	1.97	2.58	3.67
	2.0	1.69	2.23	2.91	1.68	2.06	2.76
	5.0	1.39	1.74	2.20	1.40	1.66	2.11
	10.0	1.13	1.38	1.72	1.15	1.34	1.65
75	0.5	2.66	3.81	5.02	2.66	3.41	4.65
	2.0	2.23	2.89	3.52	2.24	2.68	3.36
	5.0	1.80	2.19	2.59	1.83	2.10	2.48
	10.0	1.43	1.69	1.97	1.47	1.66	1.89
90	0.5	3.27	4.67	5.95	3.28	4.16	5.53
	2.0	2.72	3.48	4.06	2.74	3.23	3.90
	5.0	2.17	2.60	2.93	2.21	2.51	2.82
	10.0	1.71	1.98	2.20	1.75	1.94	2.11
95	0.5	3.64	5.19	6.50	3.65	4.60	6.05
	2.0	3.02	3.84	4.39	3.04	3.57	4.22
	5.0	2.39	2.84	3.14	2.44	2.75	3.03
	10.0	1.87	2.15	2.33	1.91	2.11	2.24

Table 3.8 Statistical Values of Response Amplifications (Normal Distribution - Vertical Components)

Percentile	Damping	All Records (14)			Records with a > 0.05g (8)		
		D	V	A	D	V	A
50	0.5	1.77	2.74	4.22	1.86	2.52	4.02
	2.0	1.57	2.10	2.86	1.65	1.97	2.80
	5.0	1.33	1.56	2.08	1.40	1.51	2.05
	10.0	1.09	1.22	1.62	1.16	1.17	1.59
75	0.5	2.33	3.67	5.47	2.48	3.39	5.46
	2.0	2.04	2.77	3.60	2.17	2.61	3.70
	5.0	1.70	2.06	2.52	1.81	1.97	2.57
	10.0	1.38	1.55	1.91	1.47	1.49	1.92
90	0.5	2.83	4.51	6.59	3.04	4.17	6.76
	2.0	2.46	3.37	4.27	2.63	3.18	4.51
	5.0	2.04	2.47	2.92	2.18	2.37	3.04
	10.0	1.63	1.84	2.17	1.75	1.78	2.22
95	0.5	3.13	5.02	7.26	3.37	4.64	7.53
	2.0	2.71	3.73	4.67	2.91	3.52	4.99
	5.0	2.24	2.73	3.16	2.40	2.62	3.32
	10.0	1.79	2.01	2.32	1.92	1.95	2.40

Table 3.9 Statistical Values of Response Amplifications (Ranking - Horizontal Components)

Percentile	Damping	All Records (28)			Records with a > 0.1g (20)		
		D	V	A	D	V	A
50	0.5	1.82	2.63	3.74	1.77	2.34	3.30
	2.0	1.54	2.10	2.82	1.50	1.88	2.63
	5.0	1.32	1.66	2.14	1.30	1.54	2.08
	10.0	1.10	1.35	1.71	1.08	1.29	1.64
75	0.5	2.49	3.50	4.74	2.43	3.17	4.37
	2.0	2.11	2.73	3.42	2.06	2.59	3.23
	5.0	1.74	2.14	2.55	1.75	2.07	2.45
	10.0	1.42	1.65	1.96	1.45	1.61	1.89
90	0.5	3.27	4.64	5.93	3.14	4.07	5.51
	2.0	2.69	3.39	4.04	2.68	3.05	3.82
	5.0	2.10	2.56	2.86	2.11	2.43	2.71
	10.0	1.69	1.94	2.15	1.68	1.84	2.04
95	0.5	3.64	5.03	6.43	3.59	4.45	6.10
	2.0	3.11	3.78	4.30	3.07	3.47	4.01
	5.0	2.41	2.82	3.09	2.47	2.73	2.79
	10.0	1.85	2.16	2.29	1.89	2.14	2.12

Table 3.10 Statistical Values of Response Amplifications
(Ranking - Vertical Components)

Percentile	Damping	All Records (14)			Records with a > 0.05g (8)		
		D	V	A	D	V	A
50	0.5	1.65	2.40	3.86	1.54	2.04	3.25
	2.0	1.44	1.89	2.63	1.41	1.58	2.37
	5.0	1.21	1.44	1.96	1.21	1.21	1.84
	10.0	0.97	1.14	1.60	1.02	0.98	1.54
75	0.5	2.15	3.34	5.07	2.07	2.95	4.79
	2.0	1.88	2.58	3.36	1.79	2.33	3.25
	5.0	1.57	1.96	2.40	1.52	1.82	2.40
	10.0	1.28	1.48	1.82	1.27	1.40	1.83
90	0.5	2.53	4.37	6.14	2.64	3.81	6.06
	2.0	2.22	3.31	3.99	2.31	2.94	4.16
	5.0	1.86	2.41	2.80	1.92	2.24	2.80
	10.0	1.48	1.78	2.07	1.54	1.68	2.06
95	0.5	2.97	4.94	6.96	3.20	4.33	6.98
	2.0	2.59	3.66	4.47	2.77	3.29	4.68
	5.0	2.15	2.63	3.03	2.28	2.43	3.09
	10.0	1.72	1.94	2.23	1.83	1.81	2.20

