THE USE OF SITE DEPENDENT SPECTRA

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The catalog of strong motion accelerograms has been increasing rapidly during the past few years. This is due both to the increased deployment of permanent strong motion stations and the ability to rapidly deploy sets of instruments to record aftershocks of significant events. Coupled with this increase in the number of records is an increased knowledge of the local geology at strong motion sites through the work of Silverstein (1979, 1980a, 1980b), Shannon and Wilson (1978, 1980a, 1980b, 1980c) and Fumal et al. (1982a, 1982b). This paper presents an overview of how the Nuclear Regulatory Commission (NRC), taking advantage of this increasing knowledge and data base, has made increasing use of site specific response spectra. First, a summary of what will be called a site-specific spectrum is presented, along with some examples that have been utilized by the NRC. This will be followed by a discussion of the important conclusions from our experience with site-specific spectra and the identification of important technical issues which require additional investigation before they can be resolved.

One reason why the use of site-specific spectra has been encouraged is that at various times, particularly during earlier construction permit reviews, the NRC staff has approved different methodologies of arriving at design level ground motion. An explanation for this is that the methodologies for arriving at design level ground motion has evolved with time as more data has been recorded and we have gained more knowledge of the effects of earthquake source, propagation path, and local site conditions upon strong ground motion. The past practice can generally be classified as a site independent approach, which typically uses a standardized response spectrum and a reference peak acceleration. The resulting spectral amplification factors from a standardized response spectrum are typically developed by using strong motion records recorded from earthquakes of a wide range of magnitudes, at widely recorded distances, and site conditions. They are therefore, by definition, not specifically designed for use on any one type of site. Examples of standard spectral shapes include the early work of Housner (1959), that of Newmark and Hall (1978), the Nuclear Regulatory Commission's Regulatory Guide 1.60 response spectrum. The main advantage of this general method is that it allows for standardization and relative ease of use. A disadvantage of this method is that the standard shape has changed with time and controversies have developed over the reference peak acceleration which should be used for a given size earthquake. Site-specific spectra have been used by the NRC staff to assess design basis earthquake ground motion assumptions for which various standard spectral shapes were used.

Following is the procedure which the NRC has utilized for determining site-specific spectra. Typically, this procedure involves the collection of acceleration time histories from earthquakes of similar magnitude to the target magnitude, recorded at appropriate distances, for site conditions similar to the site in question.

The NRC practice has been to utilize acceleration time histories from earthquakes whose magnitudes are within about + 0.50 magnitude units of the target. For a target of $M_L = 5.3$ this means that records between M_L of about 4.8 and 5.8 could be used. This range has been chosen to take into account the uncertainty of the assumed magnitude and more importantly, to ensure that a large enough, yet reasonable, data sample can be collected. In terms of the target distance, we have generally utilized acceleration times histories recorded within about 25 kilometers of the source, with the average distance being about 15 kilometers. The matching of site conditions is usually accomplished by comparing the shear wave velocity profile at the target site with whatever shear wave velocity information may be available for the strong motion recording stations. Important information in matching site conditions is not only the value of the shear wave velocity, but also the layer thicknesses and impedance contrasts.

Following, are a few examples of site specific spectra that have been developed by both consultants to applicants and the NRC staff. Figure 1 shows the shear wave velocity profile of a soil site in Michigan where the target magnitude was an M_L of 5.3. Figure 2 shows the shear wave velocity profiles of the strong motion recording stations that were used by the applicant to develop the spectrum. As can be observed, the match is not perfect, and in fact the decision of whether to include or exclude records requires care and judgement. Figure 3 is a plot of the response spectra (5% damping) of all the horizontal components collected by the applicant, listed in Table 1, that were used in developing this spectrum. Once this collection is accomplished, a specific fractile can be determined for use in the analysis or comparison. In the examples in this paper the 84th percentile is used.

At the particular site in Michigan, there was some controversy over one particular set of records, as to whether or not they should be included. Figure 4 shows the effect of adding three sets of records from the 1966 Parkfield earthquake, with the original collection of twenty-one sets of records. These results demonstrate that care must be exercised when choosing strong motion records because the inclusion or exclusion of specific data can have a significant effect on the spectrum. However, the advantages of using site specific spectra outweigh the precautions which must be observed. These advantages will be shown in the following figures.

One sensitivity test that was performed by the applicant, using the site specific spectrum that included the Parkfield records, was examining the impact of systematically restricting the source distance of the strong motion data collected. This test was undertaken to help assess the statistical completeness of the data set collected. Figure 5 shows the effects of changing the average distance of the collected data set from 14.6 kilometers to 11.4 kilometers. The 84th percentile spectrum increases at a rate roughly equivalent to the ratio of the decreasing distance.