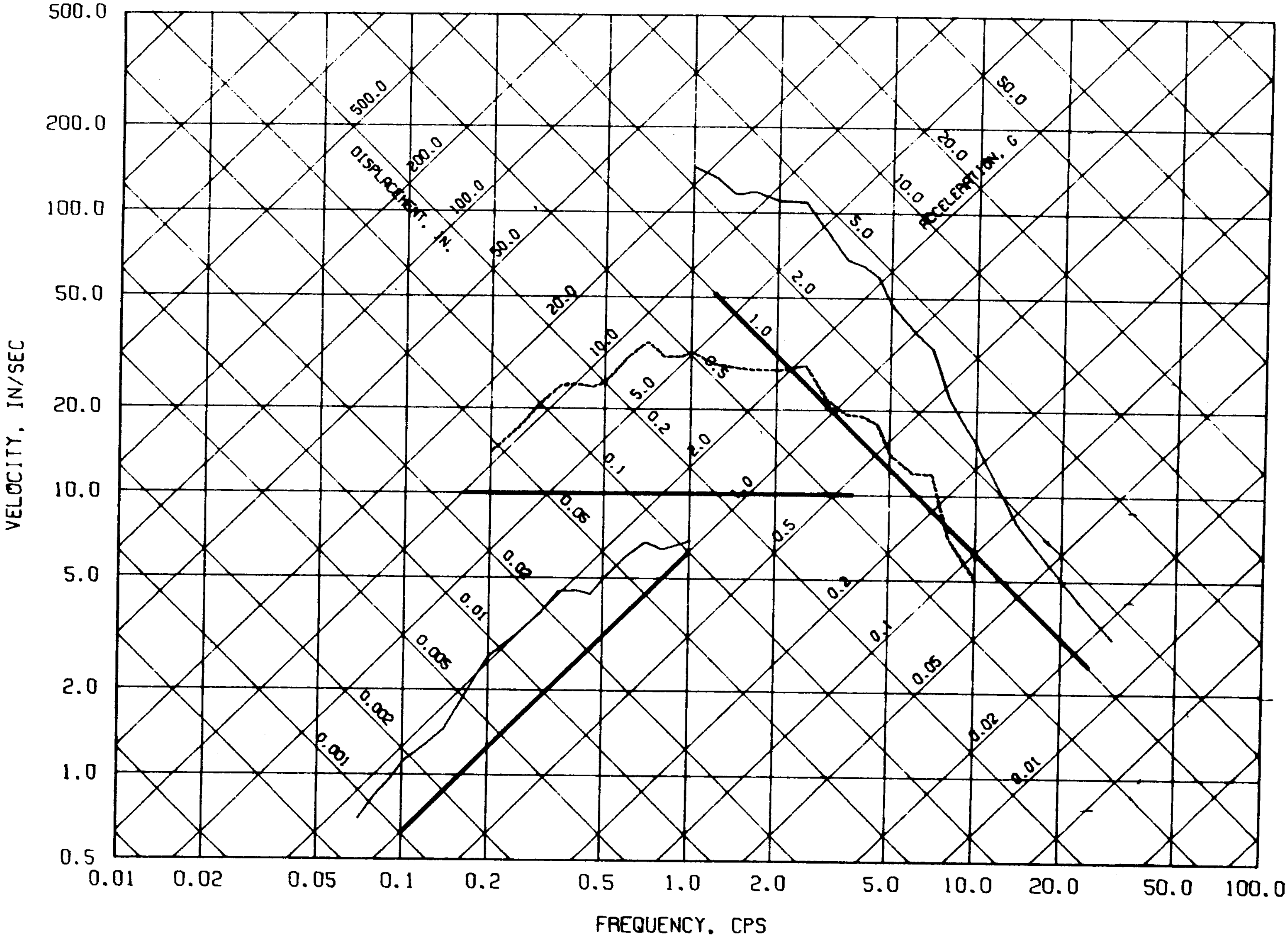


FIG 3.1 MEAN RESPONSE AMPLIFICATION – HORIZONTAL COMPONENTS
0.5 PERCENT OF CRITICAL DAMPING

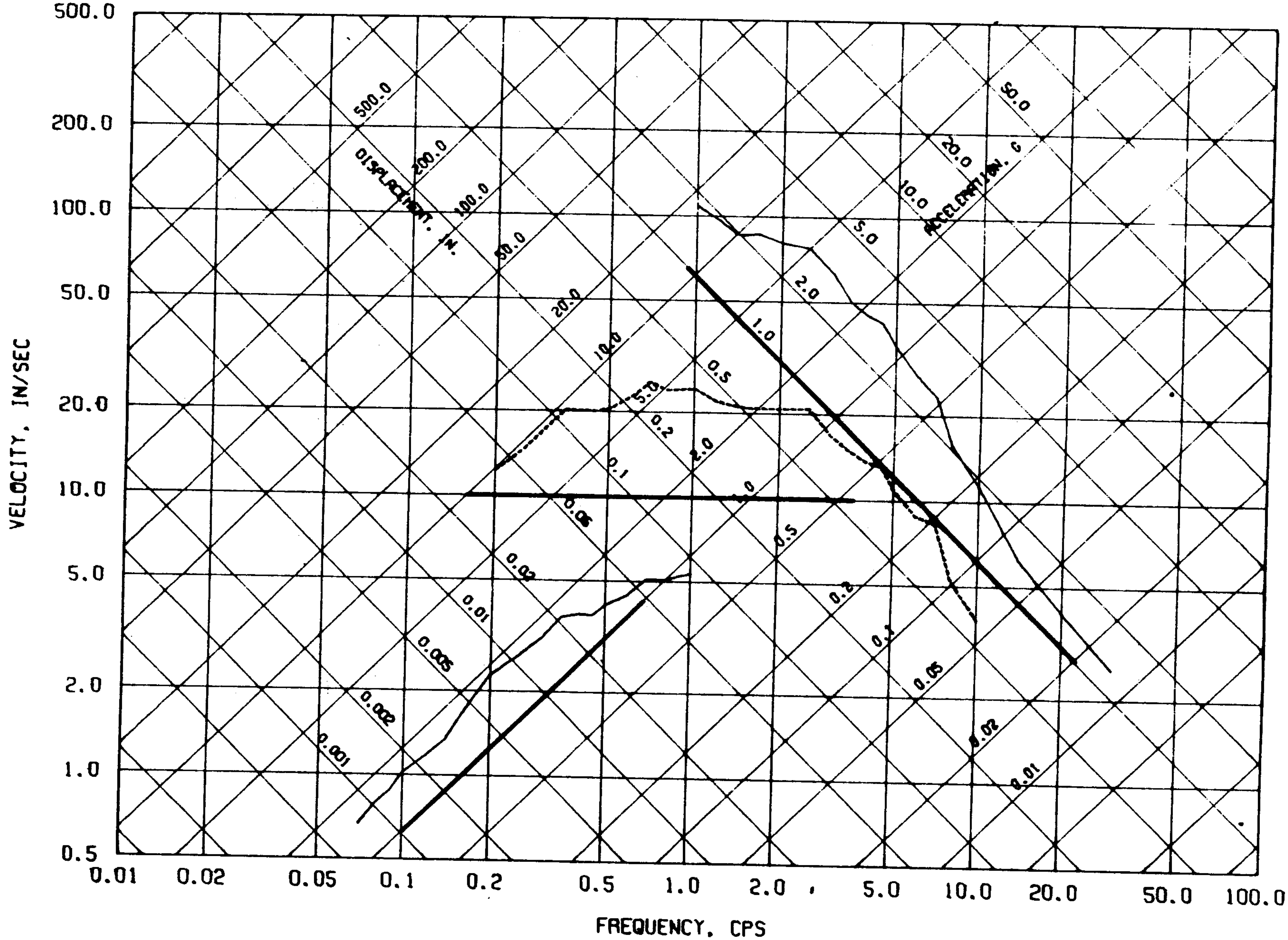


FIG 3.2 MEAN RESPONSE AMPLIFICATION - HORIZONTAL COMPONENTS
2.0 PERCENT OF CRITICAL DAMPING

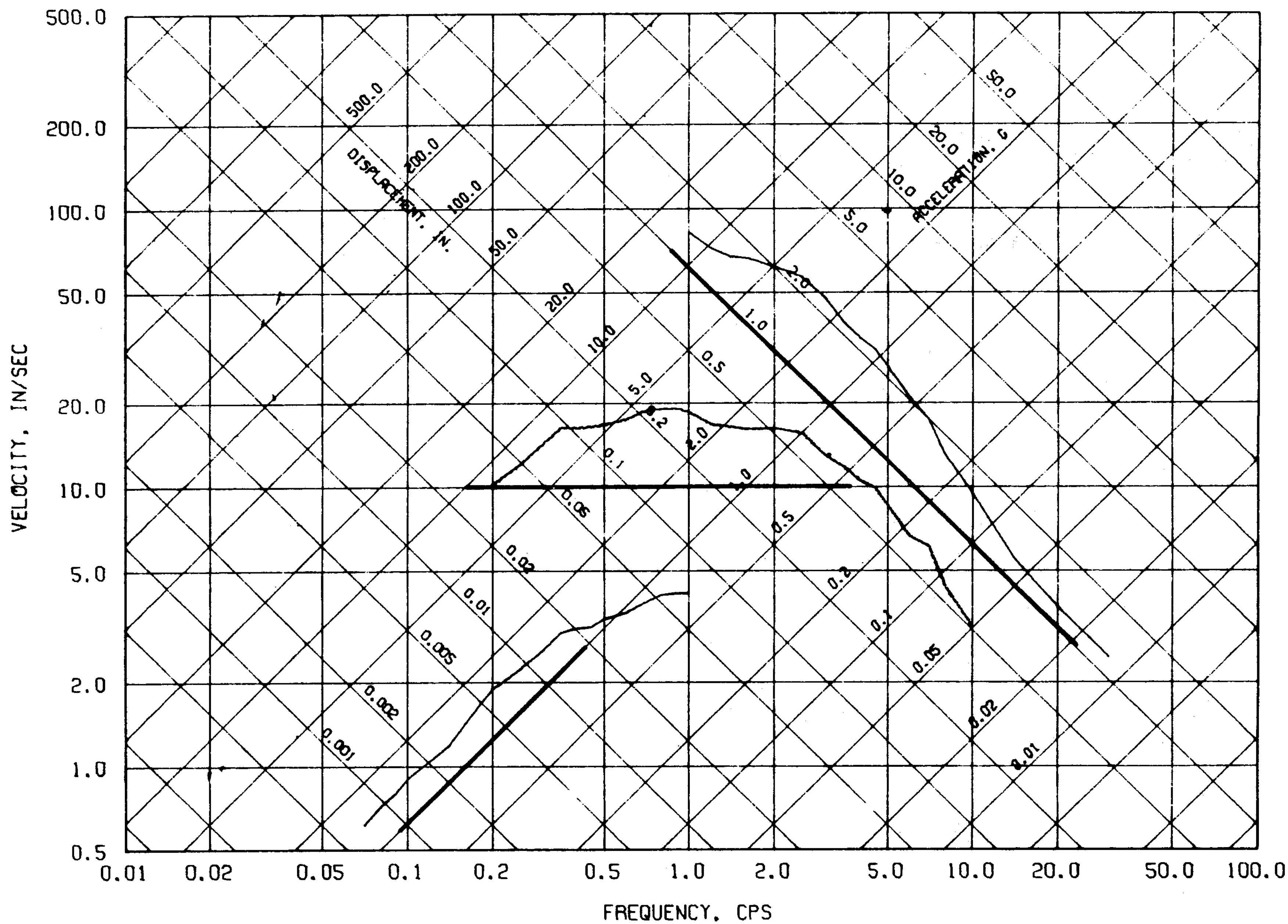


FIG 3.3 MEAN RESPONSE AMPLIFICATION - HORIZONTAL COMPONENTS
5.0 PERCENT OF CRITICAL DAMPING

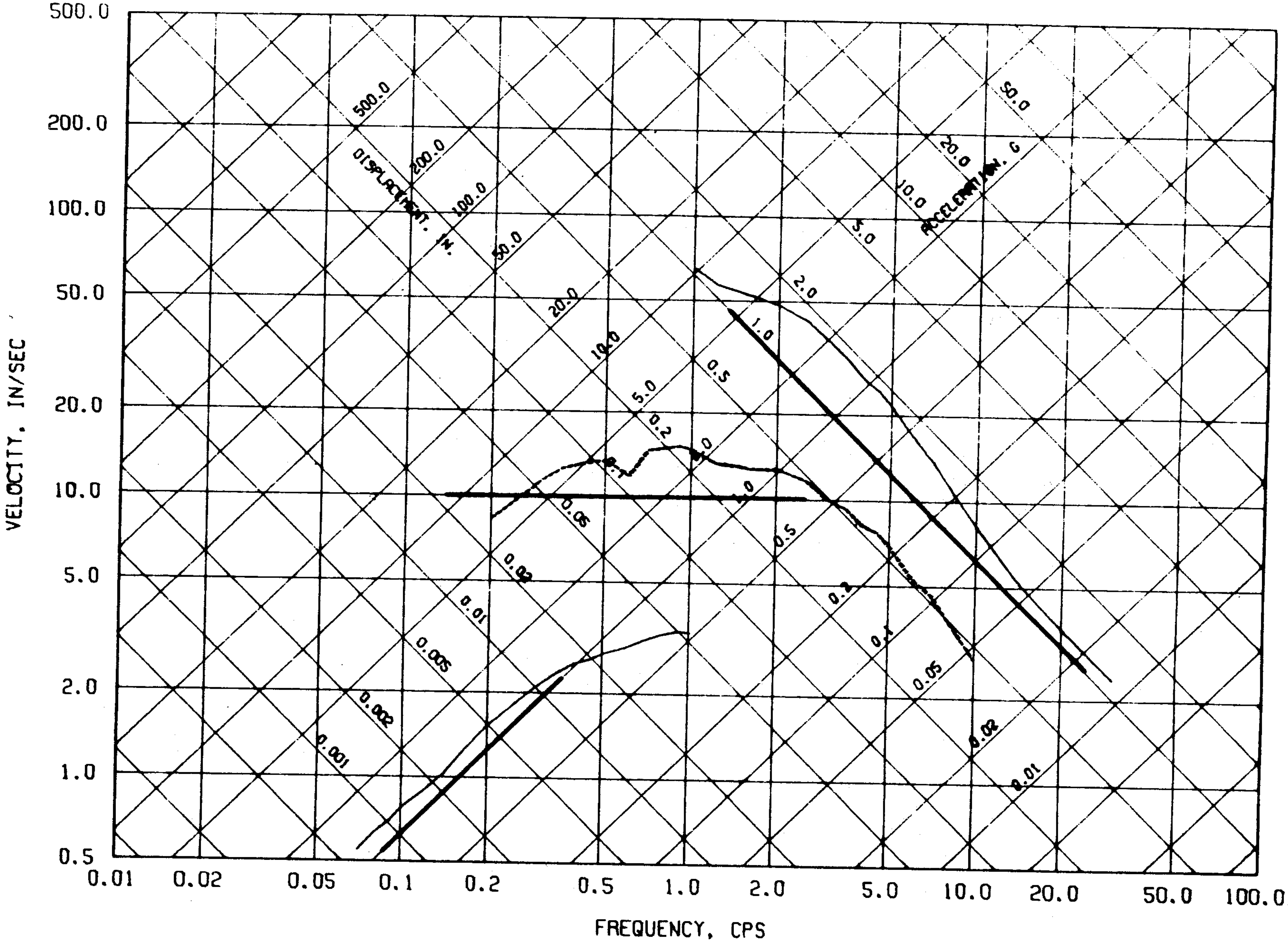


FIG 3.4 MEAN RESPONSE AMPLIFICATION - HORIZONTAL COMPONENTS
10.0 PERCENT OF CRITICAL DAMPING

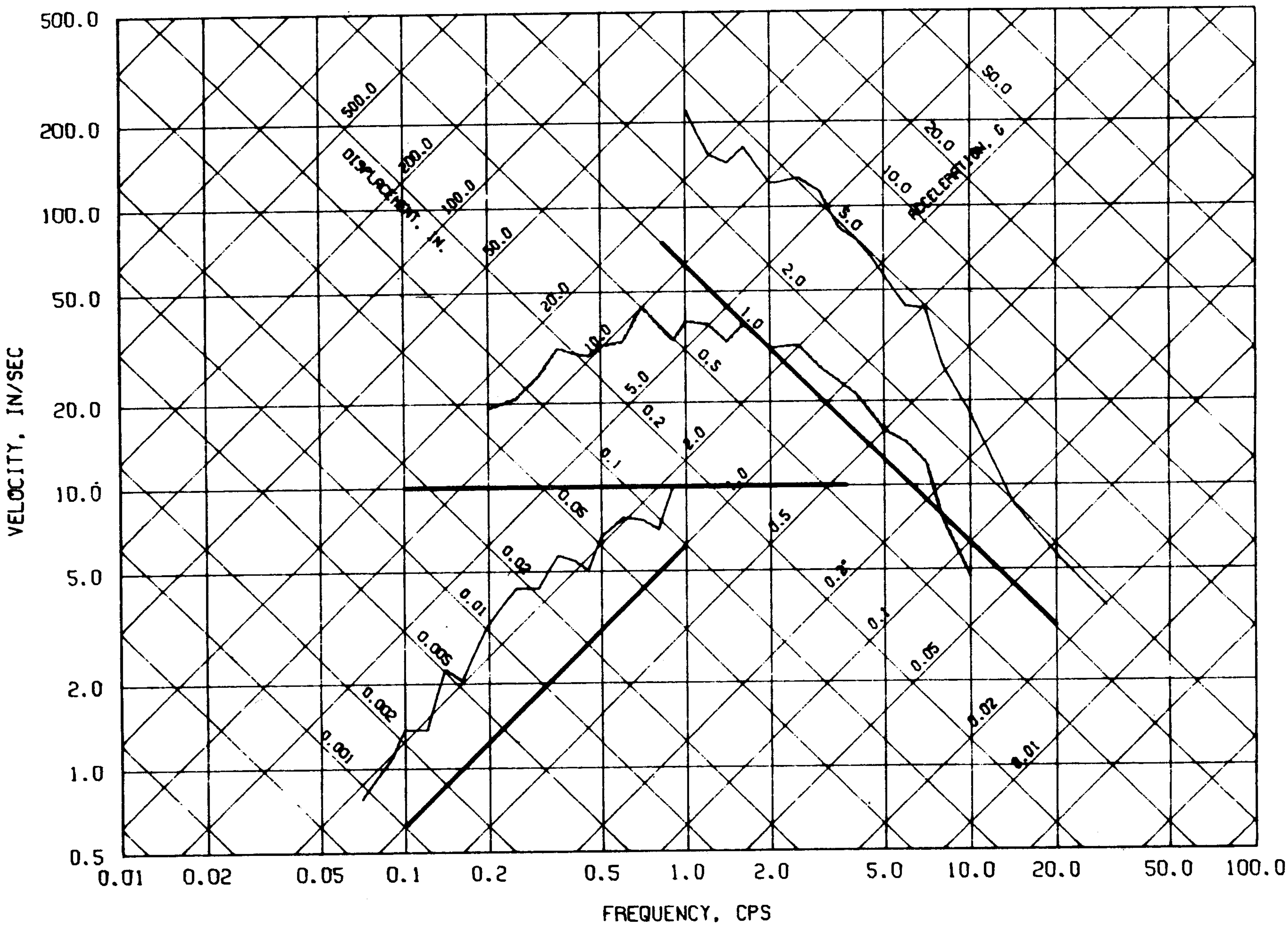


FIG 3.5 75 PERCENTILE RESPONSE AMPLIFICATION - HORIZONTAL COMPONENTS
0.5 PERCENT OF CRITICAL DAMPING

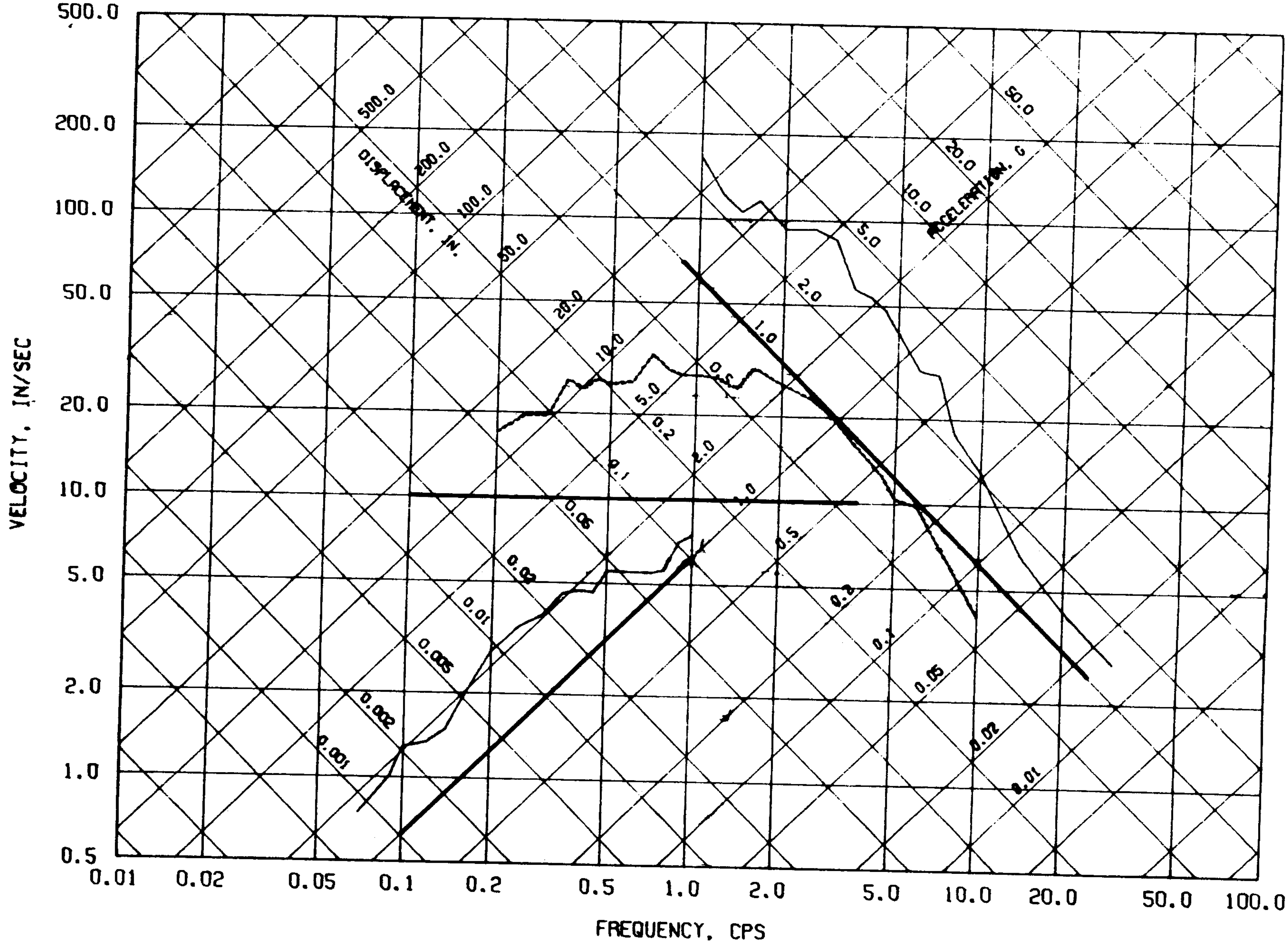


FIG 3.6 75 PERCENTILE RESPONSE AMPLIFICATION - HORIZONTAL COMPONENTS
2.0 PERCENT OF CRITICAL DAMPING

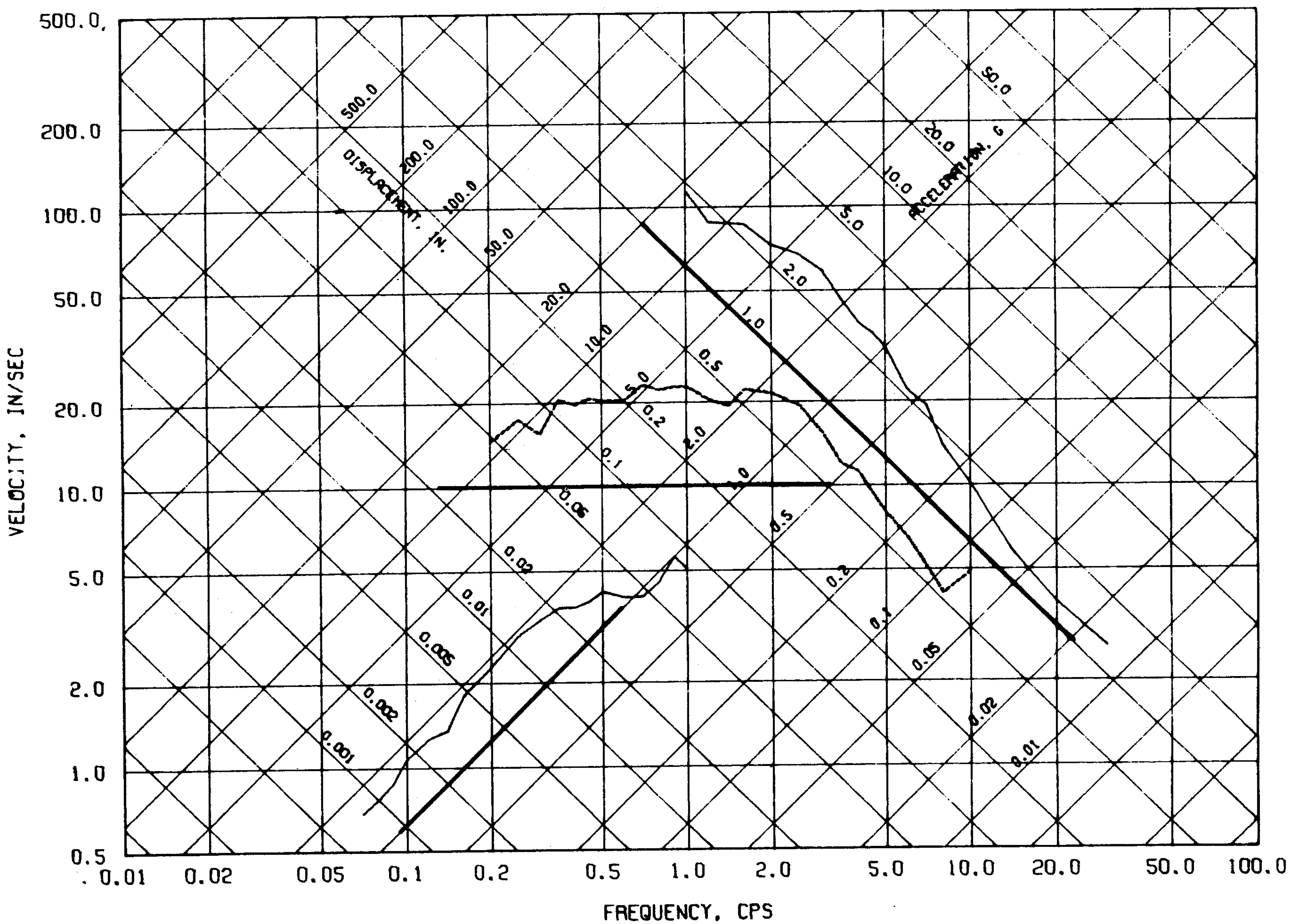


FIG 3.7 75 PERCENTILE RESPONSE AMPLIFICATION - HORIZONTAL COMPONENTS
5.0 PERCENT OF CRITICAL DAMPING

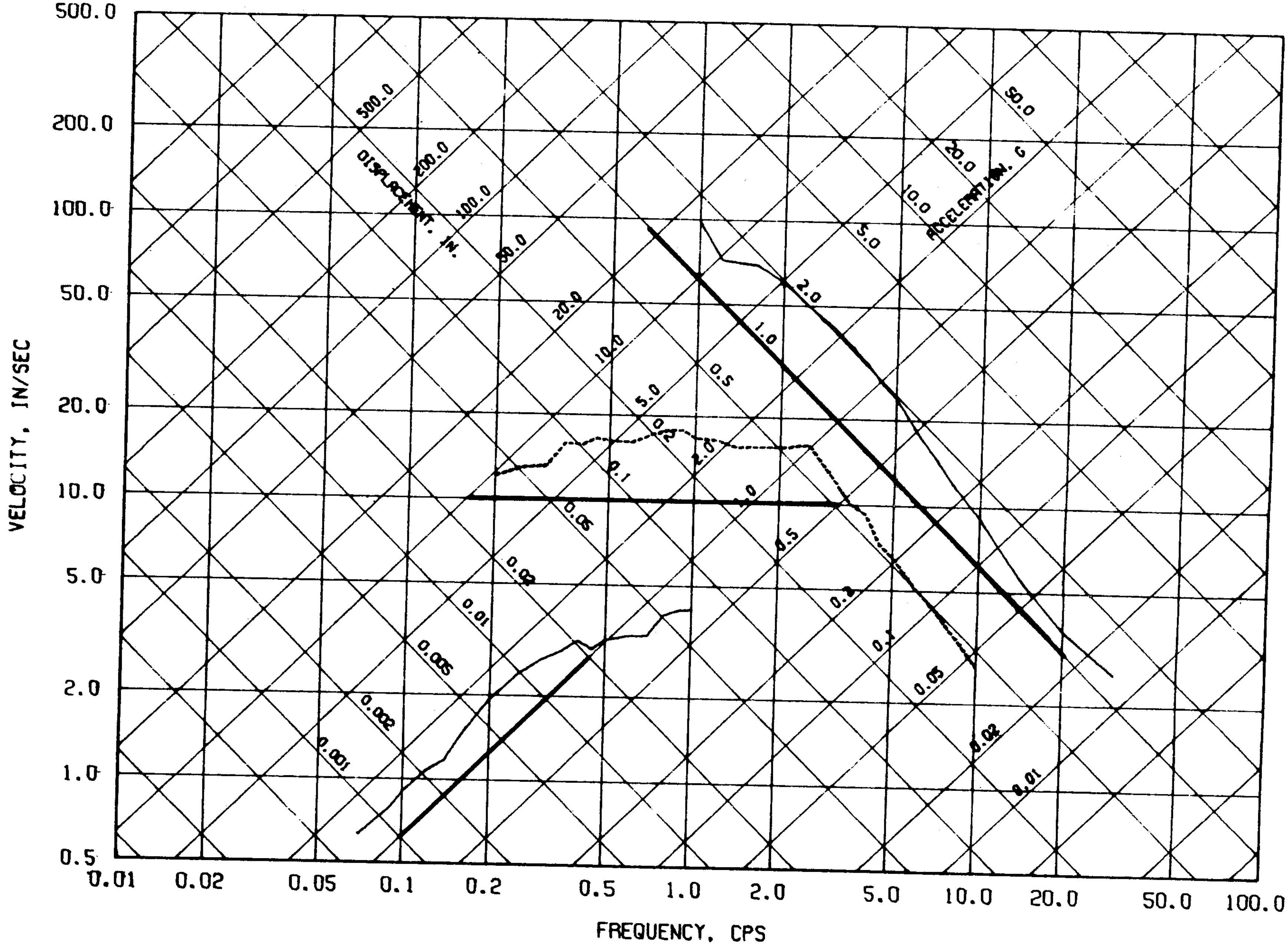


FIG 3.8 75 PERCENTILE RESPONSE AMPLIFICATION - HORIZONTAL COMPONENTS
10.0 PERCENT OF CRITICAL DAMPING

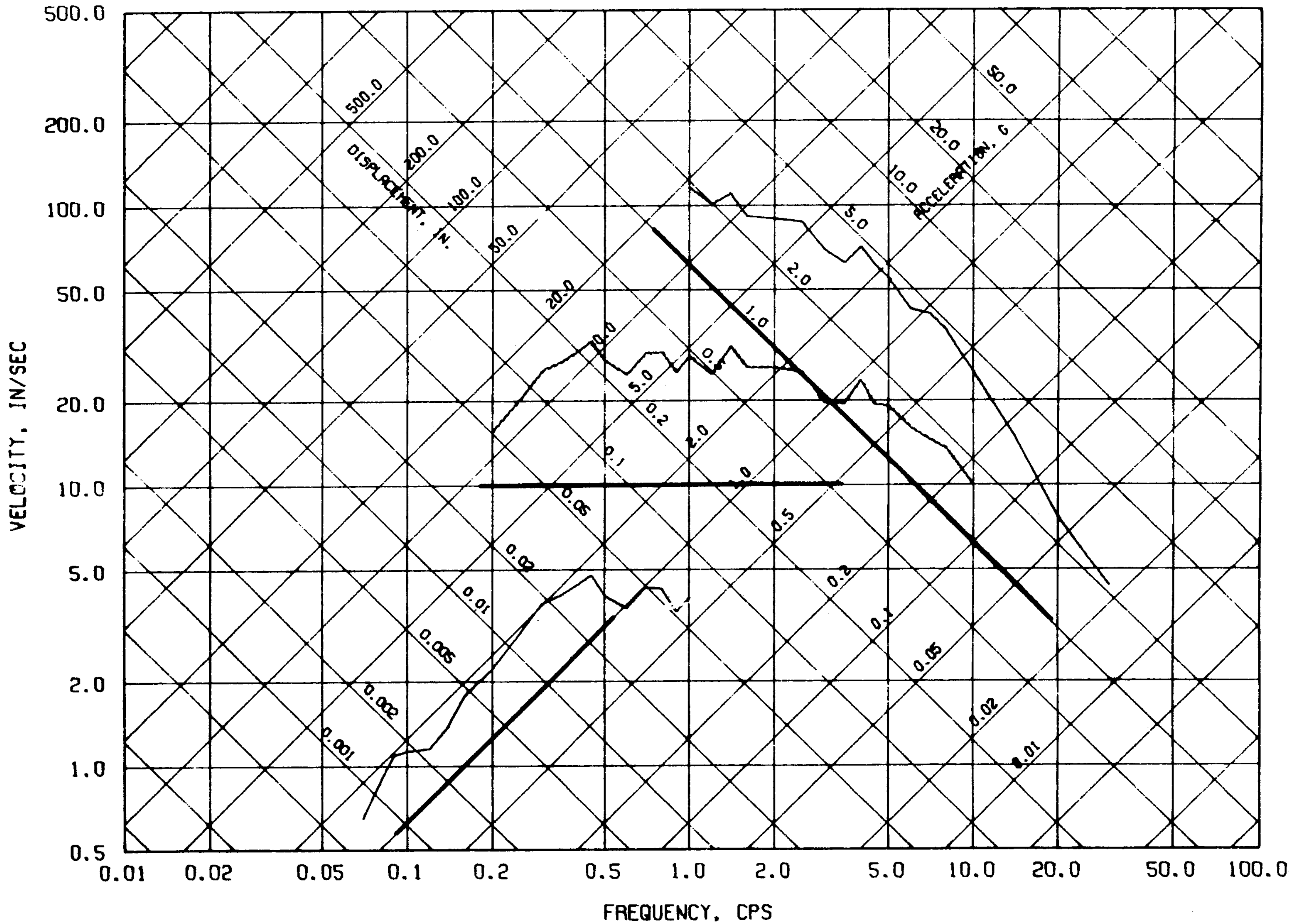


FIG 3.9 MEAN RESPONSE AMPLIFICATION - VERTICAL COMPONENTS
0.5 PERCENT OF CRITICAL DAMPING

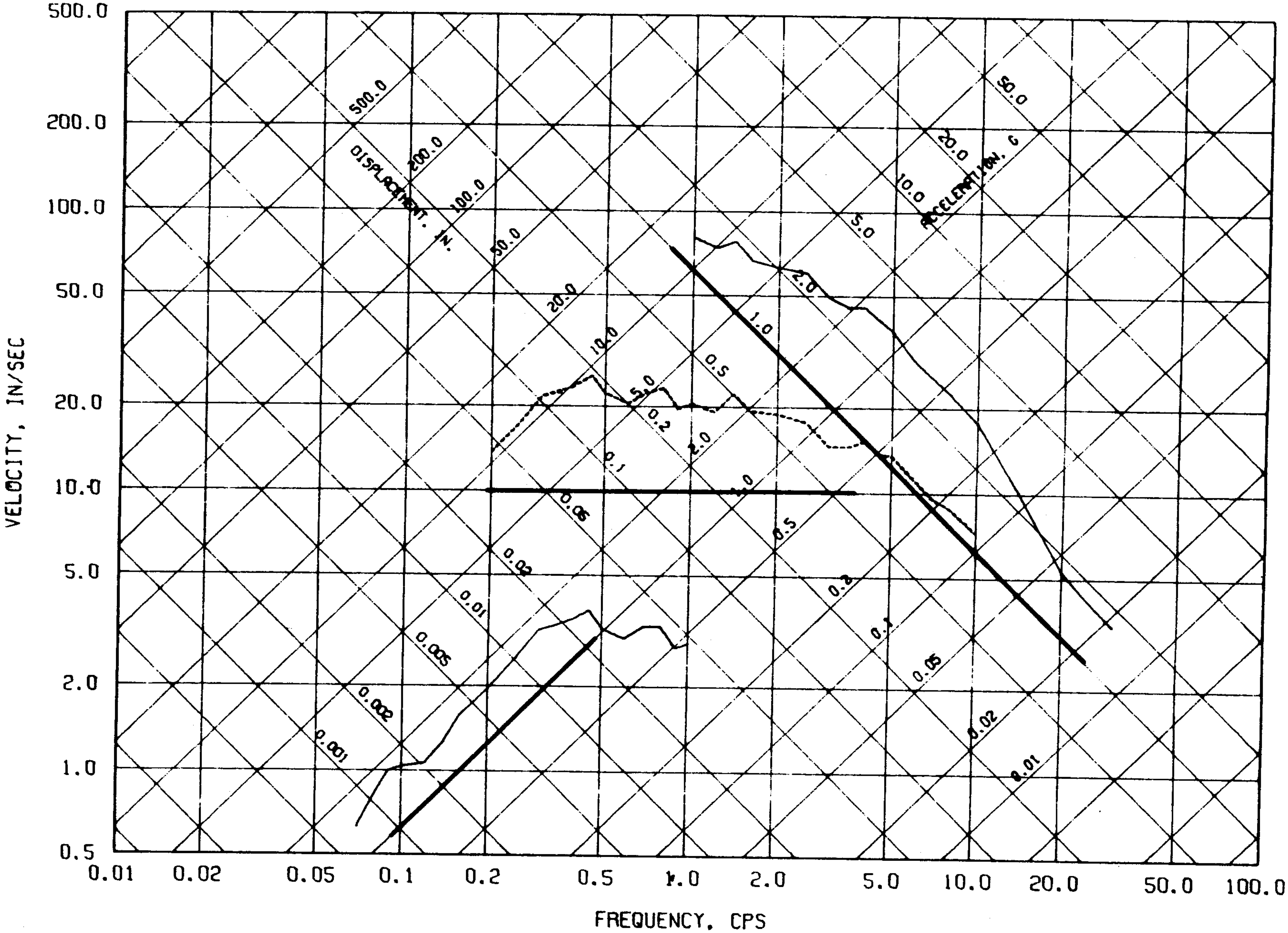


FIG 3.10 MEAN RESPONSE AMPLIFICATION - VERTICAL COMPONENTS
2.0 PERCENT OF CRITICAL DAMPING

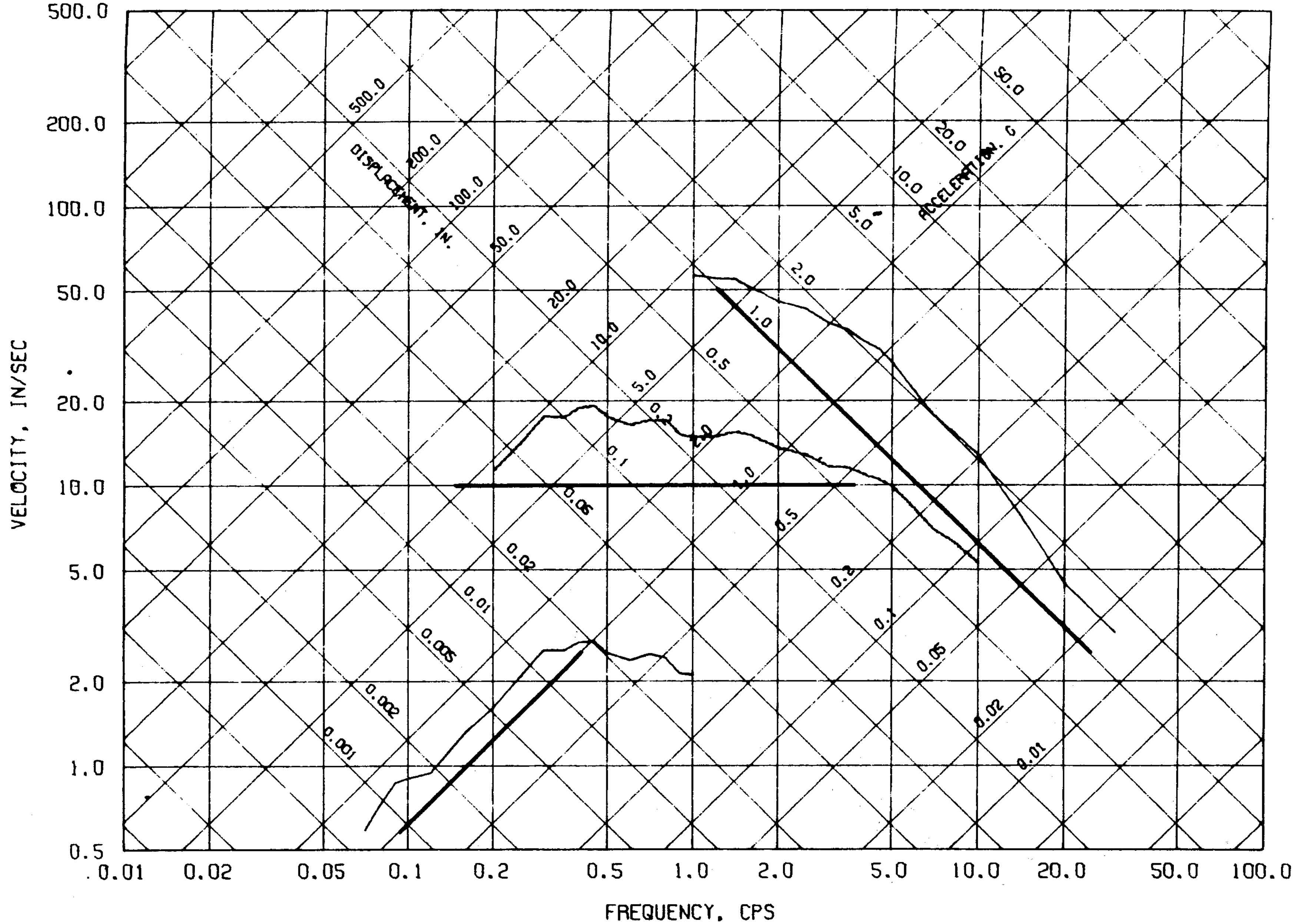


FIG 3.11 MEAN RESPONSE AMPLIFICATION - VERTICAL COMPONENTS
5.0 PERCENT OF CRITICAL DAMPING

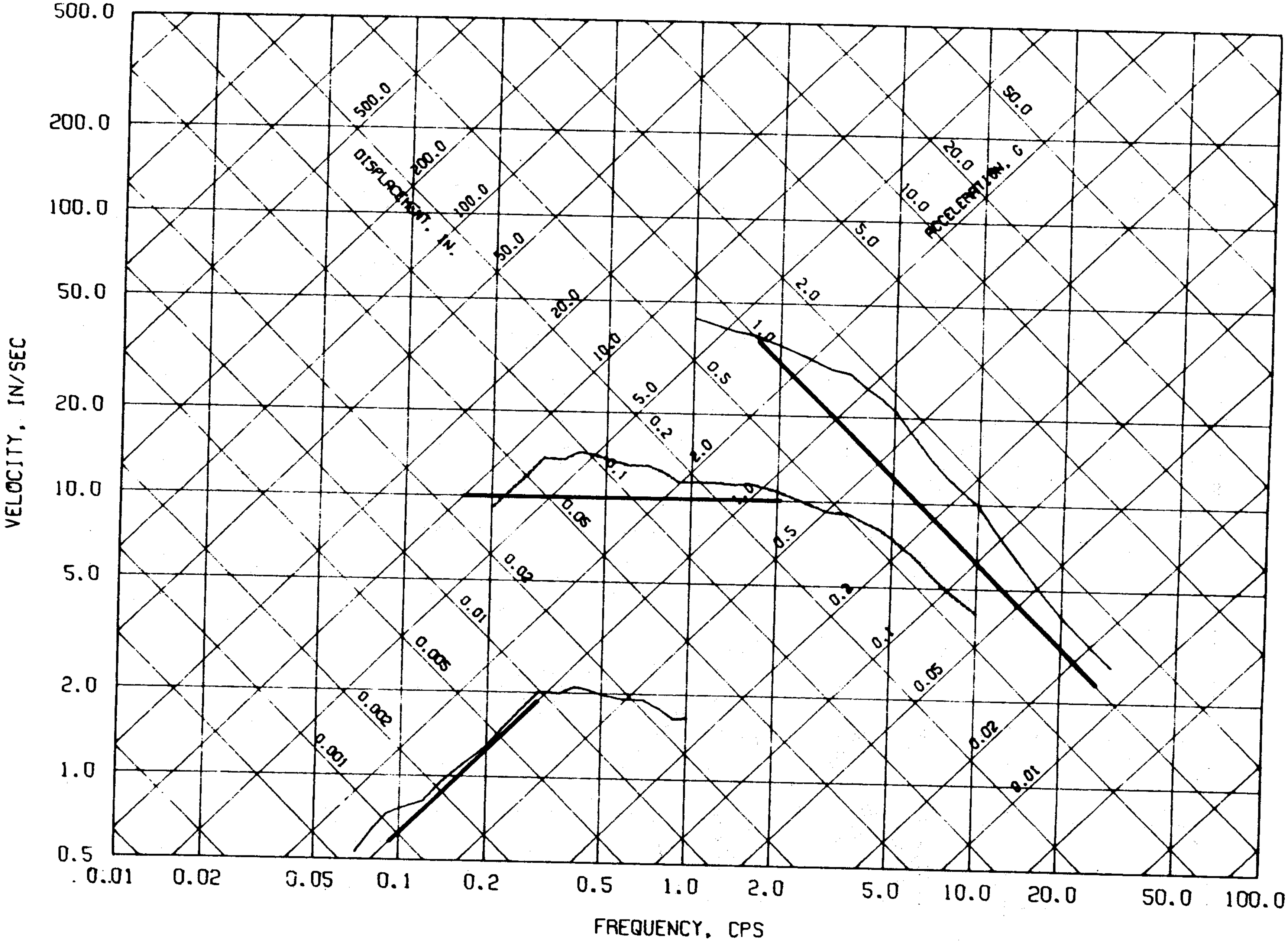


FIG 3.12 MEAN RESPONSE AMPLIFICATION - VERTICAL COMPONENTS
10.0 PERCENT OF CRITICAL DAMPING

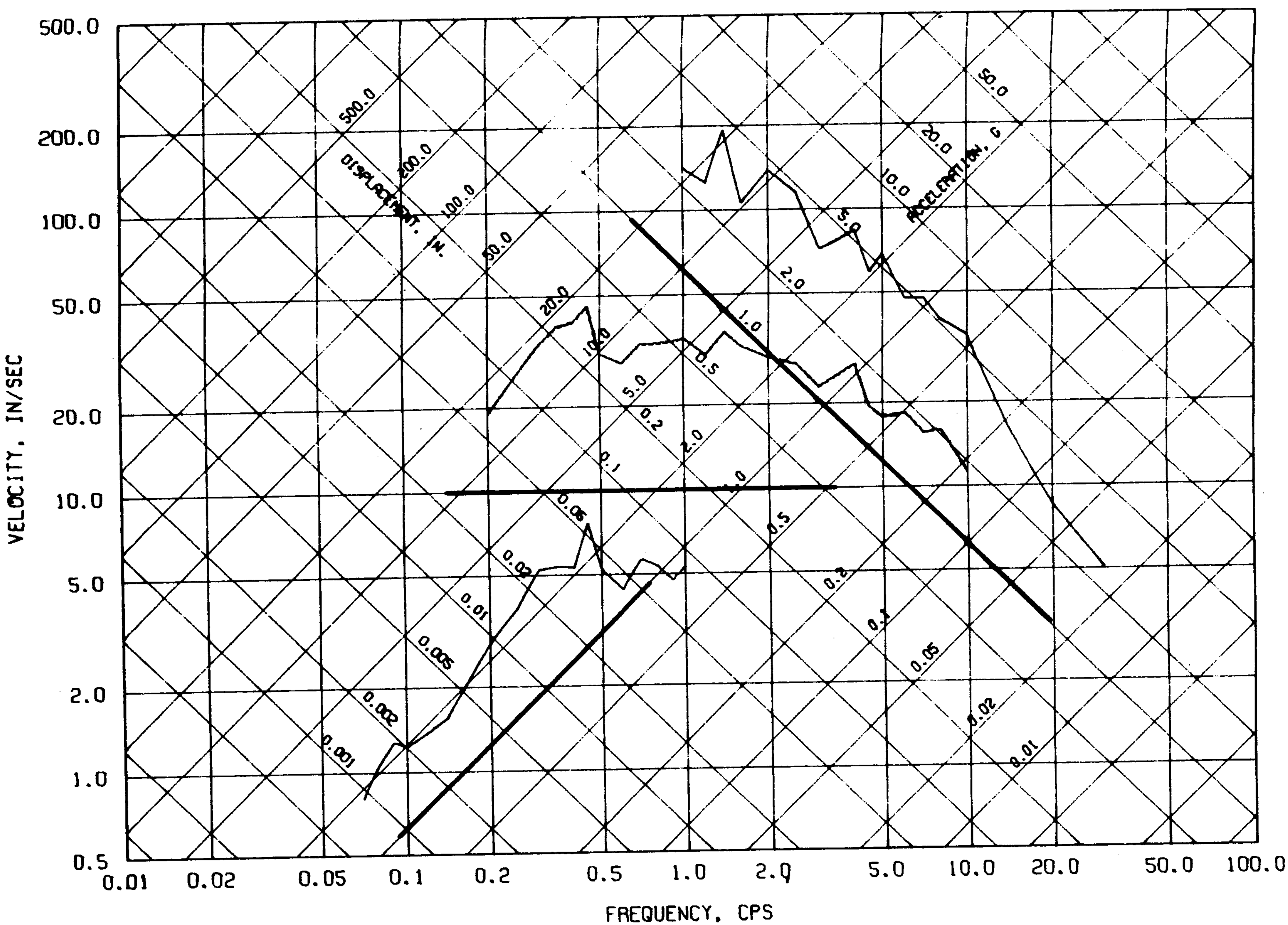


FIG 3.13 75 PERCENTILE RESPONSE AMPLIFICATION - VERTICAL COMPONENTS
0.5 PERCENT OF CRITICAL DAMPING

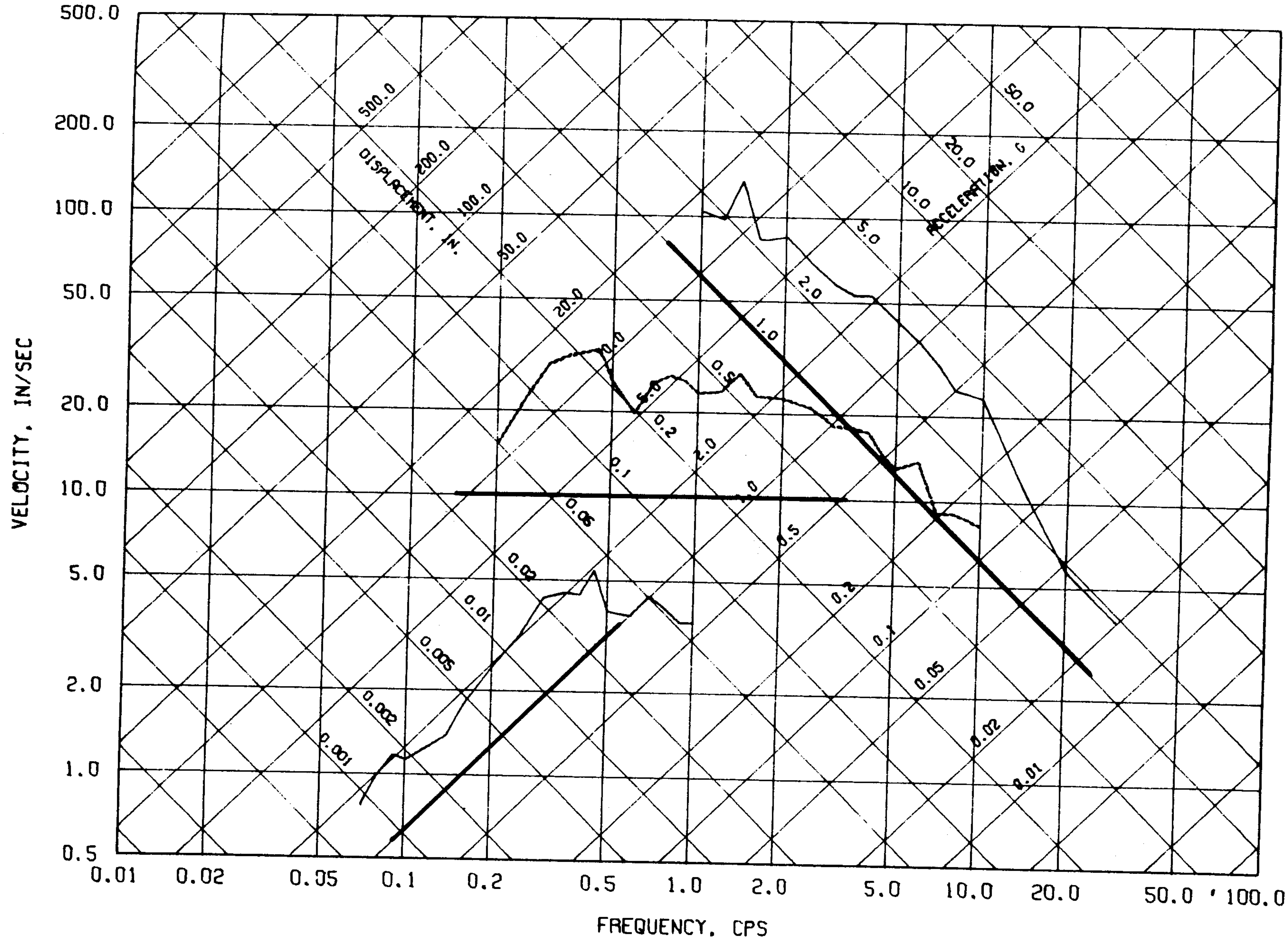


FIG 3.14 75 PERCENTILE RESPONSE AMPLIFICATION - VERTICAL COMPONENTS
2.0 PERCENT OF CRITICAL DAMPING

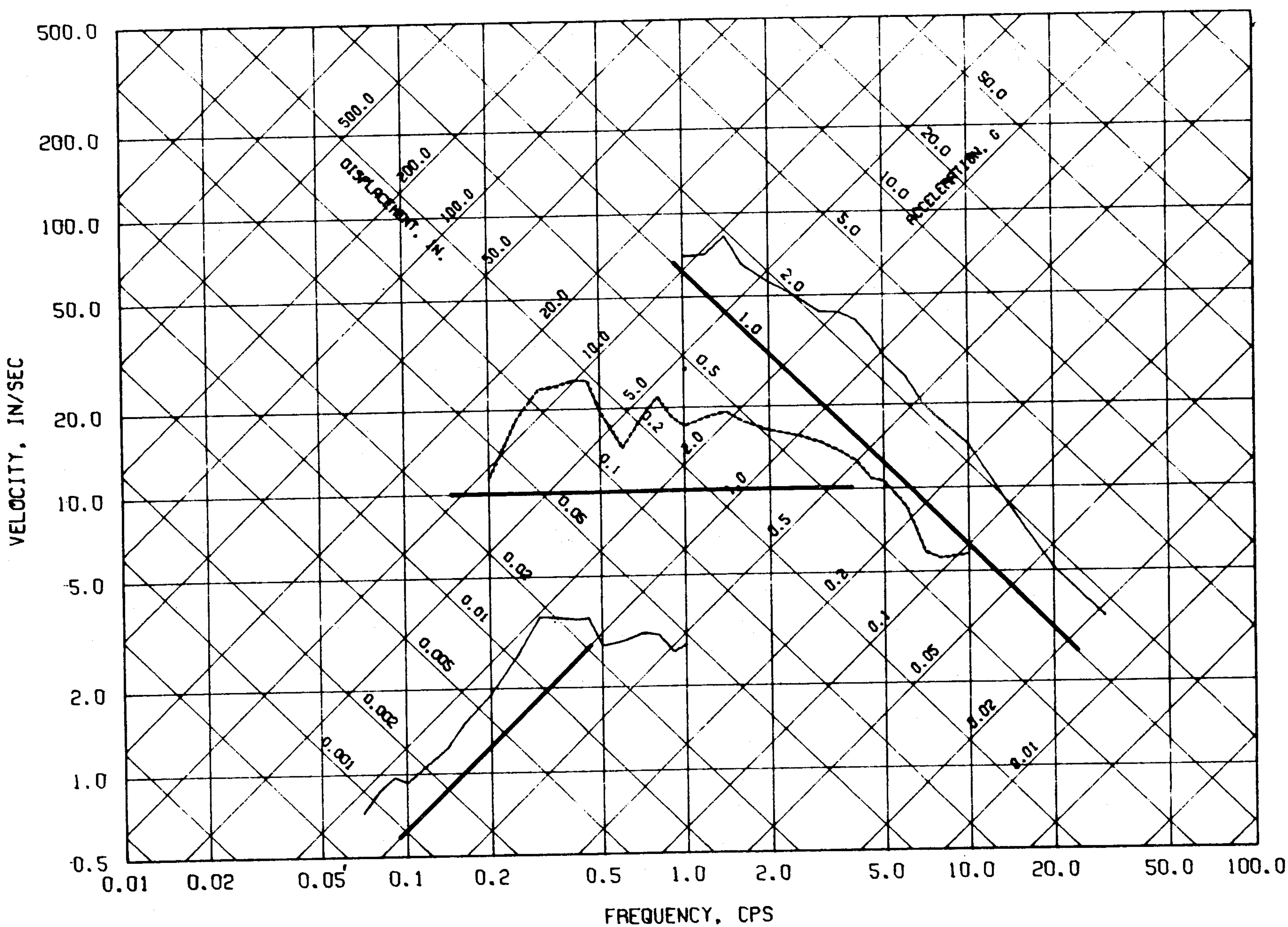


FIG 3.15 75 PERCENTILE RESPONSE AMPLIFICATION - VERTICAL COMPONENTS
5.0 PERCENT OF CRITICAL DAMPING

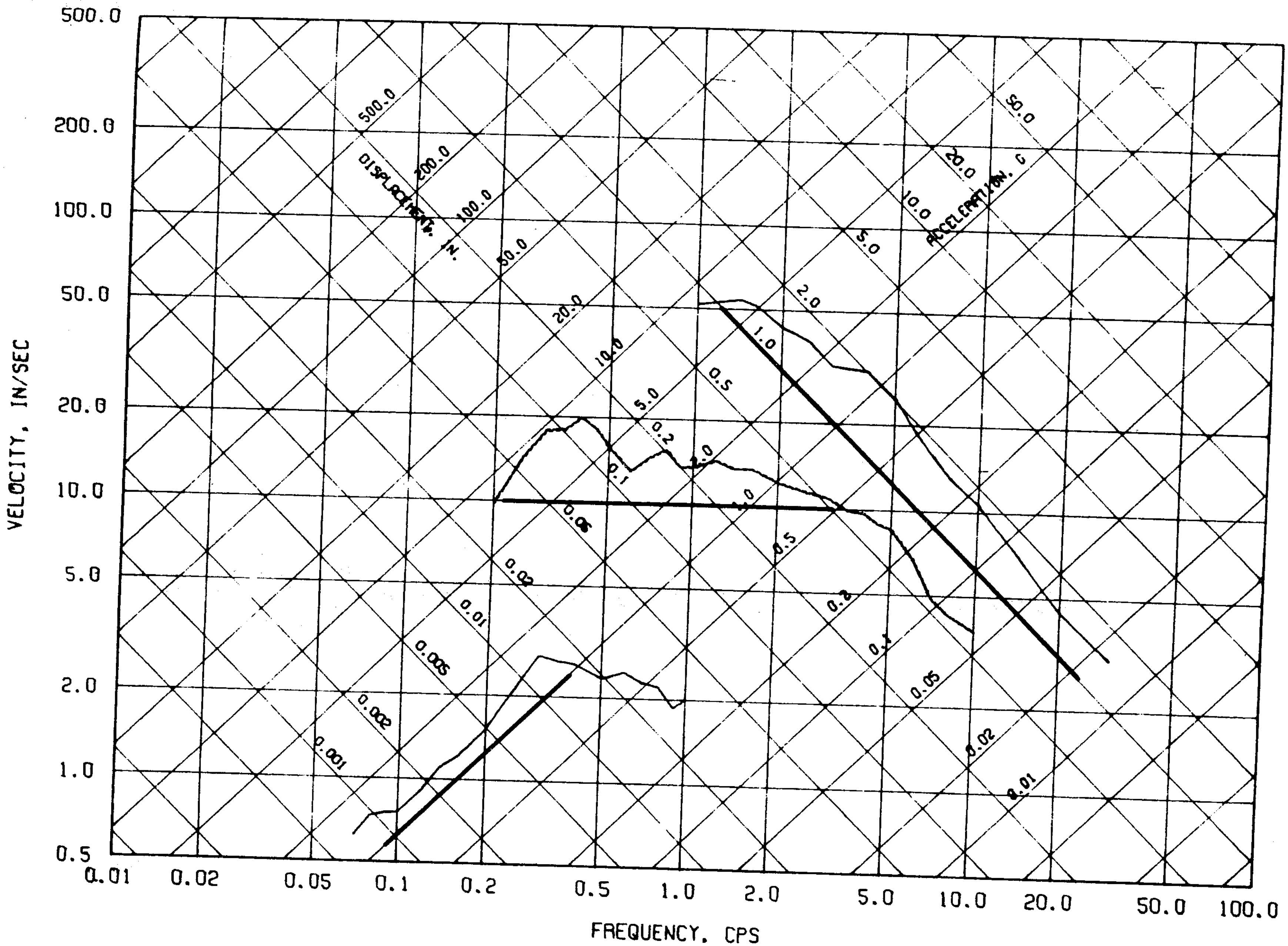


FIG 3.16 75 PERCENTILE RESPONSE AMPLIFICATION - VERTICAL COMPONENTS
10.0 PERCENT OF CRITICAL DAMPING

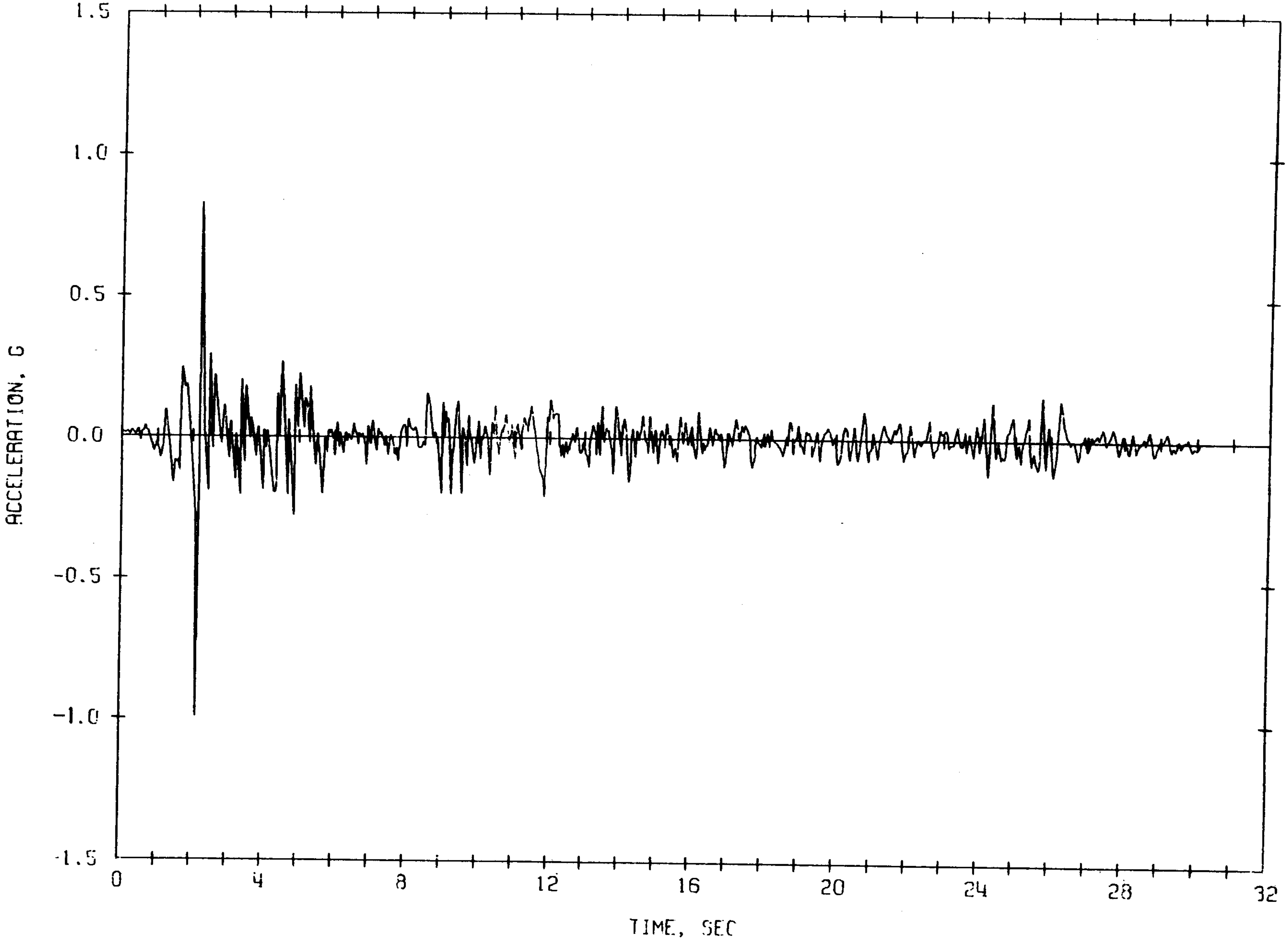


FIG. 3.17 ACCELERATION - TIME HISTORY, EL CENTRO, CALIF., 5/18/1940 - NS
SEGMENTALLY ADJUSTED RECORD - MAXIMUM ACCELERATION OF 1.0 G

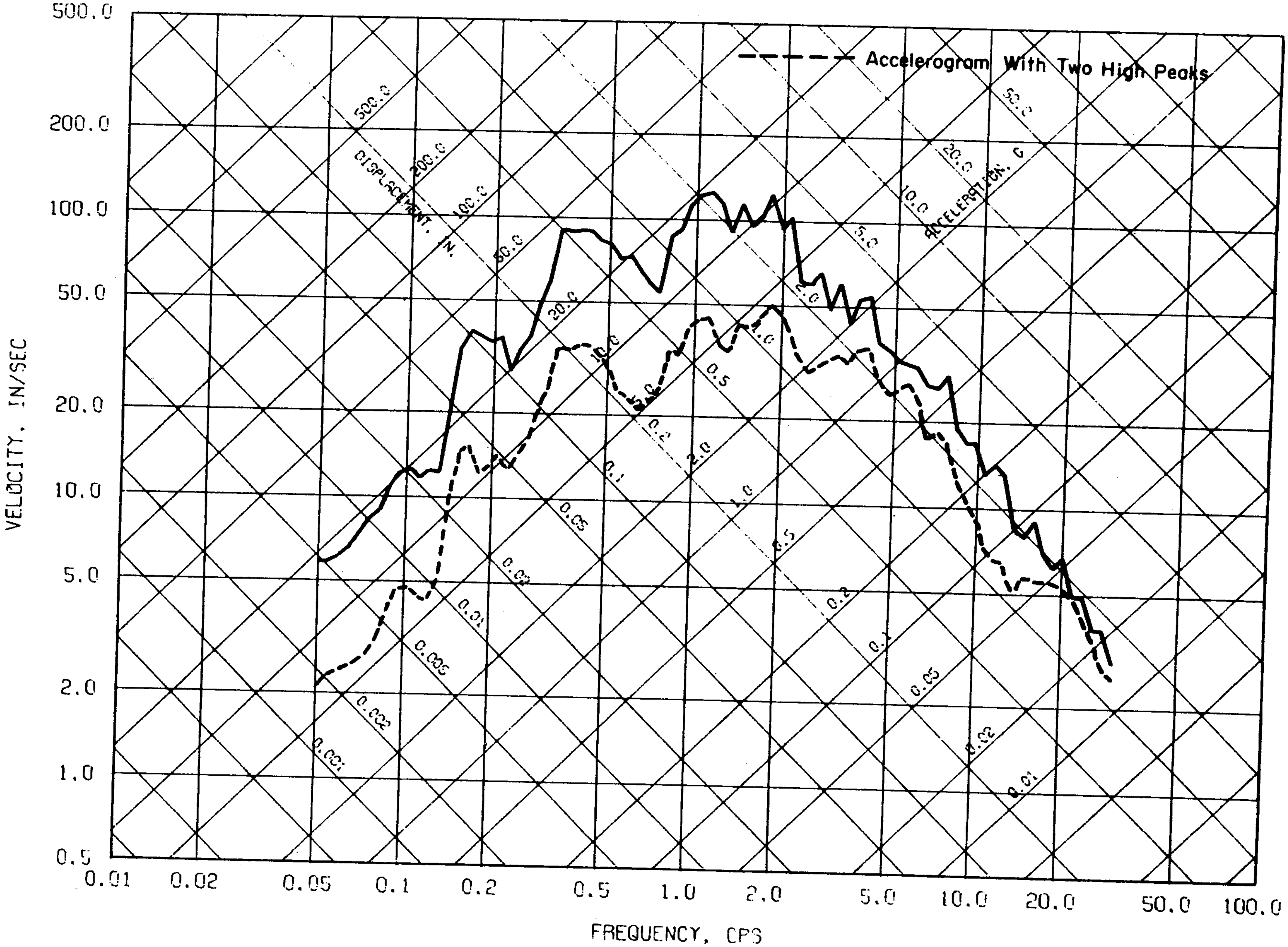


FIG. 3.18 RESPONSE SPECTRA NORMALIZED TO GROUND ACCELERATION FOR EL CENTRO EQ 1940 - NS -- 2.0 PERCENT OF CRITICAL DAMPING

4. DESIGN RECOMMENDATIONS AND CONCLUSIONS

4.1 General

On the basis of the information obtained as a result of the studies summarized in Chapter 3, it is possible to construct design response spectra.[10] In general, the procedure employed is to select the maximum values of the ground motions (acceleration, velocity and displacement) and to plot these on a four-way log plot of frequency, relative displacement, pseudo-velocity and pseudo-acceleration. Next, for each degree of damping and as a function of the percentile amplification limit selected for design, each ground motion bound is multiplied by the appropriate amplification coefficient to obtain the controlling bound in each of the displacement, velocity and acceleration regions. These amplified values are applicable in certain frequency domains. For extreme low and high frequency ranges the response is fared back to the maximum ground motion values.

On the basis of the findings in this study, the recommendations for arriving at the parameters necessary for constructing response spectra follow.

4.2 Ground Motions

ad/v^2 Values

By way of the review, in Table 3.1, there are presented the values of maximum ground acceleration, velocity and displacement as observed from the balanced time-histories for each of the three components of motion of the seismic event studied. In addition, there is recorded for each component of motion the value of ad/v^2, a nondimensional quantity which serves as a good index for monitoring the shape -- especially the breadth -- of the spectra. The values of ad/v^2 range from 1.84 to 30.58

but as noted in Ref. (6) for most cases of seismic events, the values of ad/v^2 are found to range from about 5 to 15, which is the case also for this study. In general it will be noted that the ad/v^2 values are higher for the vertical excitation, as would be expected in part because the high frequency components in the vertical direction are more pronounced than in horizontal directions.

The procedure that was employed to arrive at the average or representative ad/v^2 values was one of computing the value of ad/v^2 for each individual component of a given record and, taking the mean of these values of ad/v^2. Another approach which was examined was that of averaging the values of acceleration, velocity and displacement for the horizontal components and similarly for the vertical components, and then computing the ad/v^2 values from the average values computed. For the horizontal motions, the ad/v^2 values computed by either of the two methods were essentially the same, namely falling between values of 5 and 6. In the case of the vertical components, the ad/v^2 values computed by the former method was about 10.7, whereas the value computed by the latter method was about 7.9. It is believed that the study based on the characteristics of the individual traces is much more meaningful than that based on the characteristics of overall averaging of data without any particular attention to the trace by trace characteristics.

As may be deduced from the discussion in Appendix A, the maximum value of the ground displacement is very sensitive to the adjustment procedure used since it is obtained through double integration of the accelerograms. For this reason, in arriving at recommended bounds of maximum ground motions (acceleration, velocity and displacement) as mentioned in the previous chapter, it is felt that, on the basis of the data in hand and with appreciation of the manner in which they were obtained, the primary emphasis in arriving at the maximum ground motion bounds should be placed upon the acceleration and velocity bounds and a representative value of the ad/v^2. At this point it is desirable to give some attention to the site characteristics, and especially with respect to the ad/v^2 values. For the most part, the data studied were those obtained from alluvial sites and studies of the ad/v^2 values showed (see Table 3.2) that for all sites taken together the ad/v^2 value for horizontal motions was about 5.6; for the alluvial values only (with the three rock sites removed) it was 5.7; and for the three rock sites it was 5.4. In the case of the vertical values, for all 14 sites the average was 10.7; for the alluvial sites excluding three rock sites the value was 10.0; and for the three rock sites it was 13.0. Obviously, on the basis of the number of sites studied and the number of traces involved in drawing conclusions, much more confidence can be placed on the values for the alluvial sites than for the rock values.

As noted earlier in the report, after the study of all the data from the 14 records, it was ascertained that the low intensity data apparently had a significant influence on the amplification values obtained and possibly on the other characteristics associated with the development of design spectra. On this basis it was decided to re-examine the data, casting out all traces which had accelerations less than 0.1g in the case of horizontal motion and 0.05g in the case of vertical excitation. The summary of the ad/v^2 data computed on this basis is presented in Table 3.2, along with the data from the original study. It suffices to say that in the case of the horizontal excitation, the values of ad/v^2 were not changed markedly by the restructuring of the data. In the case of the vertical excitation, the restructured analyses did exhibit a slightly wider variation in values of ad/v^2 from 7.3 to 13.0 as a function of site characteristics, but on the whole were not greatly different than what had been observed earlier.

In summary then, on the basis of the studies just noted for the strong motion data, it would appear that the ad/v^2 values of 6 for the horizontal direction and 10 for the vertical direction are reasonable for both rock and alluvial sites. It is believed that the value of 13 for ad/v^2 in the vertical direction for the three rock sites studied may be high in view of the limited rock data; in any event the "rock sample" is small and a better basis for judgment can only be obtained when more strong motion rock data can be considered.

v/a Ratios

In order to arrive at a basis for estimating the ratio of the velocity to the acceleration, the data summarized in Table 3.4 were studied. It may be observed that the ratio v/a for all data for the horizontal excitation is about 45 in/sec/g for all sites, 52 for just the alluvial sites, and about 22 for the rock sites. Again, it is believed that the limited rock data provide a highly biased value and it would not be recommended that the design values be based on these, at least for the present. On the basis of the study of the data in hand, and reflecting the re-examination of the truly strong motion data as described previously, a v/a value of about 48 in/sec/g is suggested for alluvium and about 28 for rock. The ratio of v/a for the vertical data to that for the horizontal data, Table 3.5, is about 0.90 regardless of site.

a_v/a_h Ratios

A study of the ratio of the ground acceleration in the vertical direction to that in the horizontal direction, Table 3.6, shows a value of about 0.53 for all the data, and there seems to be little difference between that for the alluvial sites alone or the rock data alone. However, for alluvium this ratio increases to 0.65 when earthquake records with a horizontal acceleration greater than 0.1g and a vertical acceleration greater than 0.05g were considered in computations. On this basis then, the acceleration ground value for a given site for the vertical spectrum should be based on an acceleration value of roughly 2/3 that for the horizontal motion and thereafter the velocity bounds should be taken as 2/3 times 0.9 or 0.6 times that of the corresponding value for the horizontal case.

4.3 Amplification of Ground Motion

The expected responses to a given ground motion of a single-degree-of-freedom damped oscillator as a function of frequency, in other words, the response spectra, may be obtained if the amplification values as a function of frequency are known. Amplification data are presented in Tables 3.7-3.10 for various probability percentile values based on normal distribution calculations and also on ranking of the actual data. It will be noted that the differences between the normal distribution calculations and the ranking of data are quite small. A value of 75 percent for ranking means that 75 percent of the values fall at or below that particular amplification value. It is necessary to point out that the amplification values given were calculated on a frequency-by-frequency basis and varied considerably as a function of frequency as discussed in Chapter 2. The frequency band over which the amplifications are presented was selected from a study of the plotted response spectra plots of Figs. 2.10 through 2.51. Each value given was considered to be constant over the frequency range used. In particular, the horizontal accelerations were averaged over a frequency band of 2 to 6 hertz, the horizontal velocity over a frequency range of 0.4 to 2.0 hertz and the displacements over a frequency range of 0.2 to 0.4 hertz. In a like manner, for the vertical acceleration the frequency band over which the amplifications were calculated were 3 to 10 hertz, for the velocity 0.3 to 3 hertz, and for displacement 0.1 to 0.3 hertz.