At this same site in Michigan, a portion of the facility was founded on about 40 feet of soft fill material on top of the stiff soil. A second suite of strong motion records was collected by the applicant matching the same target magnitude and distance but for strong motion sites with slightly deeper soil profiles then those originally selected. In this case some of the same records fit both the soil and the soil-plus-the-fill profile equally well. Figure 6 compares the 84th percentile of these two sets of data. As expected, the deeper soil site spectrum is "richer" in low frequencies while it is approximately the same as the shallower soil site-specific spectrum at frequencies of 4 hertz and greater.

The applicant in the above case, had also calculated theoretical amplification of the soft fill on top of the stiff soil using the SHAKE computer code. Figure 7 shows the ratio of soil-plus-fill over soil from both the site-specific response spectra and the SHAKE calculations. The shape (peaks and valleys) of the amplification curve is roughly the same for both methods, however, the magnitude of the amplification appears to be underestimated by about a factor of 2, using the theoretical technique. In this case the empirical results were directly used to evaluate the site, while the theoretical results verified the shape of the amplification of ground motion through the fill material.

Figures 8 and 9 show the 84th percentile spectra in a comparison of rock sites (100's of feet of still soil) for target magnitudes of 5.3 and 5.8 completed by the applicant and NRC staff's consultant, respectively. In these examples, the rock spectra are more deficient in the lower frequencies. In the above examples the higher frequency spectral values are roughly equivalent. Figure 10 compares a rock spectrum and a shallow soil (10's of feet) site-specific spectrum completed by the NRC staff's consultant, again for a target magnitude of about 5.3. In this example the shallow-soil spectrum is very much richer in the higher frequencies compared to the rock case.

The above examples show one advantage of site specific spectra, that is, the ability to model a difference in the predominant frequency content of the ground motion for different site conditions. Use of a standard spectral shape would not reproduce the above variations observed in site specific spectral shapes and would require assumptions regarding the choice of peak acceleration and/or velocity. These assumptions are unnecessary if site specific spectra is calculated.

In the above cases, the target magnitude and recorded distance of records collected was kept roughly constant and different site conditions were compared. The next examples show what happens when the site conditions and distance are held roughly constant, and the target magnitude is varied. Figure 11 contains the the 84th percentile level spectra collected by consultants to applicants and the NRC staff, for rock sites, with the average magnitudes of the 3 curves being 5.3, 5.7 and 6.0. Figure 12 shows the 84th percentile spectra collected by consultants to applicants for deep stiff soil sites with the average magnitudes of about 5.4 and 6.1. These two cases suggest that, in this magnitude range, the lower frequency ground motion increases at a faster rate compared to the high frequencies for a given increase in magnitude. The log of spectral acceleration (measured at 25 Hz on response spectrum to roughly correspond with peak acceleration frequency) roughly scales at 0.20 to 0.25 times the magnitude whereas the log of spectral velocity (measured at 1 to 2 Hz on response spectrum to roughly correspond to peak velocity frequencies) roughly scales at 0.45 to 0.50 times the magnitude. The scaling of spectral acceleration and spectral velocity, in these two examples is very close to the scaling of peak acceleration and peak velocity estimated by Joyner and Boore (1981). Thus, the above observations using site specific spectra demonstrates a way of accounting for the change in the frequency content of ground motion as the size of the earthquake changes.