On the basis of the study of the amplification values and the spectra, it was ascertained that on the high frequency (acceleration) side of the spectrum, for horizontal motions the drop-off of acceleration beyond 6 hertz down to the maximum ground motion value should occur over a frequency span that would lead to a faring to ground acceleration at about 40 hertz for 0.5 percent damping, 30 hertz for 2 percent damping, and 20 hertz for 5 and 10 percent damping. It is appreciated that the data in this high frequency region is not as reliable as might be desired, and these bounds probably require further study.

In the case of the low frequency spectral domain, i.e., in the displacement region, the data indicated a slight decrease as the frequency decreased, as would be expected, because eventually the displacement spectra must fare back to the ground displacement. However, so little data exists on which to base decisions here that for purposes of design at the moment, it is suggested that the constant displacement bounds be carried to 0.05 hertz; such an approximation will not be greatly in error based on our studies to date. In any event, the faring into the ground displacement apparently takes place at a very low frequency.

In the case of the vertical data, it was found that in the high frequency (acceleration) region, carrying the drop-off to 50 hertz for all 4 values of damping (0.5, 2, 5 and 10 percent of critical) seemed to be representative of the data studied. As noted earlier in this report, the data studied did not extend out to a frequency of 50 hertz, but the 50 hertz faring point for the ground acceleration was an extrapolation of the trends of the decreasing acceleration amplification as a function of frequency in the ranges in which the study was conducted.

In the case of the low frequency end of the spectrum for the vertical spectra, just as in the case for the horizontal spectra, it is recommended that the displacement bounds be carried out without decrease to the 0.05 hertz level.

The design amplification factors were computed for damping values of 0.5, 2, 5 and 10 percent of critical. Plots of acceleration, velocity and displacement design amplifications versus percent of critical damping for both the horizontal and vertical components and for various probability levels are shown in Figs. 4.1 through 4.6. The design amplification for any value of damping can be obtained easily from these figures.

4.4 Design Spectra

On the basis of the summary presentations given concerning ad/v^2 values, and acceleration and velocity values for both horizontal and vertical spectra for sites on alluvium and rock, the ground displacement, velocity, acceleration and ad/v^2 values are shown in Table 4.1. The displacement values were calculated on the basis of the ad/v^2 (6 and 10 for horizontal and vertical effects, respectively), the a and v values, and were then rounded to a representative number. For purposes of completeness at this point, the actual ad/v^2 value was computed and is tabulated; it will be seen that for the horizontal case these are nearly 6 and for the vertical case nearly 10.

The next step in arriving at response spectrum bounds is to select the appropriate amplification value and multiply this by the appropriate ground motion parameters. The amplification values derived as a part of this study are presented in Tables 4.2 and 4.3 for horizontal and vertical components, respectively. The amplification values in Tables 4.2 and 4.3 are the same as those presented in Tables 3.7 and 3.8 for accelerations greater than 0.1g horizontal and 0.05g vertical. Tables 4.2 and 4.3 also include amplification factors for mean plus one and plus two standard deviations based on a normal distribution. The spectrum bounds given in Tables 4.2 and 4.3 are obtained by multiplying the ground motion values of Table 4.1 by the appropriate amplification values. The faring frequencies given in Tables 4.2 and 4.3 are in accordance with those discussed in Section 4.3. The response spectra based on the tabulated values for 50, 75, and 90 percentile are presented in Figs. 4.7 through 4.18.

4.5 Combined Effects

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.

Hence 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 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).

4.6 Recommendations for Future Studies

Although the data studied in this project are believed to be representative, it should be obvious that there was a limited amount of data available for rock sites. Also, we have indicated the importance of studying high intensity "strong motion" data and not having these intermixed with lower intensity data. For these reasons, it would be our recommendation that there be a further study of a broader spectrum of data, for both low and high intensities, to define more clearly the ranges in ground motion bounds and amplification factors that may occur as a function of the intensity of the ground motion and the site characteristics.

Table 4.1 Horizontal and Vertical Design Ground Motions

Site	Direction	Acceleration a, g	Velocity v, in/sec	Displacement d, in	ad/v^2
alluvium	horizontal	1.0	48	36	6.04
rock	horizontal	1.0	28	12	5.92
alluvium	vertical	2/3	29	33	10.10
rock	vertical	2/3	17	11	9.80

Table 4.2

Horizontal Design Spectra Amplifications and Bounds

Percentile	Damping percent	Amplification D	Amplification V	Amplification A	Faring frequency hertz	Spectrum bounds (alluvium) D in	Spectrum bounds (alluvium) V in/sec	Spectrum bounds (alluvium) A g	Spectrum bounds (rock) D in	Spectrum bounds (rock) V in/sec	Spectrum bounds (rock) A g
50	0.5	1.97	2.58	3.67	40	71	124	3.67	24	72	3.67
	2.0	1.68	2.06	2.76	30	60	99	2.76	20	58	2.76
	5.0	1.40	1.66	2.11	20	50	80	2.11	17	46	2.11
	10.0	1.15	1.34	1.65	20	41	64	1.65	14	38	1.65
75	0.5	2.66	3.41	4.65	40	96	164	4.65	32	95	4.65
	2.0	2.24	2.68	3.36	30	81	129	3.36	27	75	3.36
	5.0	1.83	2.10	2.48	20	66	101	2.48	22	59	2.48
	10.0	1.47	1.66	1.89	20	53	80	1.89	18	46	1.89
84.1 (1 σ)	0.5	2.99	3.81	5.12	40	108	183	5.12	36	107	5.12
	2.0	2.51	2.98	3.65	30	90	143	3.65	30	83	3.65
	5.0	2.04	2.32	2.67	20	73	111	2.67	25	65	2.67
	10.0	1.62	1.81	2.01	20	58	87	2.01	19	51	2.01
90	0.5	3.28	4.16	5.53	40	118	200	5.53	39	116	5.53
	2.0	2.74	3.23	3.90	30	99	155	3.90	33	90	3.90
	5.0	2.21	2.51	2.82	20	80	120	2.82	27	70	2.82
	10.0	1.75	1.94	2.11	20	63	93	2.11	21	54	2.11
95	0.5	3.65	4.60	6.05	40	131	220	6.05	44	129	6.05
	2.0	3.04	3.57	4.22	30	109	171	4.22	36	100	4.22
	5.0	2.44	2.75	3.03	20	88	132	3.03	29	77	3.03
	10.0	1.91	2.11	2.24	20	69	101	2.24	23	59	2.24
97.7 (2 σ)	0.5	4.01	5.04	6.57	40	144	242	6.57	48	141	6.57
	2.0	3.34	3.89	4.54	30	120	187	4.54	40	109	4.54
	5.0	2.67	2.98	3.23	20	96	143	3.23	32	83	3.23
	10.0	2.08	2.28	2.37	20	75	109	2.37	25	64	2.37

Ground motions	a, g	v, in/sec	d, in
alluvium	1.0	48	36
rock	1.0	28	12

Table 4.3

Vertical Design Spectra Amplifications and Bounds

Percentile	Damping percent	Amplification D	Amplification V	Amplification A	Faring frequency hertz	Spectrum bounds (alluvium) D in	Spectrum bounds (alluvium) V in/sec	Spectrum bounds (alluvium) A g	Spectrum bounds (rock) D in	Spectrum bounds (rock) V in/sec	Spectrum bounds (rock) A g
50	0.5	1.86	2.52	4.02	50	61	73	2.68	20	43	2.68
	2.0	1.65	1.97	2.80	50	54	57	1.87	18	33	1.87
	5.0	1.40	1.51	2.05	50	46	44	1.37	15	26	1.37
	10.0	1.16	1.17	1.59	50	38	34	1.06	13	20	1.06
75	0.5	2.48	3.39	5.46	50	82	98	3.64	27	58	3.64
	2.0	2.17	2.61	3.70	50	72	76	2.47	24	44	2.47
	5.0	1.81	1.97	2.57	50	60	57	1.71	20	33	1.71
	10.0	1.47	1.49	1.92	50	49	43	1.28	16	25	1.28
84.1 (1 σ)	0.5	2.78	3.81	6.15	50	92	110	4.10	31	65	4.10
	2.0	2.41	2.91	4.13	50	80	84	2.75	27	49	2.75
	5.0	2.01	2.18	2.82	50	66	63	1.88	22	37	1.88
	10.0	1.62	1.64	2.08	50	54	48	1.09	18	28	1.09
90	0.5	3.04	4.17	6.76	50	100	121	4.51	33	71	4.51
	2.0	2.63	3.18	4.51	50	87	92	3.01	29	54	3.01
	5.0	2.18	2.37	3.04	50	72	69	2.03	24	40	2.03
	10.0	1.75	1.78	2.22	50	58	52	1.48	19	30	1.48
95	0.5	3.37	4.64	7.53	50	111	134	5.02	37	79	5.02
	2.0	2.91	3.52	4.99	50	96	102	3.32	32	60	3.32
	5.0	2.40	2.62	3.32	50	79	76	2.21	26	45	2.21
	10.0	1.92	1.95	2.40	50	63	57	1.60	21	33	1.60
97.7 (2 σ)	0.5	3.70	5.09	8.29	50	122	147	5.52	41	86	5.52
	2.0	3.18	3.86	5.46	50	105	112	3.64	35	66	3.64
	5.0	2.62	2.85	3.60	50	87	83	2.40	29	48	2.40
	10.0	2.09	2.11	2.58	50	69	61	1.72	23	36	1.72

Ground motions	a, g	v, in/sec	d, in
alluvium	2/3	29	33
rock	2/3	17	11

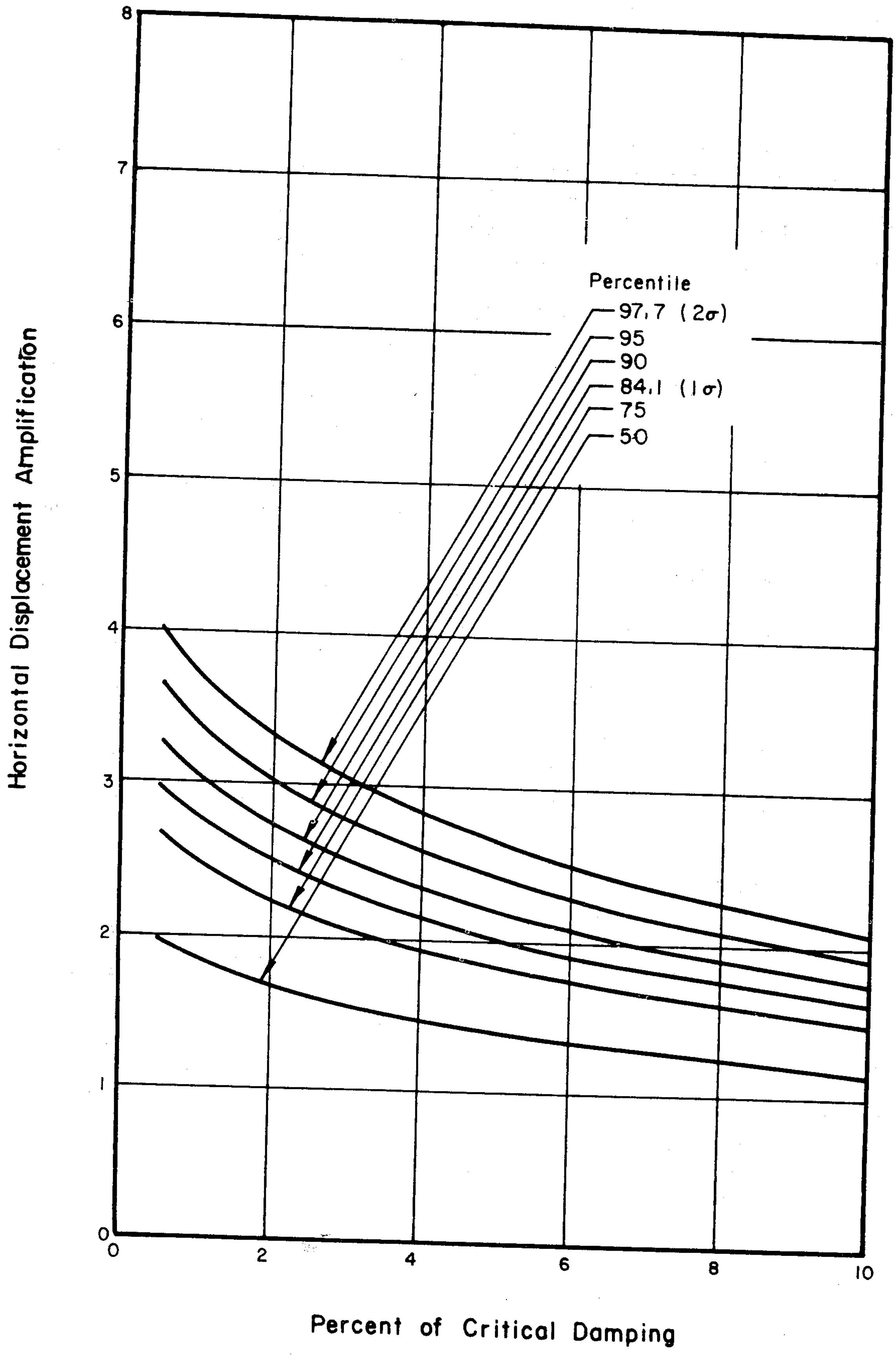


FIG. 4.1 DESIGN AMPLIFICATIONS

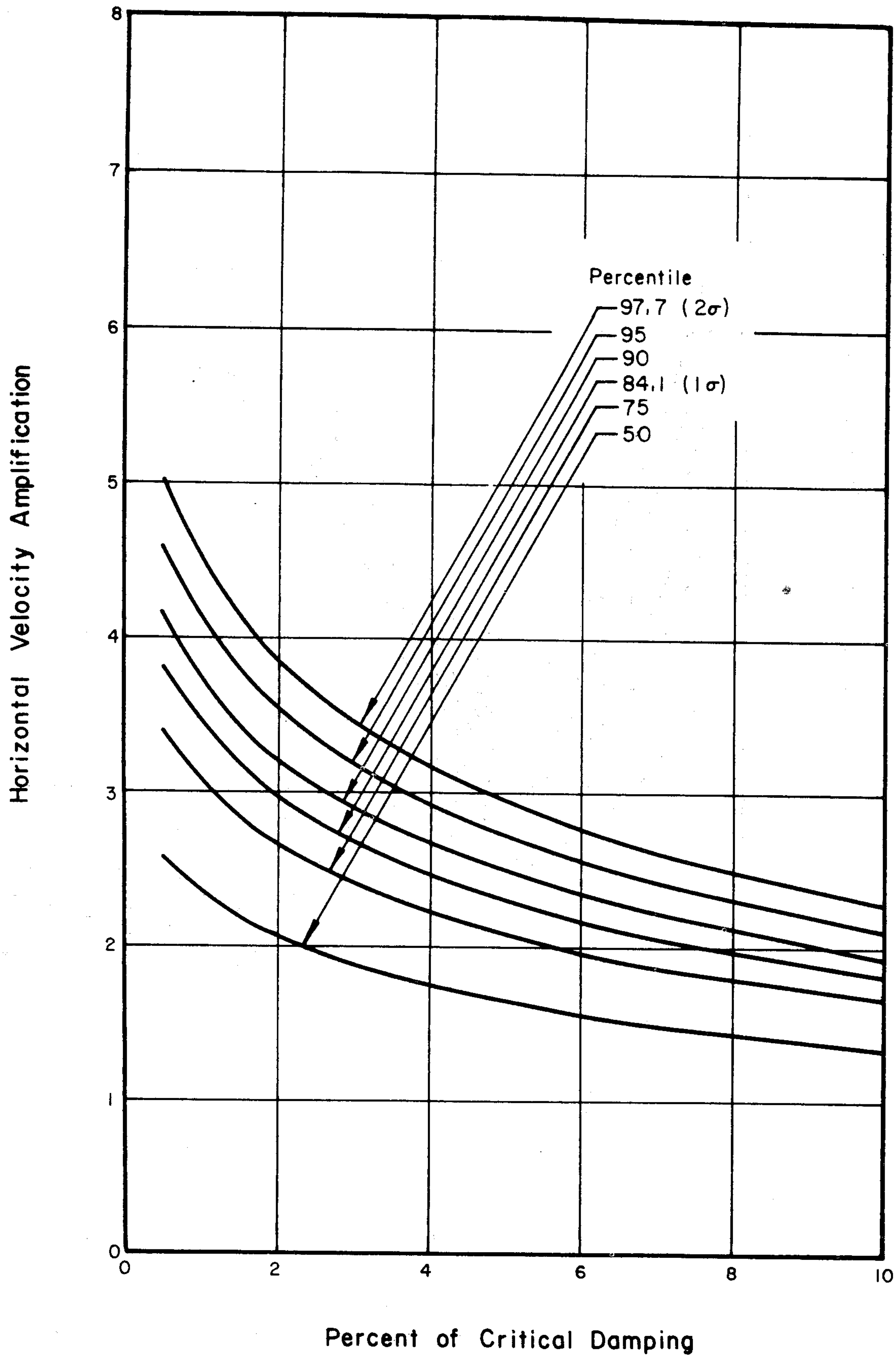
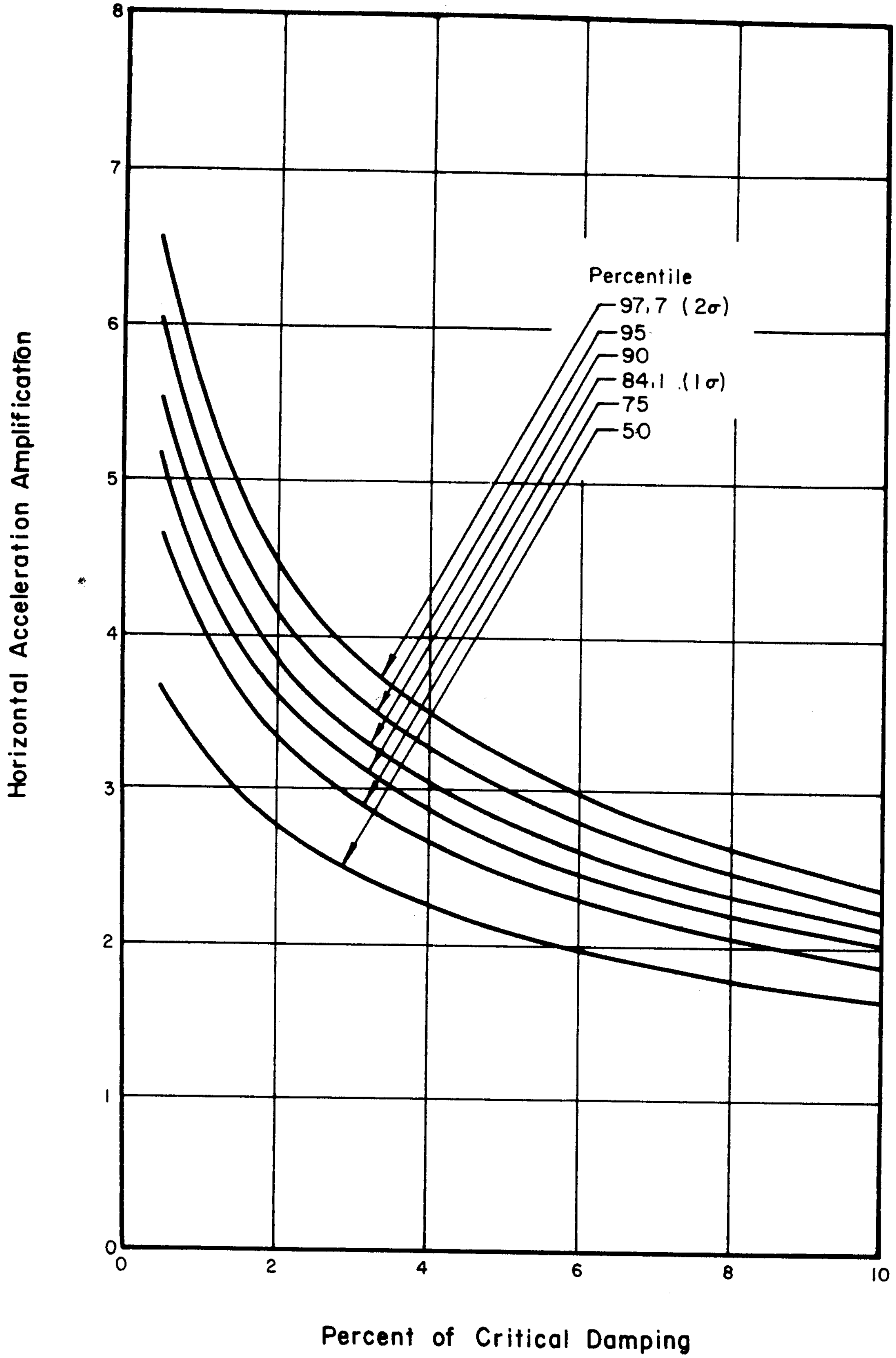


FIG. 4.2 DESIGN AMPLIFICATIONS



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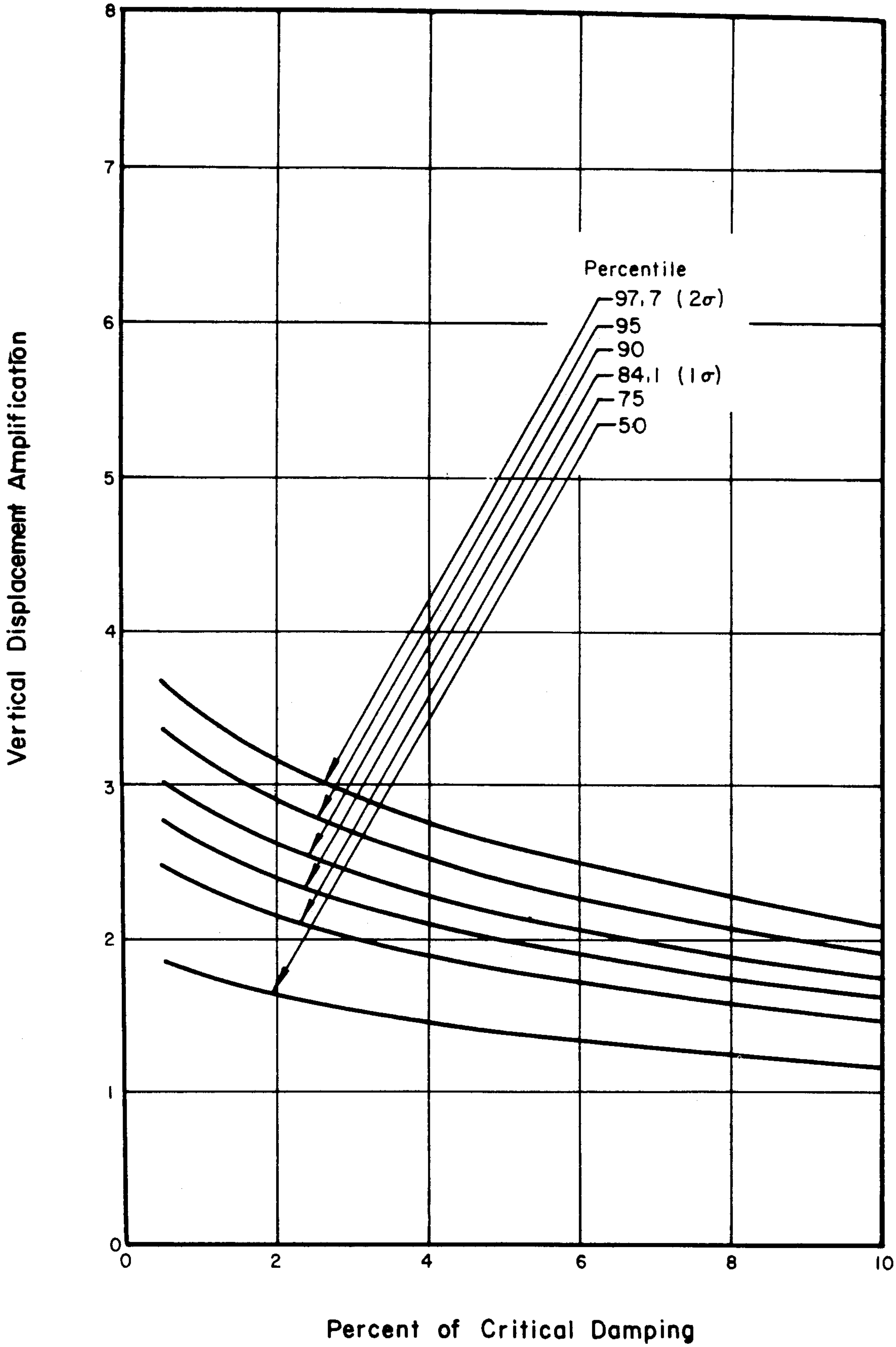

FIG. 4.4 DESIGN AMPLIFICATIONS

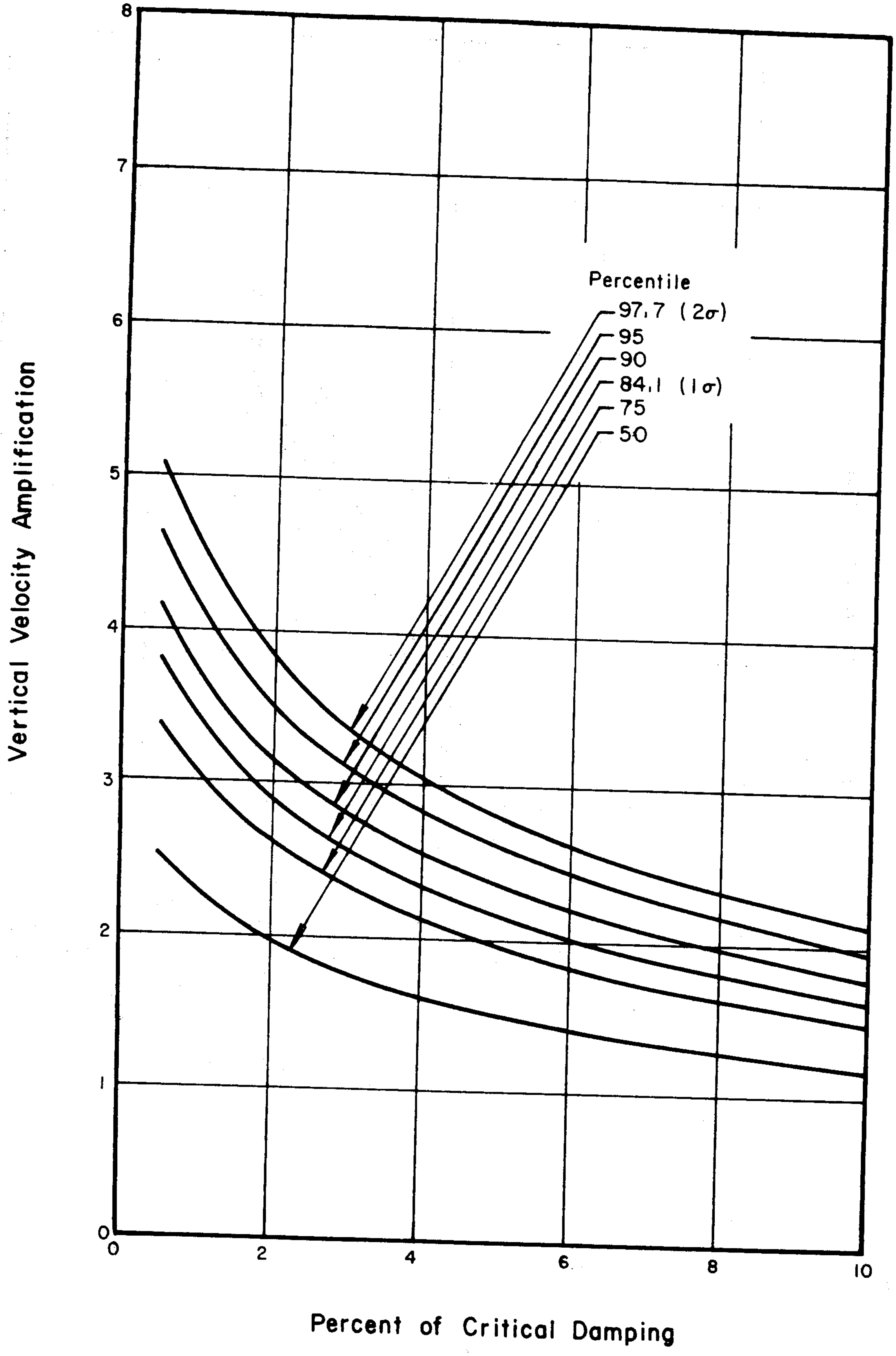

FIG. 4.5 DESIGN AMPLIFICATIONS

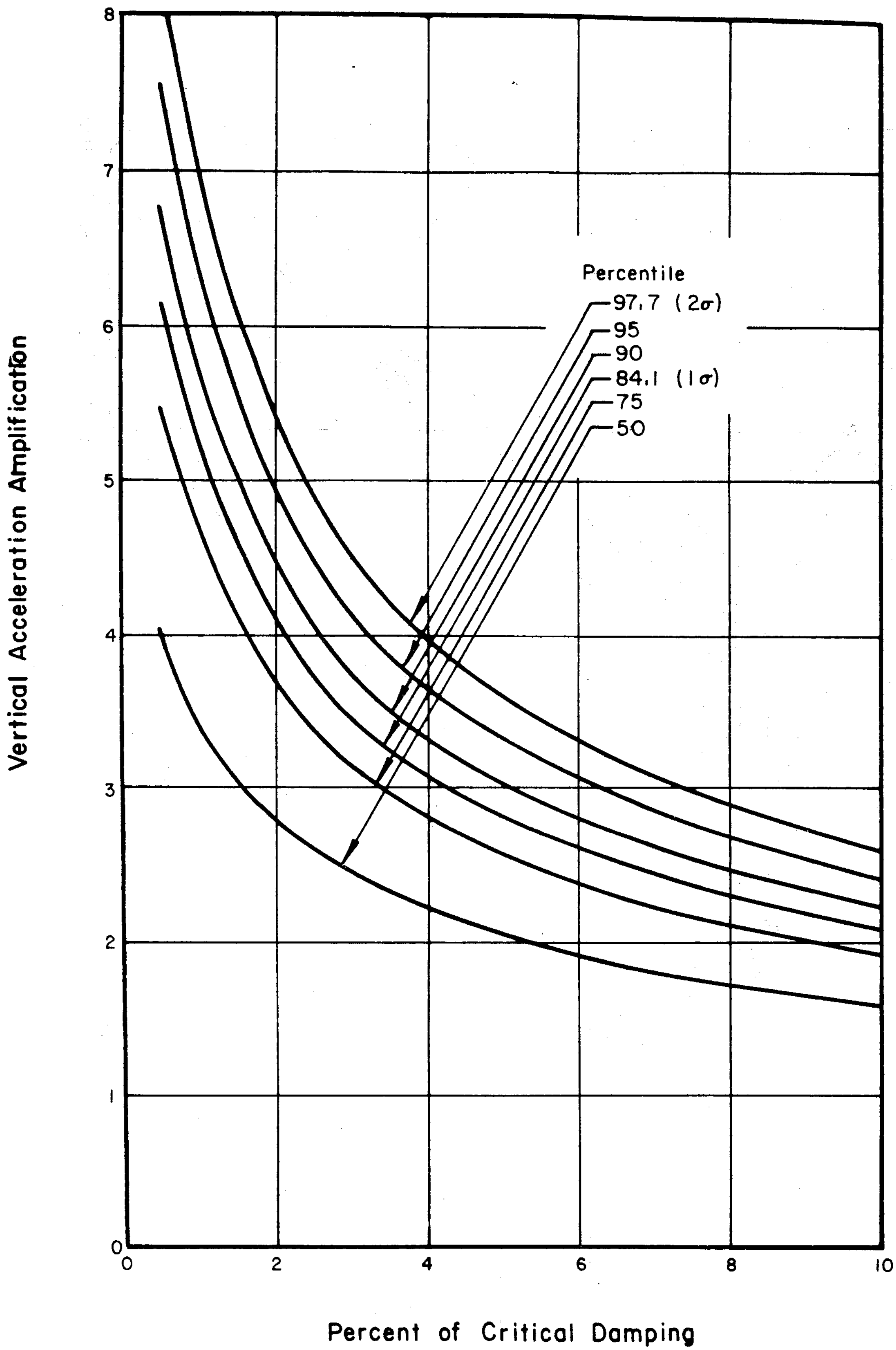

FIG. 4.6 DESIGN AMPLIFICATIONS

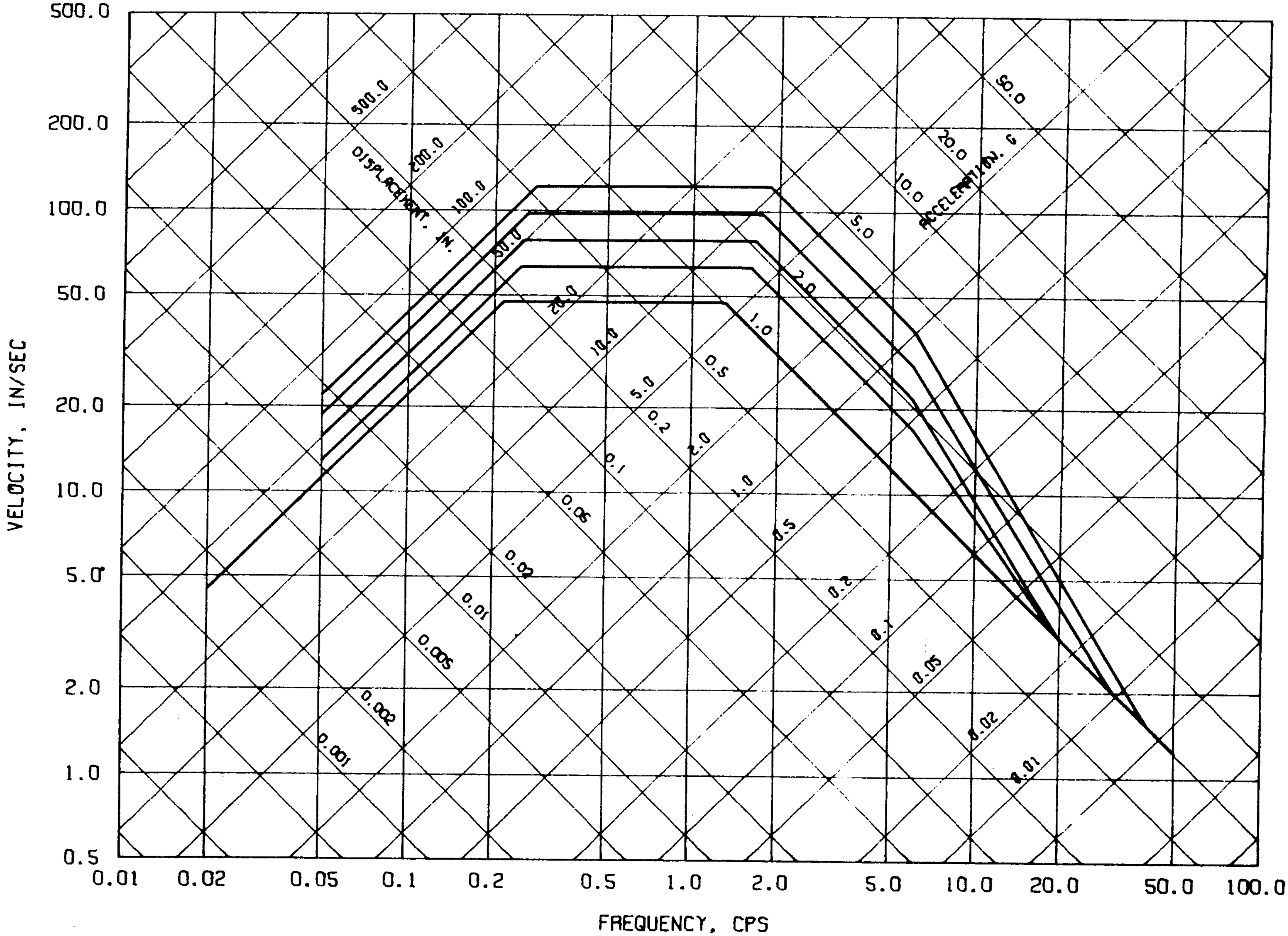

FIG. 4.7 DESIGN SPECTRA, HORIZONTAL DIRECTION, ALLUVIUM, 50 PERCENTILE 0.5, 2, 5, & 10 PERCENT CRITICAL DAMPING

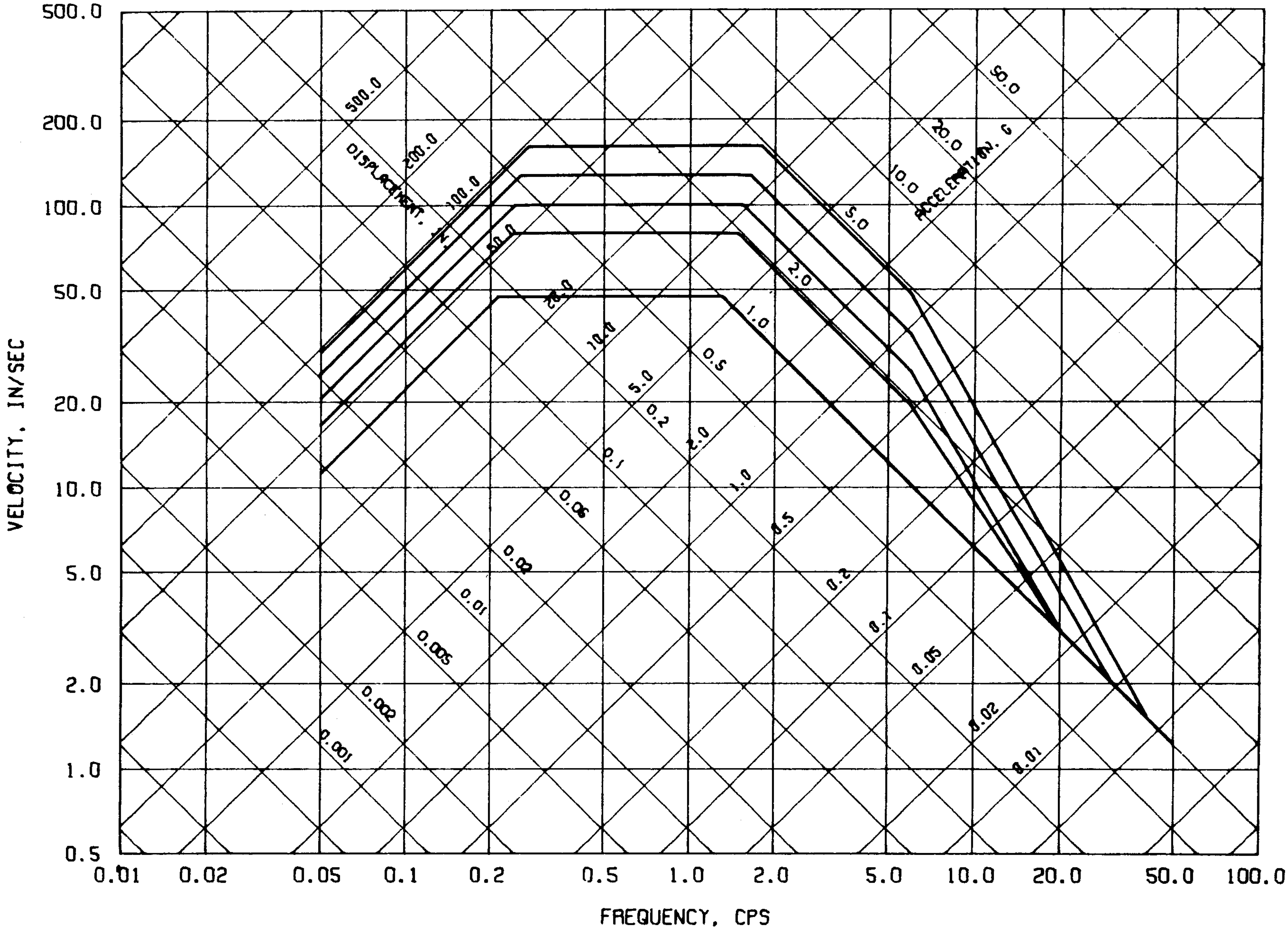

FIG. 4.8 DESIGN SPECTRA, HORIZONTAL DIRECTION, ALLUVIUM, 75 PERCENTILE 0.5, 2, 5, & 10 PERCENT CRITICAL DAMPING

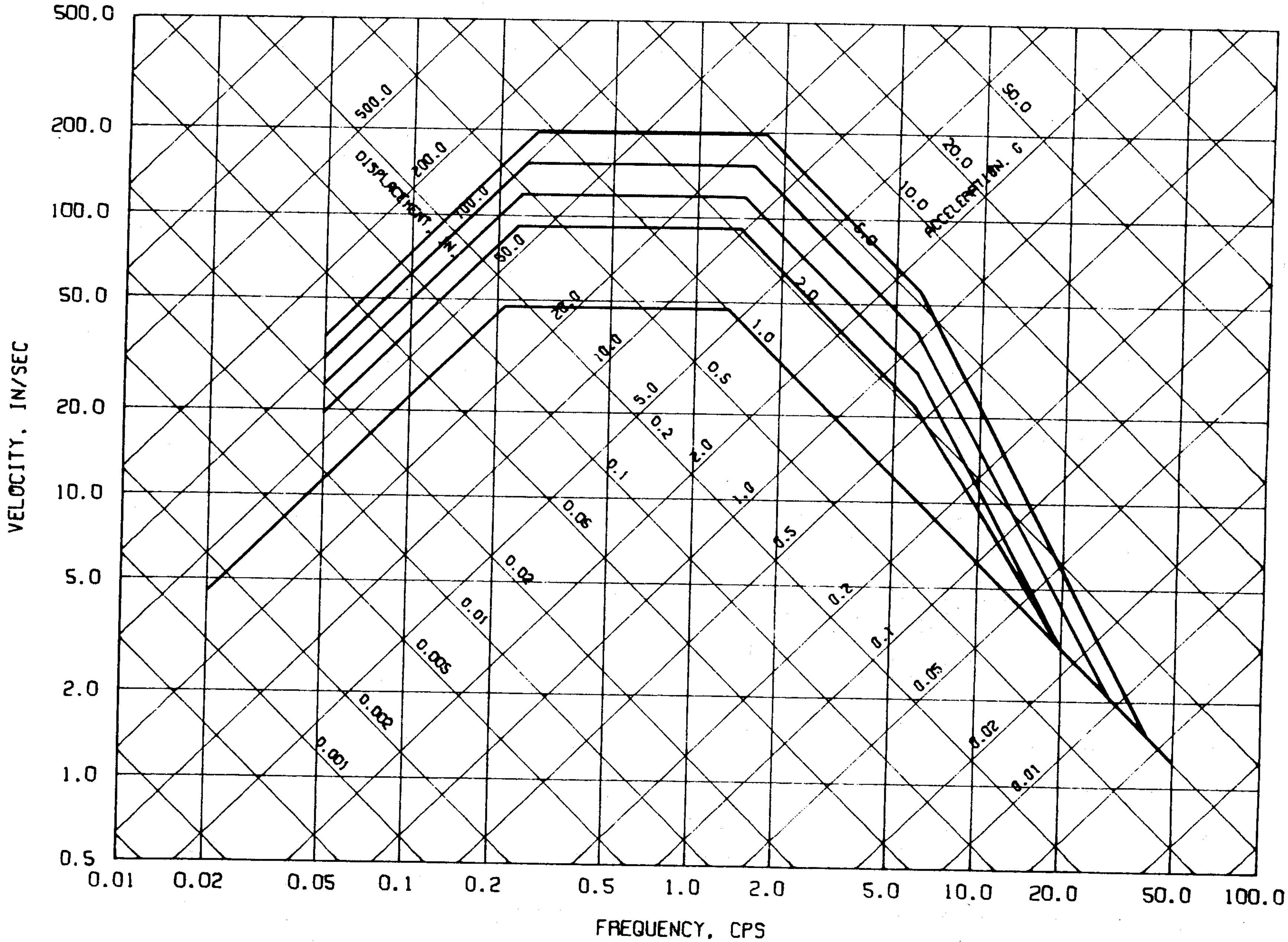

FIG.4.9 DESIGN SPECTRA, HORIZONTAL DIRECTION, ALLUVIUM, 90 PERCENTILE
0.5, 2, 5, & 10 PERCENT CRITICAL DAMPING

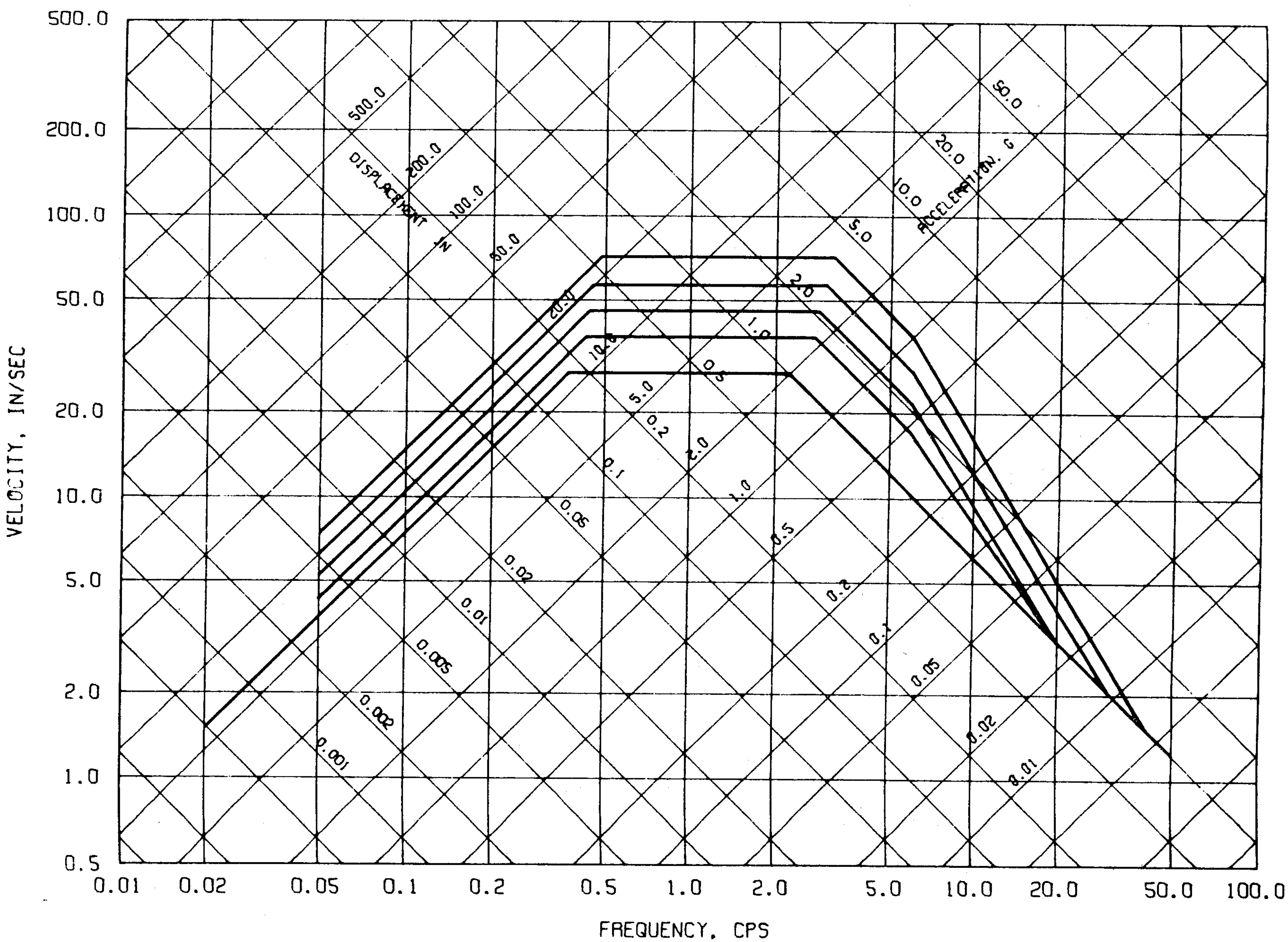

FIG.4.10 DESIGN SPECTRA, HORIZONTAL DIRECTION, ROCK, 50 PRCENTILE
0.5, 2, 5, & 10 PERCENT CRITICAL DAMPING

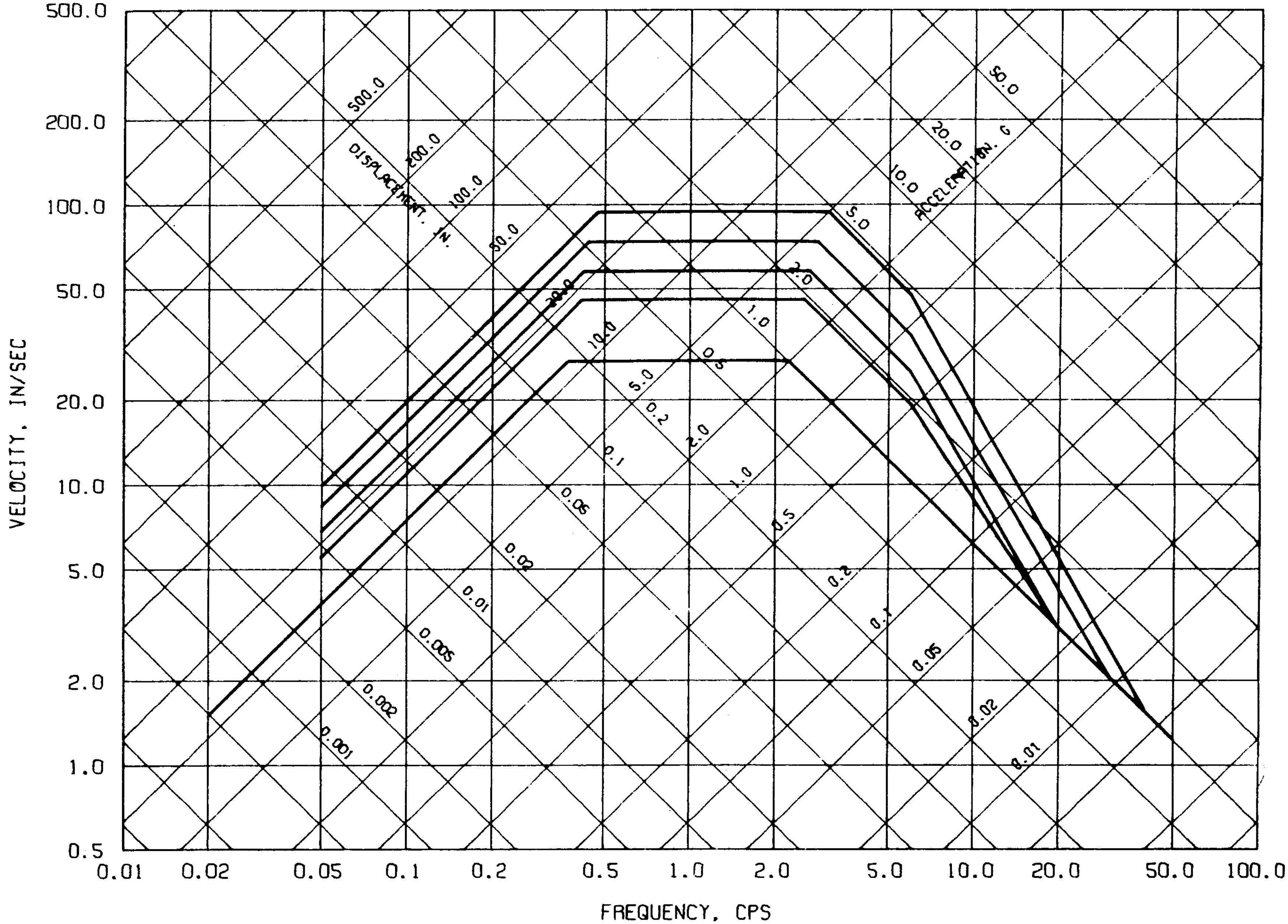

FIG. 4.11 DESIGN SPECTRA, HORIZONTAL DIRECTION, ROCK, 75 PRCENTILE
0.5, 2, 5, & 10 PERCENT CRITICAL DAMPING

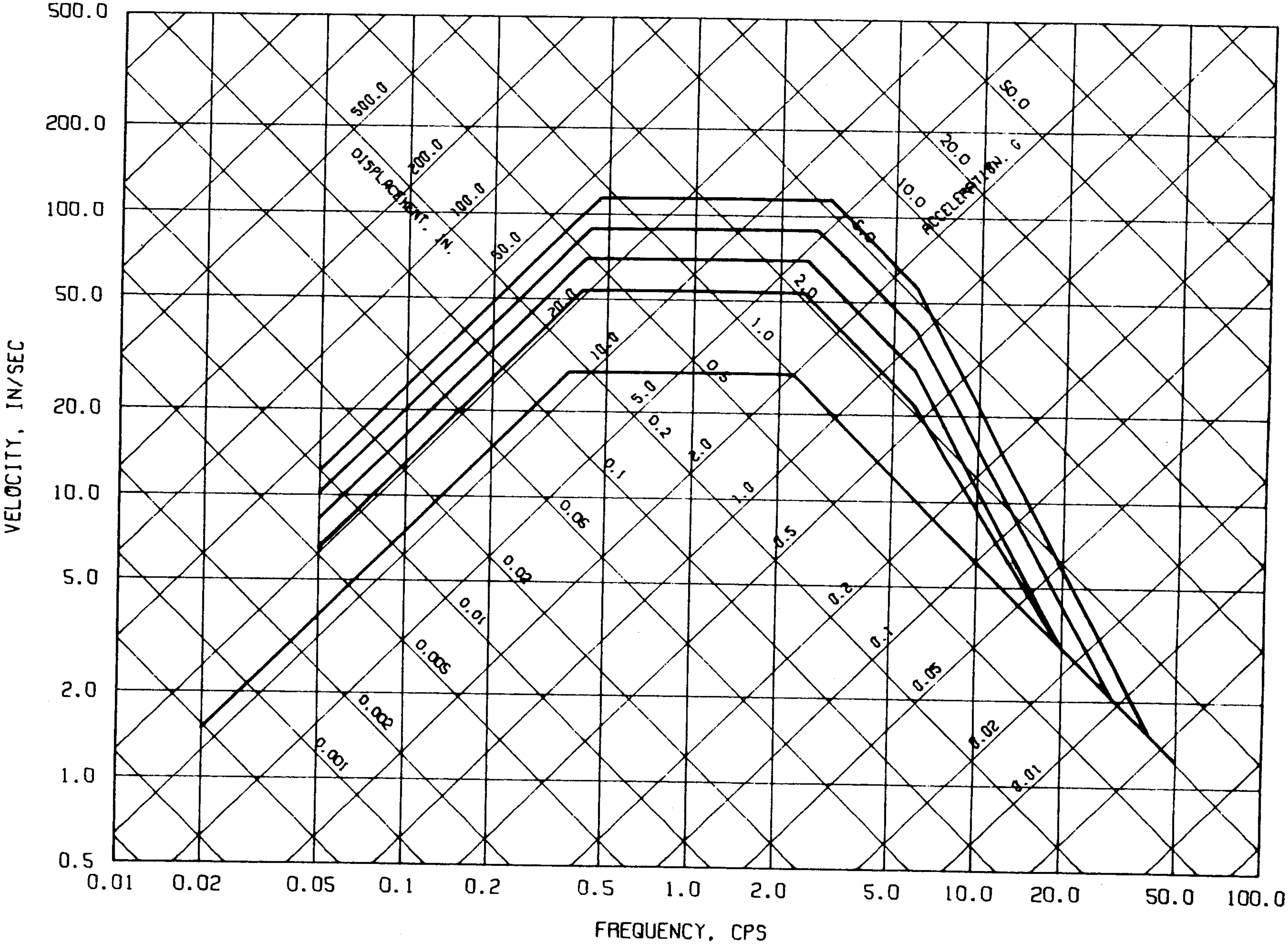

FIG.4.12 DESIGN SPECTRA, HORIZONTAL DIRECTION, ROCK, 90 PRCENTILE
0.5, 2, 5, & 10 PERCENT CRITICAL DAMPING

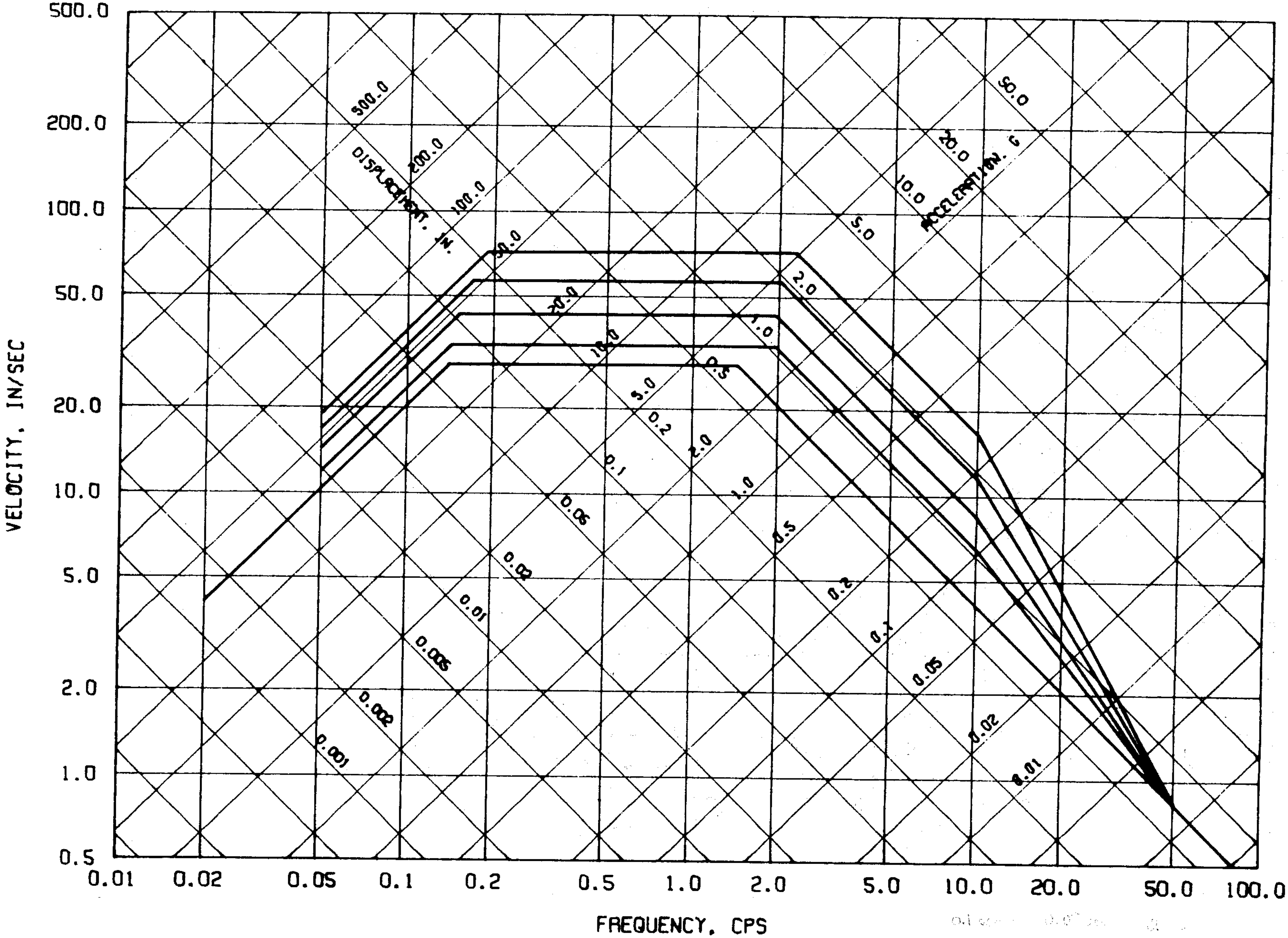

FIG.4.13 DESIGN SPECTRA, VERTICAL DIRECTION, ALLUVIUM, 50 PERCENTILE
0.5, 2, 5, & 10 PERCENT CRITICAL DAMPING

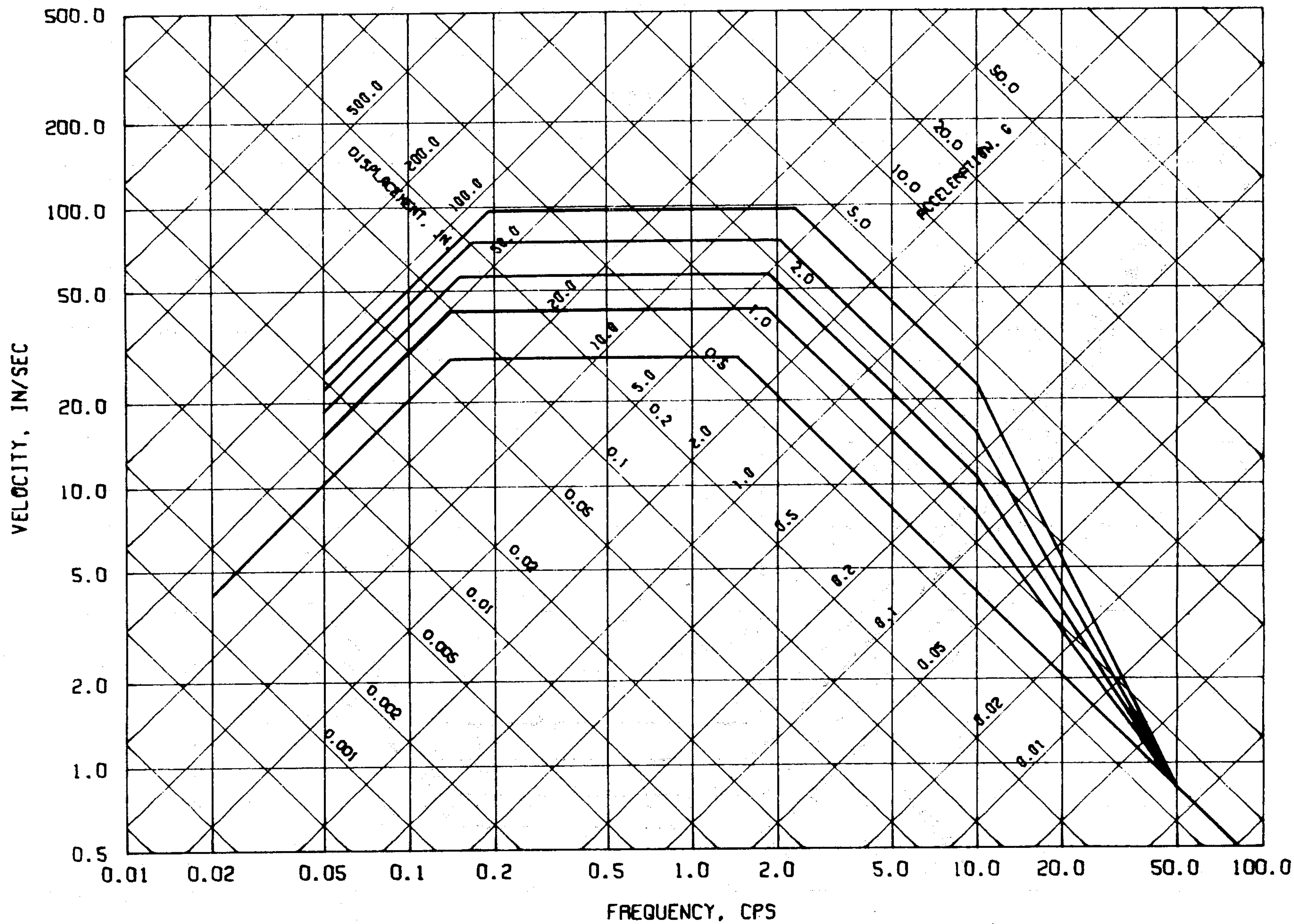

FIG.4.14 DESIGN SPECTRA, VERTICAL DIRECTION, ALLUVIUM, 75 PERCENTILE
0.5, 2, 5, & 10 PERCENT CRITICAL DAMPING

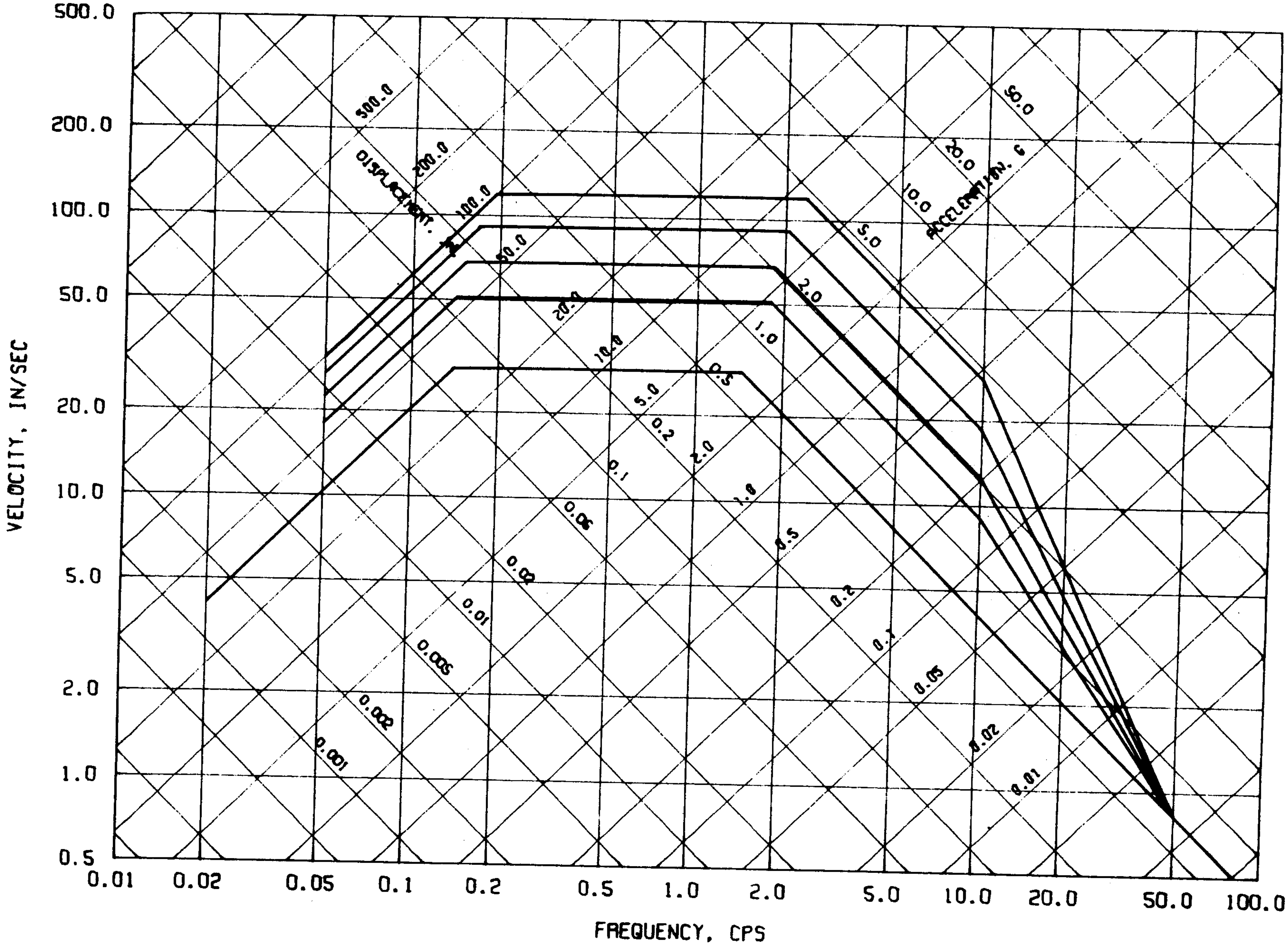

FIG.4.15 DESIGN SPECTRA, VERTICAL DIRECTION, ALLUVIUM, 90 PERCENTILE
0.5, 2, 5, & 10 PERCENT CRITICAL DAMPING

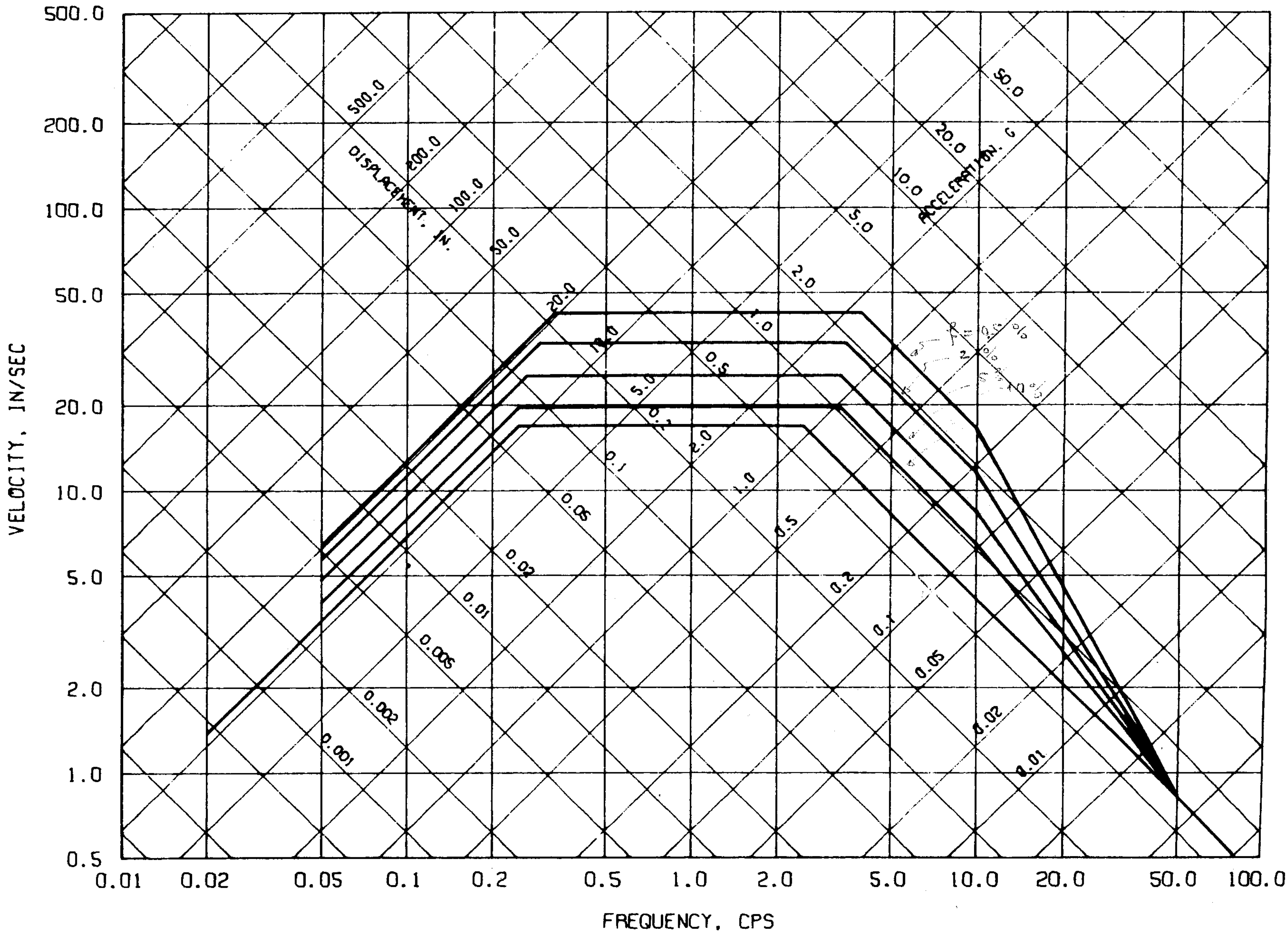

FIG. 4.16 DESIGN SPECTRA, VERTICAL DIRECTION, ROCK, 50 PERCANTILE
0.5, 2, 5, & 10 PERCENT CRITICAL DAMPING

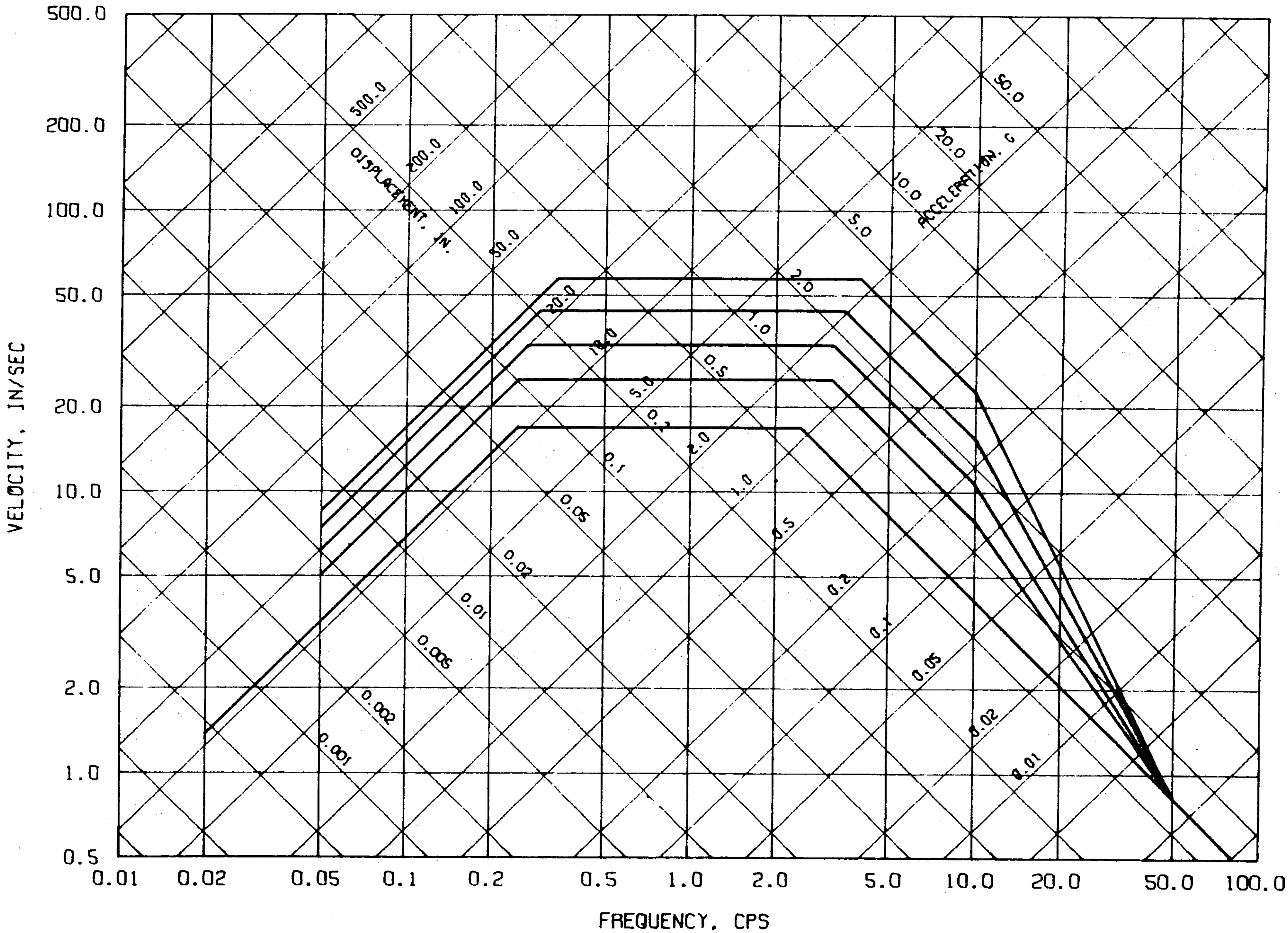

FIG.4.17 DESIGN SPECTRA, VERTICAL DIRECTION, ROCK, 75 PERCANTILE
0.5, 2, 5, & 10 PERCENT CRITICAL DAMPING

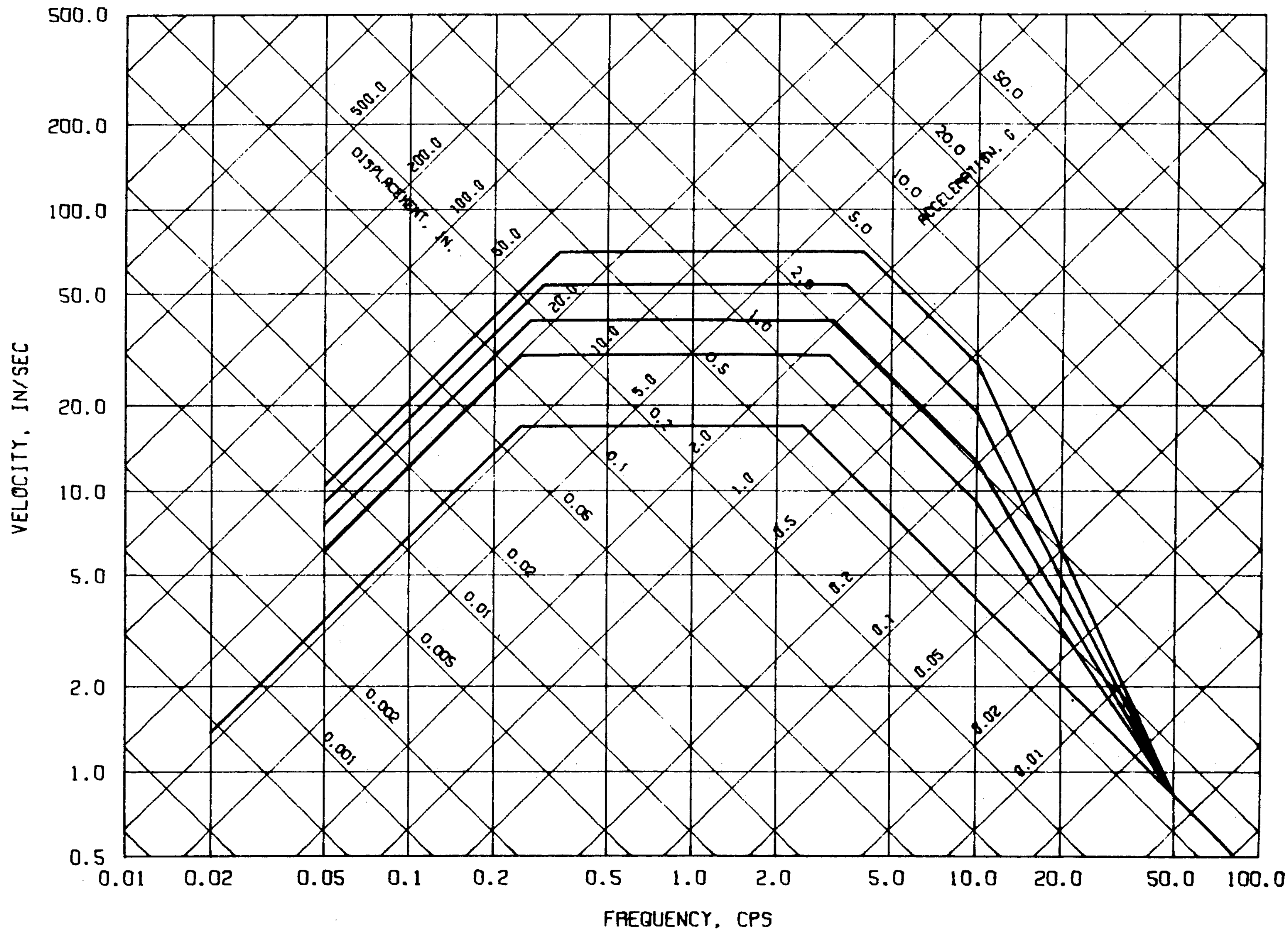

FIG.4.18 DESIGN SPECTRA, VERTICAL DIRECTION, ROCK, 90 PERCANTILE
0.5, 2, 5, & 10 PERCENT CRITICAL DAMPING

REFERENCES

1. Amin, M. and A. H.-S. Ang, "A Nonstationary Stochastic Model for Strong-Motion Earthquakes", Civil Engineering Studies, SRS 306, University of Illinois, Urbana, Illinois (1966).

2. Blume, J. A., N. M. Newmark, and L. H. Corning, Design of Multi-Story Reinforced Concrete Building for Earthquake Motions, Portland Cement Association, Chicago, Illinois (1961).

3. Veletsos, A. S., N. M. Newmark, and C. V. Chelapati, "Deformation Spectra for Elastic and Elasto-Plastic Systems Subjected to Ground Shock and Earthquake Motions", Proceedings of the Third World Conference on Earthquake Engineering, New Zealand (1965).

4. "Analysis of Strong Motion Earthquake Accelerograms", Volume IIIA - Response Spectra, California Institute of Technology, EERL 72-80, Pasadena, California (1972).

5. Housner, G. W. and P. C. Jennings, "Generation of Artificial Earthquakes", Journal of the Engineering Mechanics Division, ASCE, Vol. 90, EMI (1964).

6. Newmark, N. M. and E. Rosenblueth, Fundamentals of Earthquake Engineering, Prentice-Hall, Inc., Englewood Cliffs, New Jersey (1971).

7. Housner, G. W., "Earthquake Ground Motion", ASCE-IABSE International Conference on Planning and Design of Tall Buildings, Vol. Ib-6, Bethlehem, Pennsylvania (1972).

8. "Strong-Motion Instrumental Data on the San Fernando Earthquake of Feb. 9, 1971", edited by D. E. Hudson, Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, California (1971).

9. Wiggins, J. H. and W. J. Hall, "Effect of Soft Surficial Layering on Earthquake Intensity", Civil Engineering Studies, SRS 216, University of Illinois, Urbana, Illinois (1961).

10. Newmark, N. M. and W. J. Hall, "Seismic Design Criteria for Nuclear Reactor Facilities", Fourth World Conference on Earthquake Engineering, Santiago, Chile (1969).

APPENDIX A

SEGMENTAL BASELINE ADJUSTMENT

A.1 Introduction

As was mentioned in Chapter 2, the errors in earthquake records may arise from any number of sources. The errors in computation of velocity and displacement time-histories which arise from the integration of accelerogram records are caused by record processing where the initial conditions and the zero acceleration line (baseline) are not known. The initial conditions are not known since some motion is required to trigger the mechanism to start the accelerograph. Baselines of recordings not on film may be slightly in error due to warping of the paper. Although the error in selecting a baseline for calculational purposes may be very small in computing the acceleration time-history, the corresponding errors in velocity and displacement may be very large. For example, for a record with duration of 30 seconds, a constant shift of 0.001g in the acceleration baseline results in an error of 11.6 in/sec in terminal velocity and 162 in in the final displacement. In addition, as was mentioned in Chapter 2, the motion during an earthquake is a to and fro type motion and a velocity time-history which is either positive or negative for an extended period is likely to be in error.

While the initial conditions are usually assumed to be zero displacement and velocity, various methods have been employed for obtaining the acceleration baseline.[1,2,3] One method which has been used often is to assume a polynomial, usually a second degree, for the acceleration baseline, obtain the velocity time-history and use a least squares procedure to minimize the error in it within the duration of the record. For some records, applying this procedure within several portions of the record instead of the total duration of the record further reduces the errors in the velocity and the displacement time-histories. This procedure is explained in the following sections.

A.2 Parabolic Baseline Adjustment

Assuming a parabolic acceleration baseline in the form(2)

$$\ddot{y}_o(t) = C_1 + C_2(t - t_o) + C_3(t - t_o)^2 \qquad t_o < t \leq t_d \qquad \text{(A-1)}$$

where $\ddot{y}_o(t)$ is the acceleration baseline in the interval t_o and t_d, and the C's are unknown coefficients, the corrected (adjusted) acceleration $\ddot{y}_c(t)$ is obtained by subtracting from the unadjusted or the "as-read" acceleration $\ddot{y}_u(t)$, the assumed acceleration baseline $\ddot{y}_o(t)$. Therefore, one obtains

$$\ddot{y}_c(t) = \ddot{y}_u(t) - \ddot{y}_o(t) = \ddot{y}_u(t) - C_1 - C_2(t - t_o) - C_3(t - t_o)^2$$

or

$$\ddot{y}_c(t) = \ddot{y}_u(t) - \sum_{j=1}^{3} C_j (t - t_1)^{j-1} \qquad t_o < t \leq t_d \qquad \text{(A-2)}$$

The method of least squares is then used to determine unknown coefficients C_j. Thus,

$$\frac{\partial}{\partial C_j} \int_{t_o}^{t_d} [\dot{y}_c(t)]^2 dt = 0 \qquad \text{for } J = 1, 2, 3 \qquad \text{(A-3)}$$

Equation (A-3) gives three simultaneous equations in terms of 3 unknown coefficients. Once coefficients C_j are determined, the corrected velocity and displacement are obtained by integrating Eq. (A-2). Therefore, one obtains

$$\dot{y}_c(t) = \dot{y}_u(t) - \sum_{j=1}^{3} \frac{1}{j} C_j (t - t_o)^j - v_o \qquad \text{(A-4)}$$

$$y_c(t) = y_u(t) - \sum_{j=1}^{3} \frac{1}{j(j+1)} C_j (t - t_o)^{j+1} - v_o(t - t_o) - d_o \qquad \text{(A-5)}$$

where v_o and d_o are determined from the corrected and uncorrected velocities and displacements for the initial or starting time t_o as follows

$$v_o = \dot{y}_u(t_o) - \dot{y}_c(t_o)$$

$$d_o = y_u(t_o) - y_c(t_o) \qquad \text{(A-6)}$$

Having the coefficients C_1, C_2, and C_3, the velocity and displacement baselines are computed from Eqs. (A-4 and A-5), respectively. Thus,

$$\dot{y}_o(t) = \sum_{j=1}^{3} \frac{1}{j} C_j (t - t_o)^j + v_o \qquad \text{(A-7)}$$

$$y_o(t) = \sum_{j=1}^{3} \frac{1}{j(j+1)} C_j (t - t_o)^{j+1} + v_o(t - t_o) + d_o \qquad \text{(A-8)}$$

A.3 Segmental Adjustment

The interval for which the square of the velocity is minimized for determining unknown coefficients C_j, is usually taken as the duration of the record. Once coefficients C_j are evaluated, the shape of the velocity and displacement baselines is determined within the interval of the record. The expression for the velocity baseline, Eq. (A-7), is a cubic equation. In cases where the velocity baseline cannot be approximated by a cubic equation, the minimizing of the square of the velocity within the duration of the record does not completely reduce the record processing error. To illustrate this point, the unadjusted velocity time-history for the North-South component of the El Centro, 5-18-40, 2037 PST* is presented in

* The record was digitized by the Earthquake Engineering Research Laboratory of the California Institute of Technology.

Fig. A.1. This record was adjusted using a second degree polynomial and minimizing the error in square of the velocity within the first 30 seconds of the record. The velocity baseline for the nonsegmental adjustment, Fig. A.1, underestimates the correction in the initial portion of the record (0 to 10 seconds), and overestimates the correction for the subsequent portion (10 to 30 seconds). In order to further reduce the error in the adjustment procedure, the baseline correction was applied in several segments of the record. Three segments of approximately 10 seconds each were selected. The three 10-second intervals were selected on the basis that within the initial portion, the unadjusted velocity is mainly negative; in the middle portion, it is both negative and positive; and in the final portion of the record, it is mainly positive. A procedure similar to that for a nonsegmental adjustment was used to obtain coefficients C_1, C_2 and C_3 in Eq. (A-1) within each segment. For the first segment, both the unadjusted and the adjusted initial displacements and velocities are assumed to be zero. However, for the subsequent segments, the unadjusted and adjusted initial displacements and velocities are taken to be the final unadjusted and adjusted displacements and velocities of the previous segment. The velocity and displacement baselines for both the nonsegmental and segmental adjustments are shown in Figs. A.1 and A.2. The adjusted velocity and displacement obtained by using the two procedures are shown in Figs. A.3 and A.4, respectively.

The unadjusted and adjusted maximum accelerations, velocities and displacements are presented below:

Case	Maximum acceleration a, g	Maximum velocity v, in/sec	Maximum displacement d, in	ad/v^2
Unadjusted	0.359	22.59	91.91	24.80
Nonsegmental adjustment	0.355	16.14	24.29	12.79
Segmental adjustment	0.352	13.88	4.74	3.35

The maximum ground motions indicate that the displacement is most sensitive to adjustment procedure. The quantity ad/v^2 which provides a bound on relative magnitudes of acceleration, velocity, and displacement is also given in the above table. It is seen that the adjustment procedure affects ad/v^2 to a large degree. The segmental adjustment results in a more realistic ad/v^2 than the nonsegmental adjustment.

The segmental adjustment procedure, while assuring the continuity of velocities and displacements from one adjustment interval of the record to another (Figs. A.1 and A.2), introduces a discontinuity in the adjusted acceleration. The error due to this discontinuity is of high frequency nature which does not affect the ground motion response spectra in the range of frequencies of interest for this study (see Fig. A.5). However, the error due to the baseline adjustment procedures is more pronounced in the displacement, causing unusually large response values in the low frequencies. This is to be expected since the difference between the two baselines in Figs. A.1 and A.2 represents a low frequency error.

A.4 Summary and Conclusions

A segmental baseline adjustment procedure for determining the zero acceleration line of earthquake records is presented. The procedure is similar to the well known polynomial baseline adjustment where the square of the error in the velocity time-history within the duration of the record is minimized. In the present procedure, different polynomials, usually a second degree, are assumed for the acceleration baseline in different portions of the record and the square of the error in the velocity time-history within each portion is minimized. The following procedure is recommended when applying segmental baseline adjustment:

a. Obtain the unadjusted velocity and displacement time-histories by integrating the accelerogram record.

b. From the plot of the unadjusted velocity time-history, determine the intervals over which the record is to be adjusted. These intervals can be determined by visual inspection, and by drawing a series of curves which would roughly represent the velocity baseline. Experience with a series of strong motion earthquake records has indicated that generally two or three adjustment intervals are sufficient.

c. Apply the polynomial, usually a second degree, baseline adjustment within each interval. For the first interval the unadjusted and the adjusted initial displacements and velocities are assumed to be zero. For the subsequent intervals, the initial displacements and velocities are taken to be the final displacements and velocities of the previous interval. This gives coefficients C_j in Eq. (A-1) for each interval.

d. Knowing coefficient C_j, obtain the acceleration baseline, Eq. (A-1), for each interval. The adjusted acceleration can then be obtained by subtracting the acceleration baseline from the unadjusted acceleration, Eq. (A-2).

e. Once the adjusted acceleration is obtained, the adjusted velocity and displacement time-histories are obtained by proper integration.

REFERENCES

1. Trifunac, M. D., "Low Frequency Digitization Errors and a New Method for Zero Baseline Correction of Strong Motion Accelerograms", Earthquake Engineering Research Laboratory, California Institute of Technology (1970).

2. Amin, M. and A. H.-S. Ang, "A Nonstationary Stochastic Model for Strong-Motion Earthquakes", Civil Engineering Studies, Structural Research Series No. 306, University of Illinois, Urbana, Illinois (1966).

3. Brady, A . G., "Studies of Response to Earthquake Ground Motion", Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, California (1966).

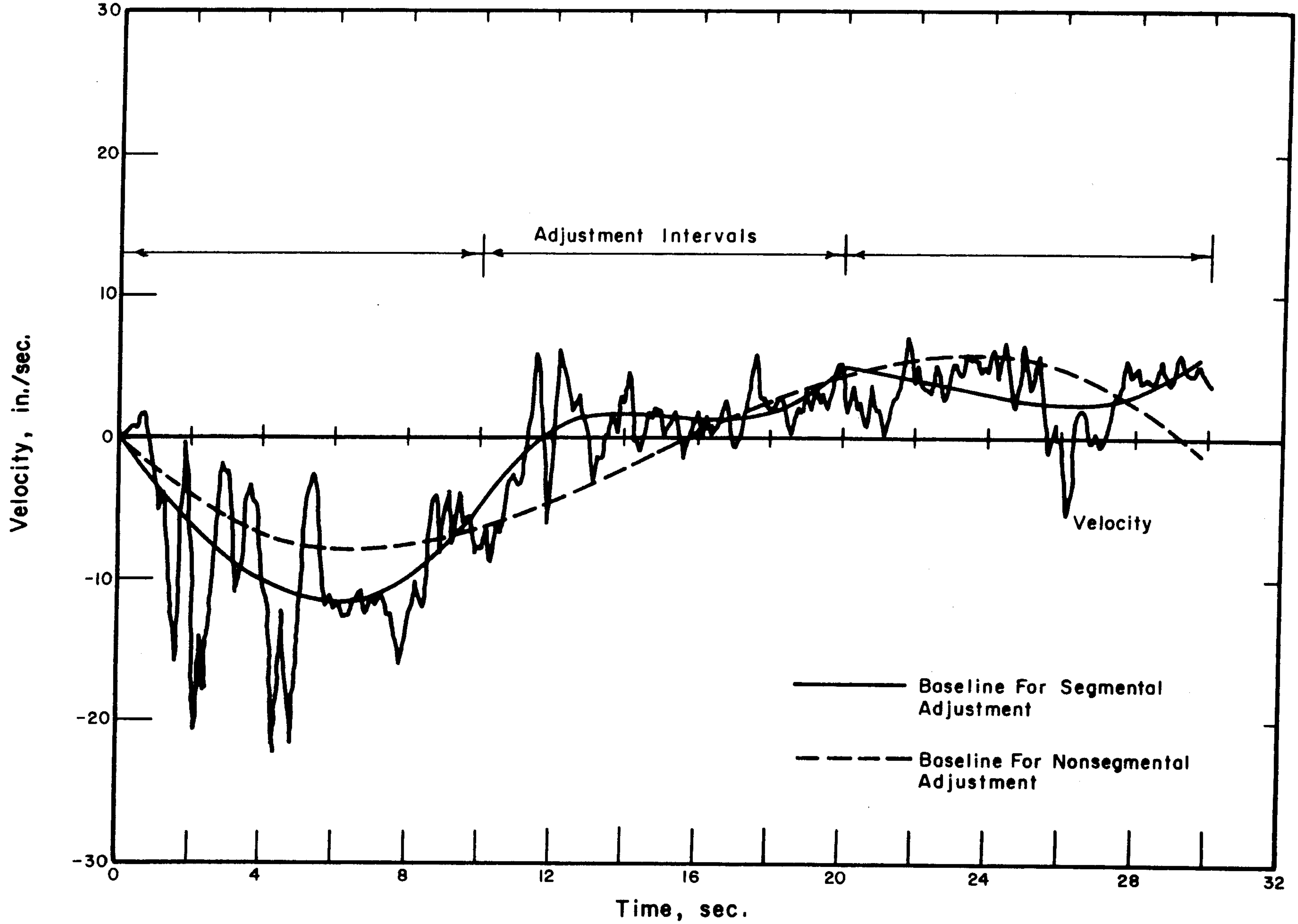

FIG. A.1 VELOCITY—TIME HISTORY, EL CENTRO, CALIF., 5/18/1940—NS UNADJUSTED RECORD

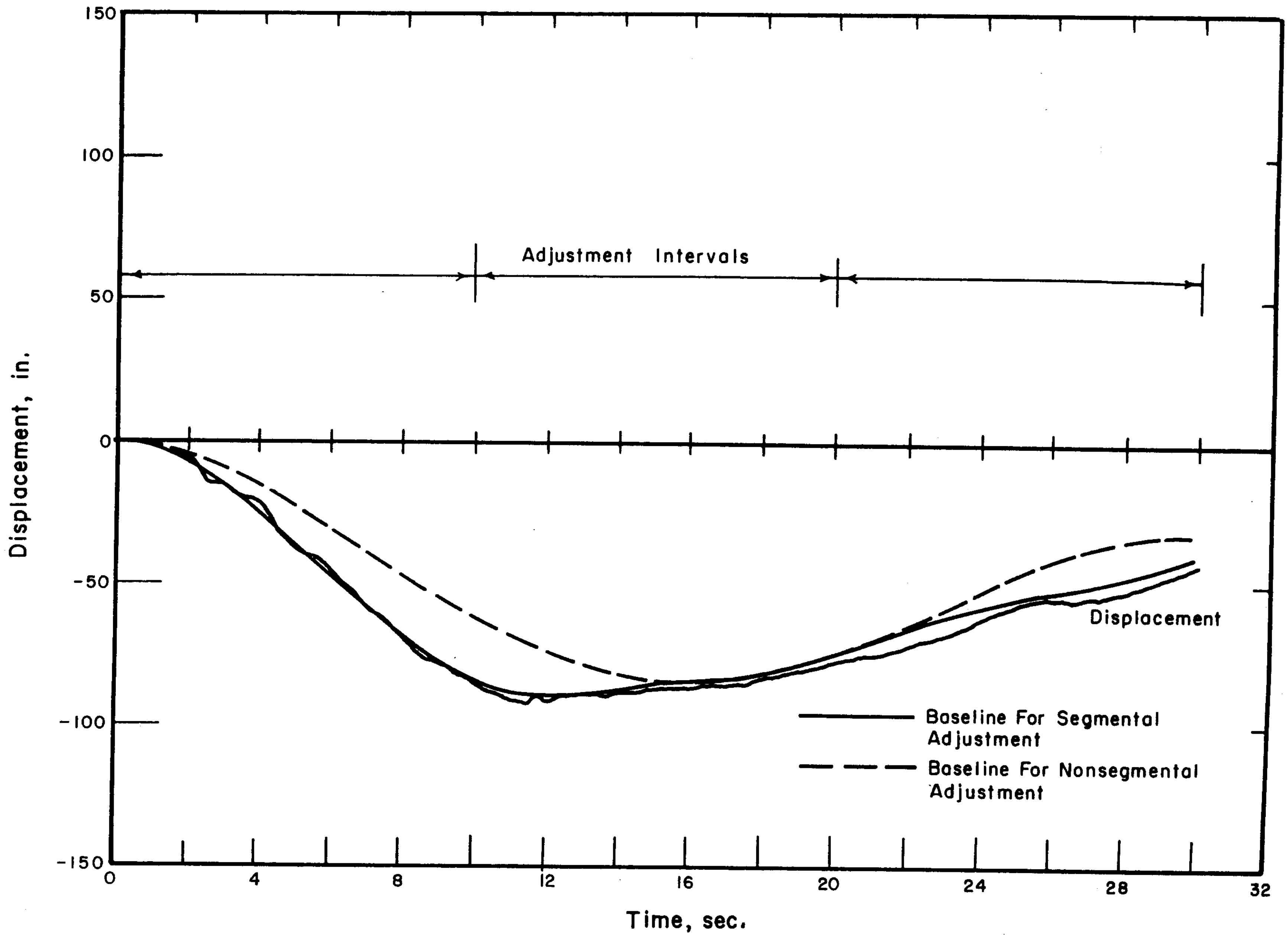

FIG. A-2 DISPLACEMENT - TIME HISTORY. EL CENTRO, CALIF. 5/18/1940 - NS UNADJUSTED RECORD

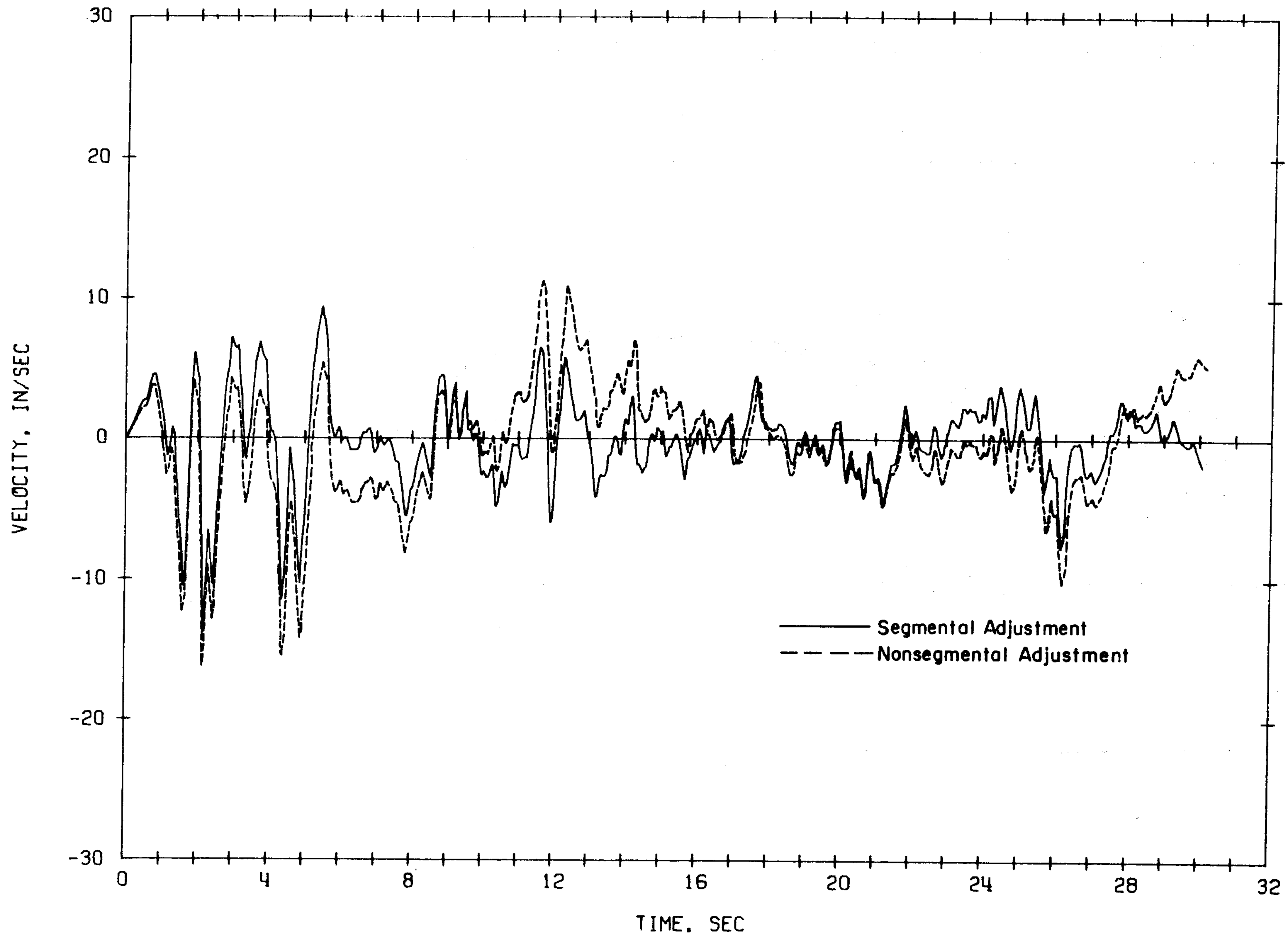

FIG.A.3 VELOCITY - TIME HISTORY, EL CENTRO, CALIF., 5/18/1940 - NS
SEGMENTALLY ADJUSTED RECORD

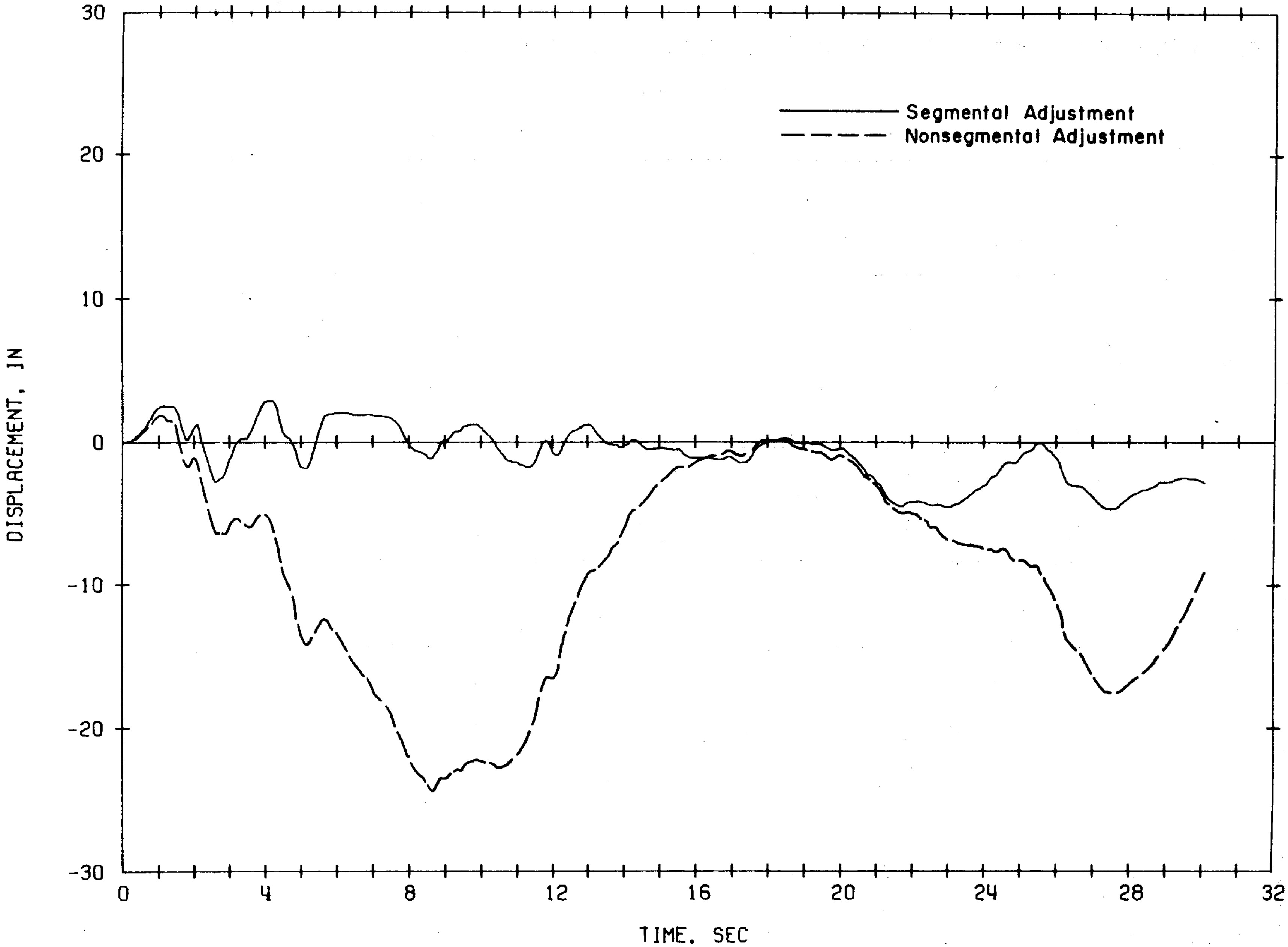

FIG.A.4 DISPLACEMENT - TIME HISTORY, EL CENTRO, CALIF., 5/18/1940 - NS
SEGMENTALLY ADJUSTED RECORD

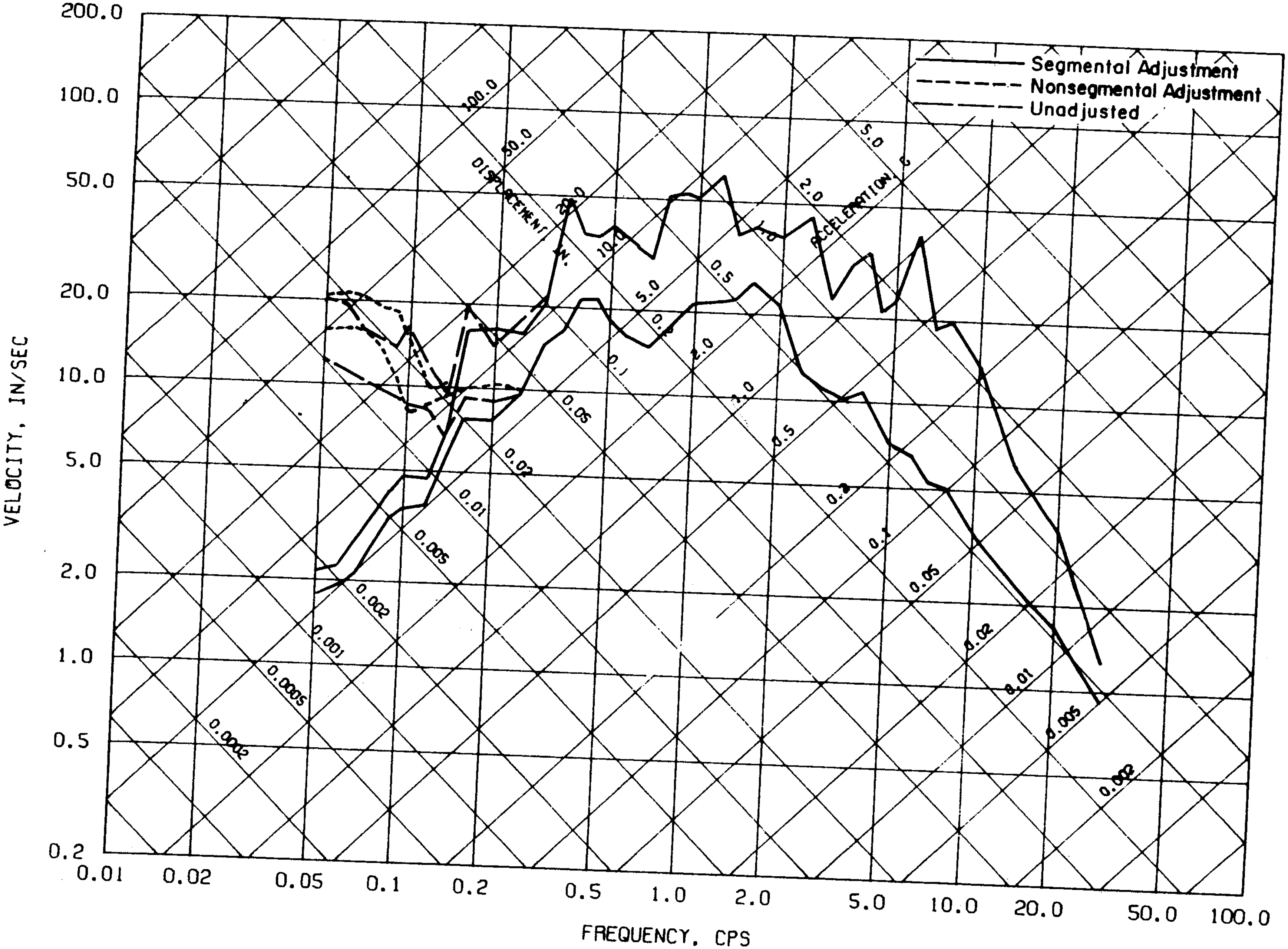

FIG. A.5 RESPONSE SPECTRA, EL CENTRO, CALIF., 5/18/1940-NS 0 AND 10 PERCENT CRITICAL DAMPING

APPENDIX B

METHODS OF NORMALIZING RESPONSE SPECTRA

B1. Introduction

The procedure employed for obtaining the amplification factors used in the statistical study was to normalize the response spectra for each component of the earthquake and for each damping value to one of the three ground motion parameters. The amplification factors were obtained by normalizing the response spectra to maximum ground acceleration for high frequencies, to maximum ground velocity for intermediate frequencies, and to maximum ground displacement for low frequencies. This procedure leads to a minimization of the standard deviation in each of the three frequency ranges, as explained in the next section.

B2. Differences in Normalization Procedures

When a single response spectra is normalized to one of the three ground motion quantities, the spectral ordinates at various frequencies are divided by a constant. The shape of the normalized response spectra is, therefore, identical to that of the response spectra itself. At any frequency, the ordinates of the response spectra obtained by the three normalization procedures are proportional to each other -- the proportionality factor being the ratio of two of the three ground motion quantities.

The mean response amplification (acceleration, velocity, or displacement) at each frequency is obtained by first normalizing the individual response spectra to the appropriate ground motion and then computing the mean amplification. Since for different earthquakes the maximum ground acceleration, velocity, and displacement and their ratios vary, the three normalization procedures do not give identical shapes for the mean response amplification. If the ratio of the ground motion quantities were the same for each record, the three normalization procedures would give identical shapes.

The mean value and the mean plus one standard deviation value of the complete horizontal response spectra for two percent of critical damping normalized to 1.0g horizontal ground acceleration are shown in Fig. B.1. Figures B.2 and B.3 show the complete horizontal spectra normalized to 1.0 in/sec and 1.0 in horizontal ground velocity and displacement, respectively. The lower curves in these figures are similar to those in Fig. 3.2 with the exception that in these figures each curve is plotted for the entire range of frequencies. In each figure the difference between the two curves at each frequency is the standard deviation, σ, of the amplification factor. The figures indicate that normalization to maximum ground acceleration gives a standard deviation which increases rather uniformly from high to low frequencies, whereas normalization to maximum ground displacement gives a standard deviation which increases from low to high frequencies. Normalization to maximum ground velocity results in a standard deviation which is nearly uniform over the entire range of frequencies. Thus, it seems reasonable that normalization should be made not to a single ground motion parameter, but to all three parameters for different ranges of frequencies. Thus, as may be seen from the figures, for high frequencies, normalization to maximum ground acceleration gives the smallest standard deviation while for low frequencies normalization to maximum ground displacement yields the smallest standard deviation. For intermediate frequencies, normalization to maximum ground velocity gives a standard deviation which is nearly constant and it is smaller than those obtained by normalizing the spectra to either ground acceleration or ground displacement. Similar results are obtained for normalized spectra for vertical components, Figs. B.4 to B.6.

The design amplification factors presented in Chapters 3 and 4 were obtained by normalization to the three ground motion parameters as just described. If normalization to a single ground motion parameter were to be used, then the maximum ground velocity would be the best of the three ground motion parameters, since it gives a standard deviation which is nearly constant over the entire frequency range.

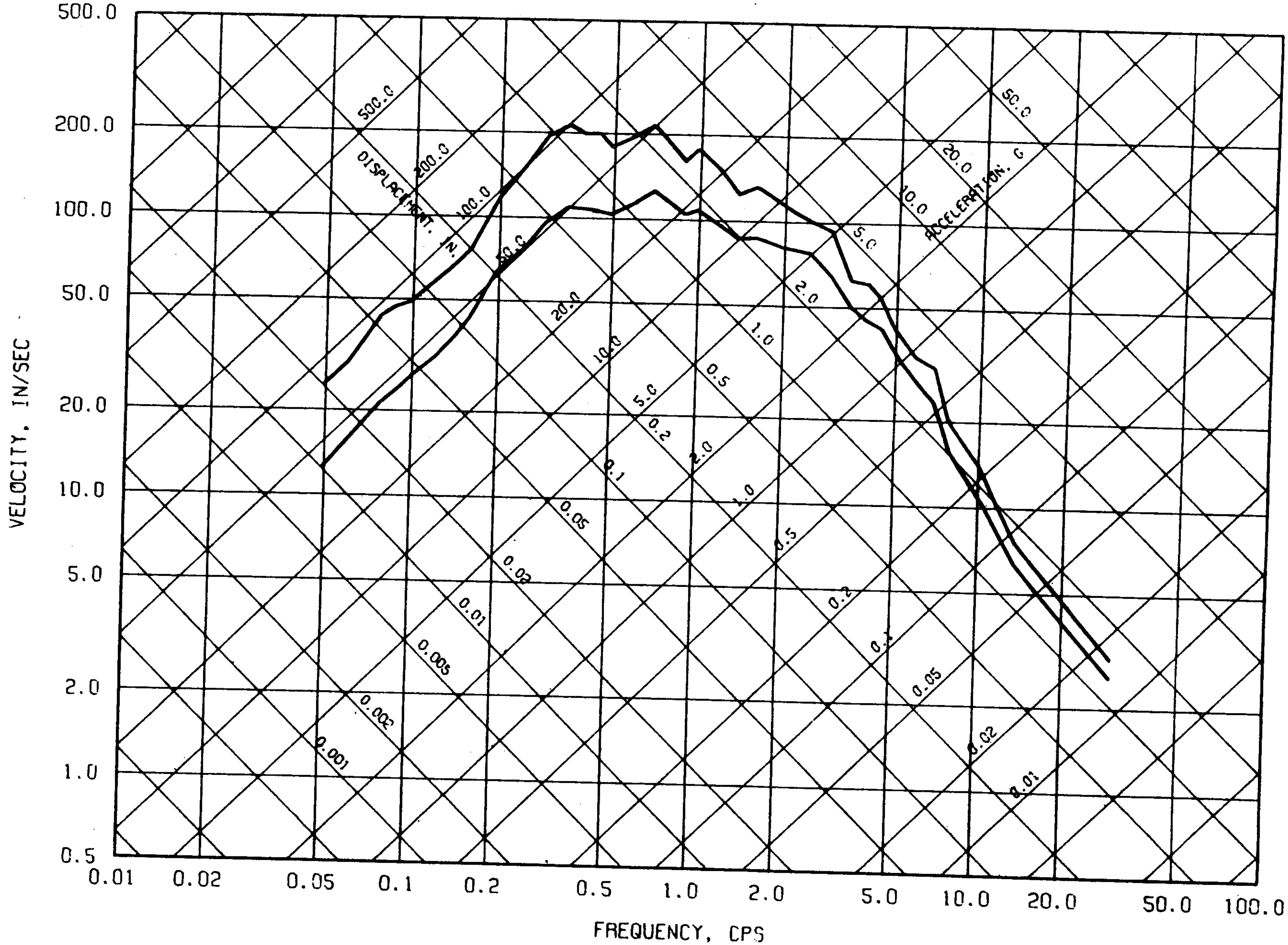

FIG.B.1 MEAN AND MEAN PLUS ONE STANDARD DEVIATION ACCELERATION AMPLIFICATION HORIZONTAL COMPONENTS - 2.0 PERCENT OF CRITICAL DAMPING

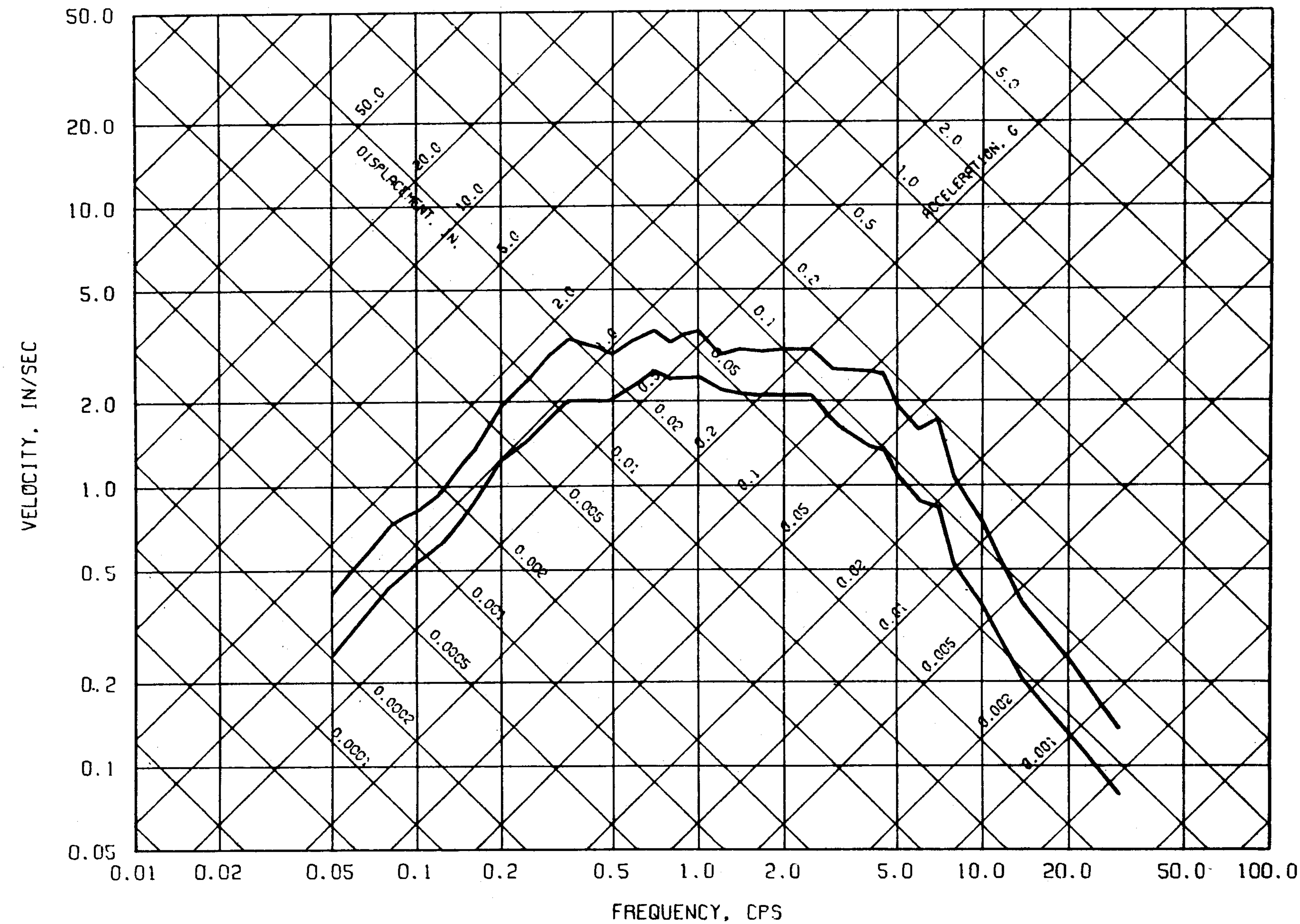

FIG. B.2 MEAN AND MEAN PLUS ONE STANDARD DEVIATION VELOCITY AMPLIFICATION HORIZONTAL COMPONENTS - 2.0 PERCENT OF CRITICAL DAMPING

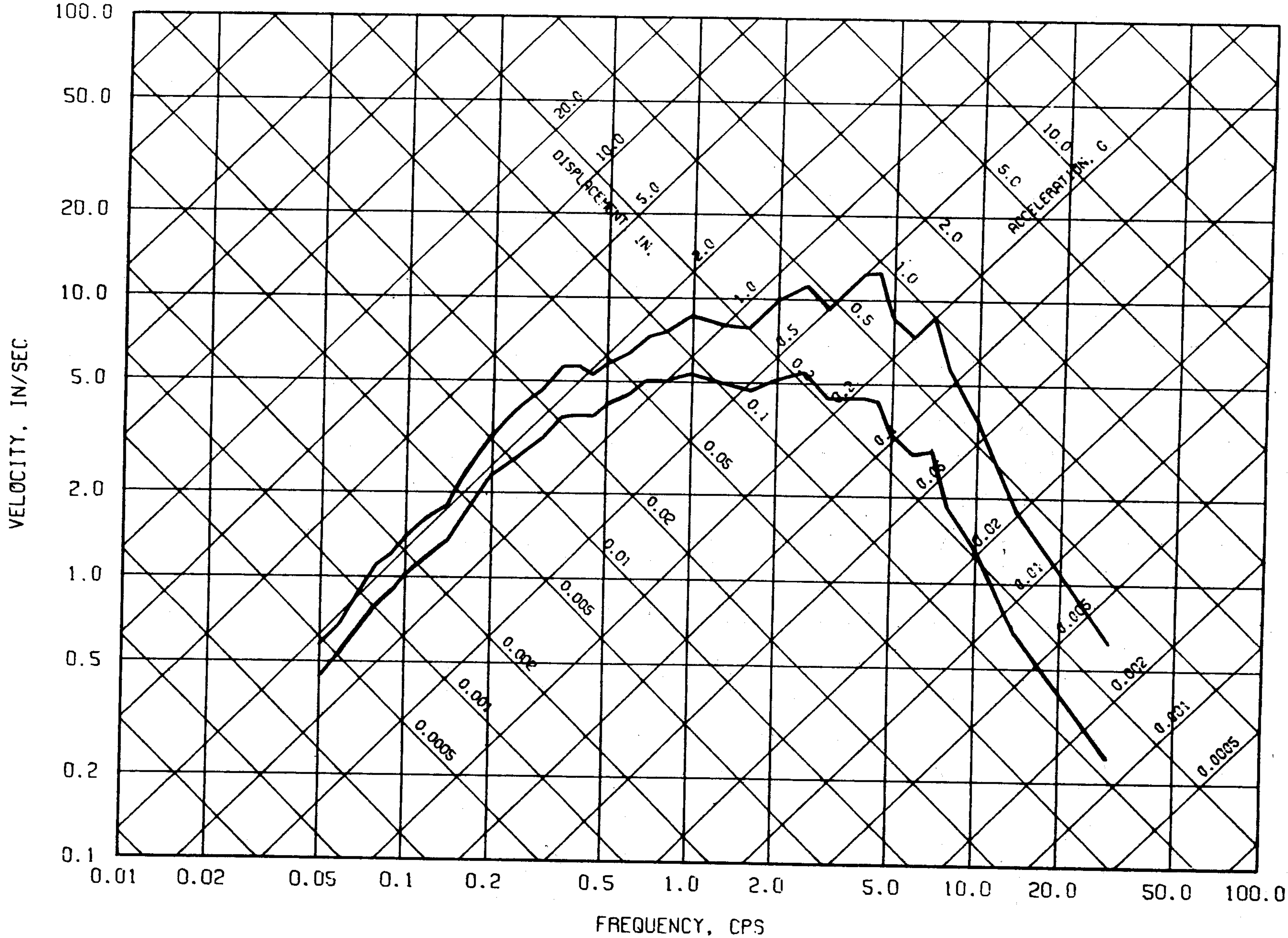

FIG. B.3 MEAN AND MEAN PLUS ONE STANDARD DEVIATION DISPLACEMENT AMPLIFICATION HORIZONTAL COMPONENTS - 2.0 PERCENT OF CRITICAL DAMPING

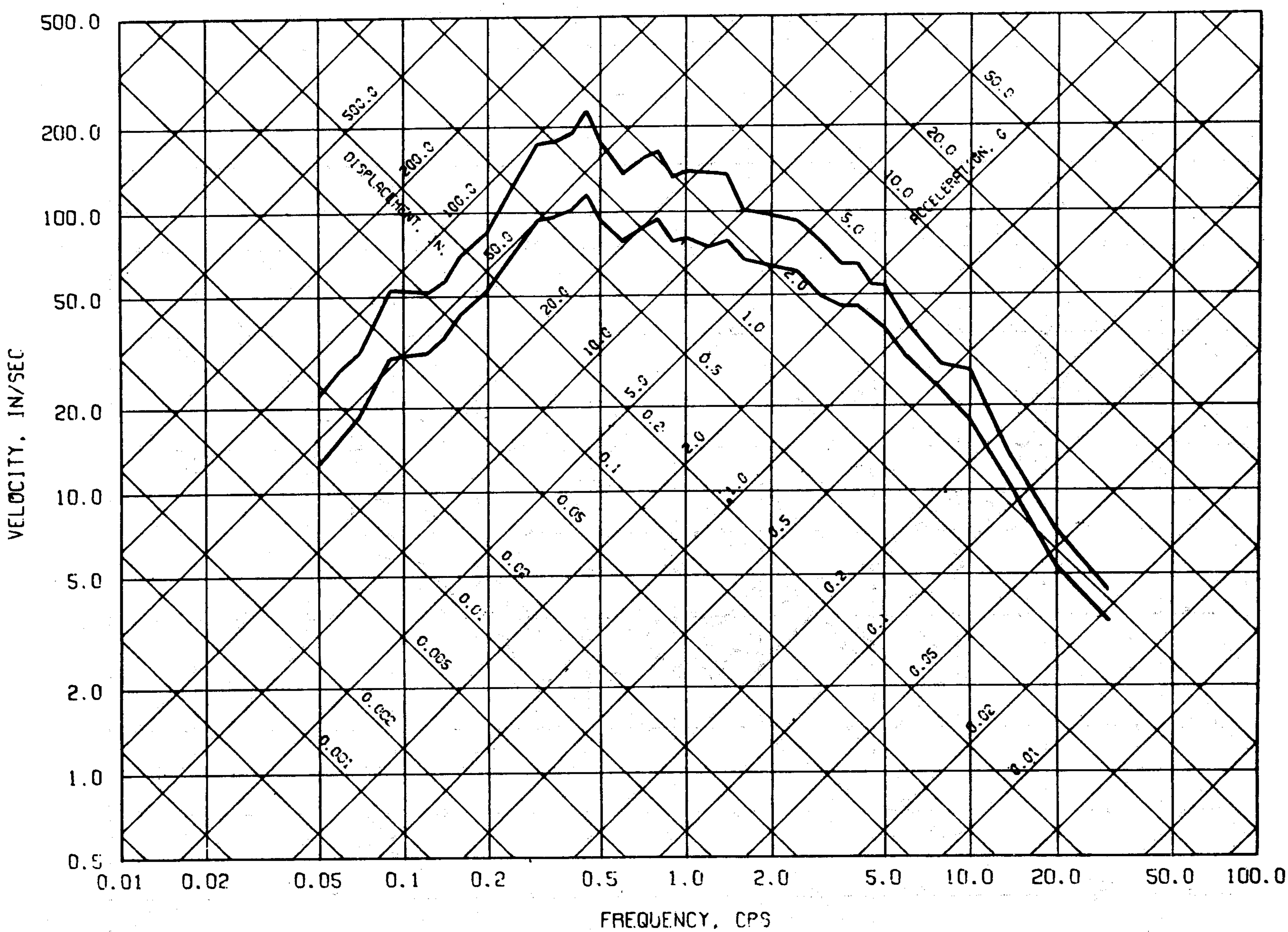

FIG. B.4 MEAN AND MEAN PLUS ONE STANDARD DEVIATION ACCELERATION AMPLIFICATION VERTICAL COMPONENTS - 2.0 PERCENT OF CRITICAL DAMPING

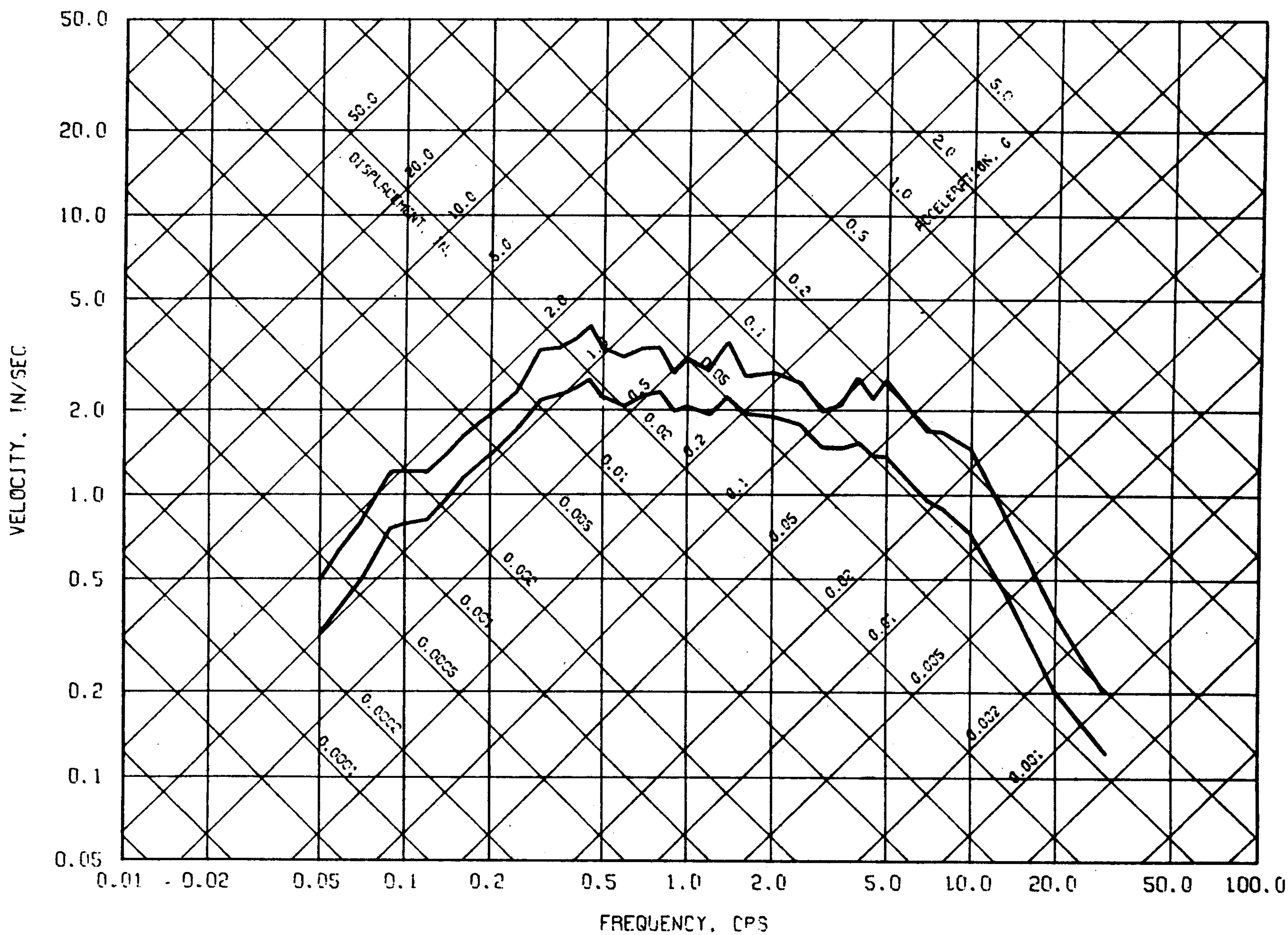

FIG. B.5 MEAN AND MEAN PLUS ONE STANDARD DEVIATION VELOCITY AMPLIFICATION VERTICAL COMPONENTS - 2.0 PERCENT OF CRITICAL DAMPING

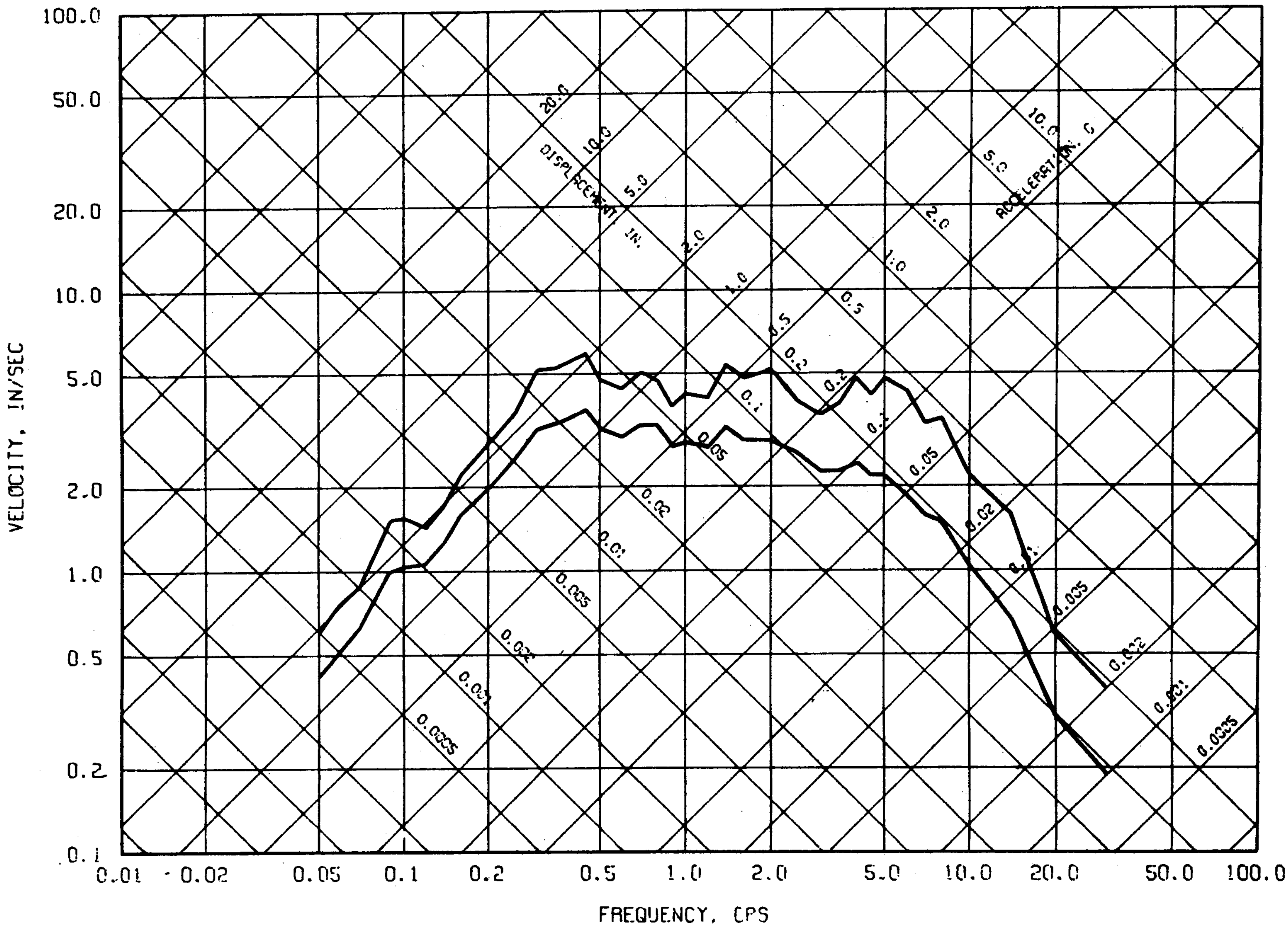

FIG. B.6 MEAN AND MEAN PLUS ONE STANDARD DEVIATION DISPLACEMENT AMPLIFICATION VERTICAL COMPONENTS - 2.0 PERCENT OF CRITICAL DAMPING