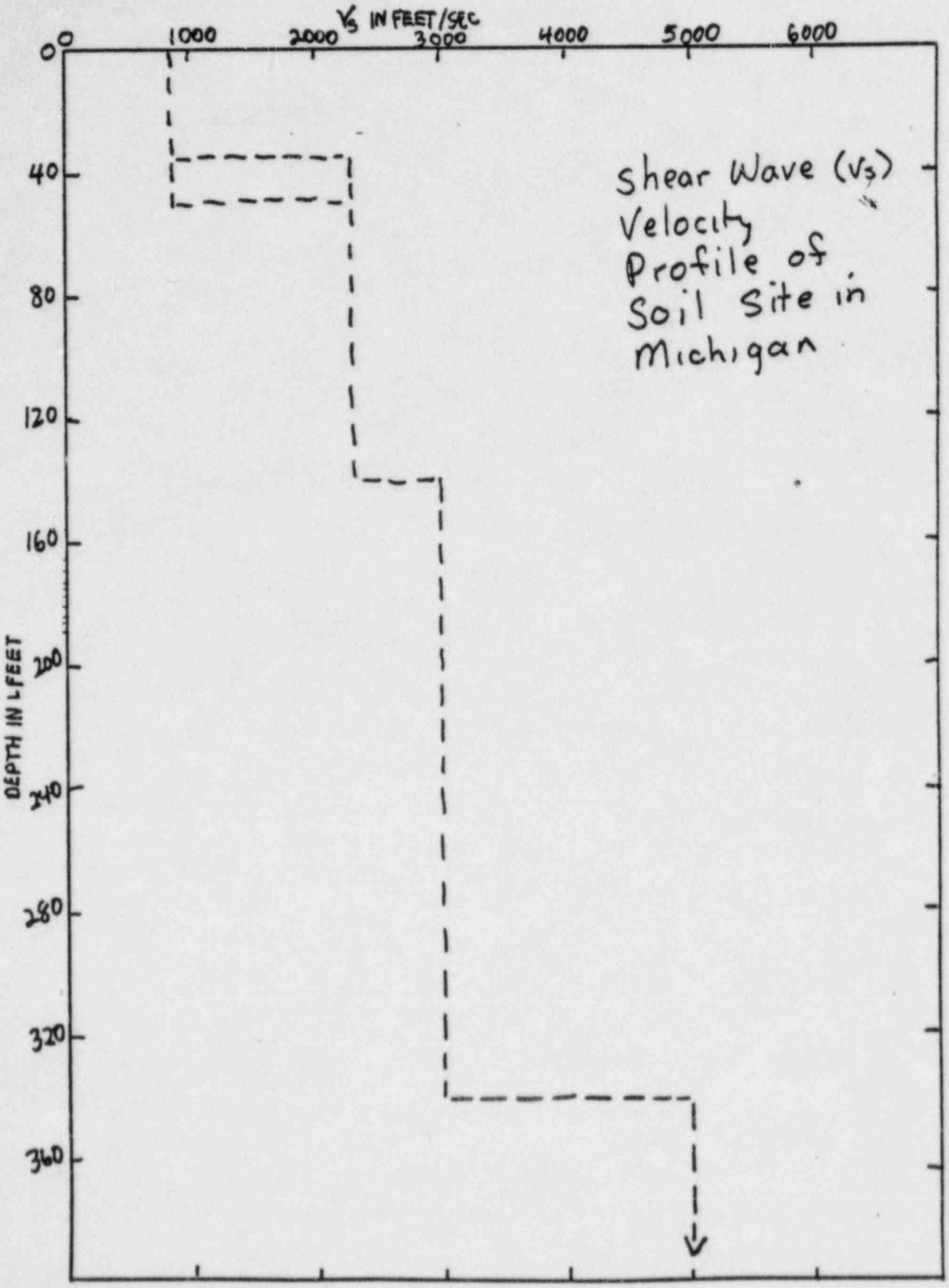
The above cases show two of the advantages of the use of site-specific spectra. However, there are still limitations to this method including technical issues that need to be investigated, and the limited size of existing data base. These technical issues include attenuation, source characteristics and the scaling of data to match the conditions of interest. Many critical facilities are located in regions of the United States where the attenuation characteristics are very different than those in California, where most of the strong ground motion data has been recorded. The examples in this paper have utilized strong motion recordings at distances of less than about 25 kilometers where these attenuation differences are minimized, yet there may be cases where the controlling earthquake will be at a greater distance such that attenuation differences are much more important. One key technical issue is, whether scaling of records in the western United States can be utilized to take into account attenuation differences for different regions of the country. In addition to attenuation differences, there also may exist source characteristic differences between various regions of the United States. Research into quantifying these potential source differences is an area which requires work. Once this is quantified, Western United States strong motion records may again need some type of scaling to be utilized in other regions of the United States, particularly if there continues to be a lack of strong motion data in the East.

Although the general shift in the frequency content for differing site conditions has been observed, as shown in the present paper, more research is needed to document the effect that local site conditions have on modifying strong motion. This includes a better documentation of which specific subsurface properties should be used to better model potential amplification effects. In addition, care needs to be exercised in deploying strong motion instruments, both permanent and portable, in areas where the site conditions have been, or could be, easily documented. As an example, there appear to be no rock recordings, which do not have at least some thin soil cover, from the Mammoth Lakes strong motion data set. In addition, the current data base, although rapidly expanding, is still limited particularly for magnitudes greater than about 6.5 at small source distances.

In conclusion, the NRC has utilized site specific spectra in an attempt to more realistically account for both the spectral level and frequency content of strong motion at different sites. However, this use is limited by both the extent of the existing data base, and regional differences in attenuation and uncertainties of source characteristics. With additional research an expanded use of the existing data may be possible.

TABLE 1

Date	M_L	Location	Stations Used
3/22/57	5.3	San Francisco, CA	Southern Pacific Bldg. Alexander Bldg. Golden Gate Park
6/28/66	5.6	Parkfield, CA	Cholame 5 Cholame 8 Cholame 12
9/12/70	5.4	Lytle Creek, CA	Cedar Springs Pump House San Bernardino Hall of Records Colton Wrightwood
11/28/74	5.2	Gilroy, CA	Gavilan College
1/12/75	5.2	Cape Mendocino, CA	Petrolia Gen. Store
6/7/75	5.2	Cape Mendocino, CA	Petrolia Gen. Store
5/7/76	4.9	Friuli, Italy	Tolmezzo
5/9/76	5.5	Friuli, Italy	Forgaria Maiano Tolmezzo
5/11/76	5.3	Friuli, Italy	Forgaria Maiano Tolmezzo Torcento
9/11/76	5.5		Forgaria Tarcento
9/15/76	5.0		Forgaria



Shear Wave (V_s)
Velocity
Profile of
Soil Site in
Michigan

Figure 1

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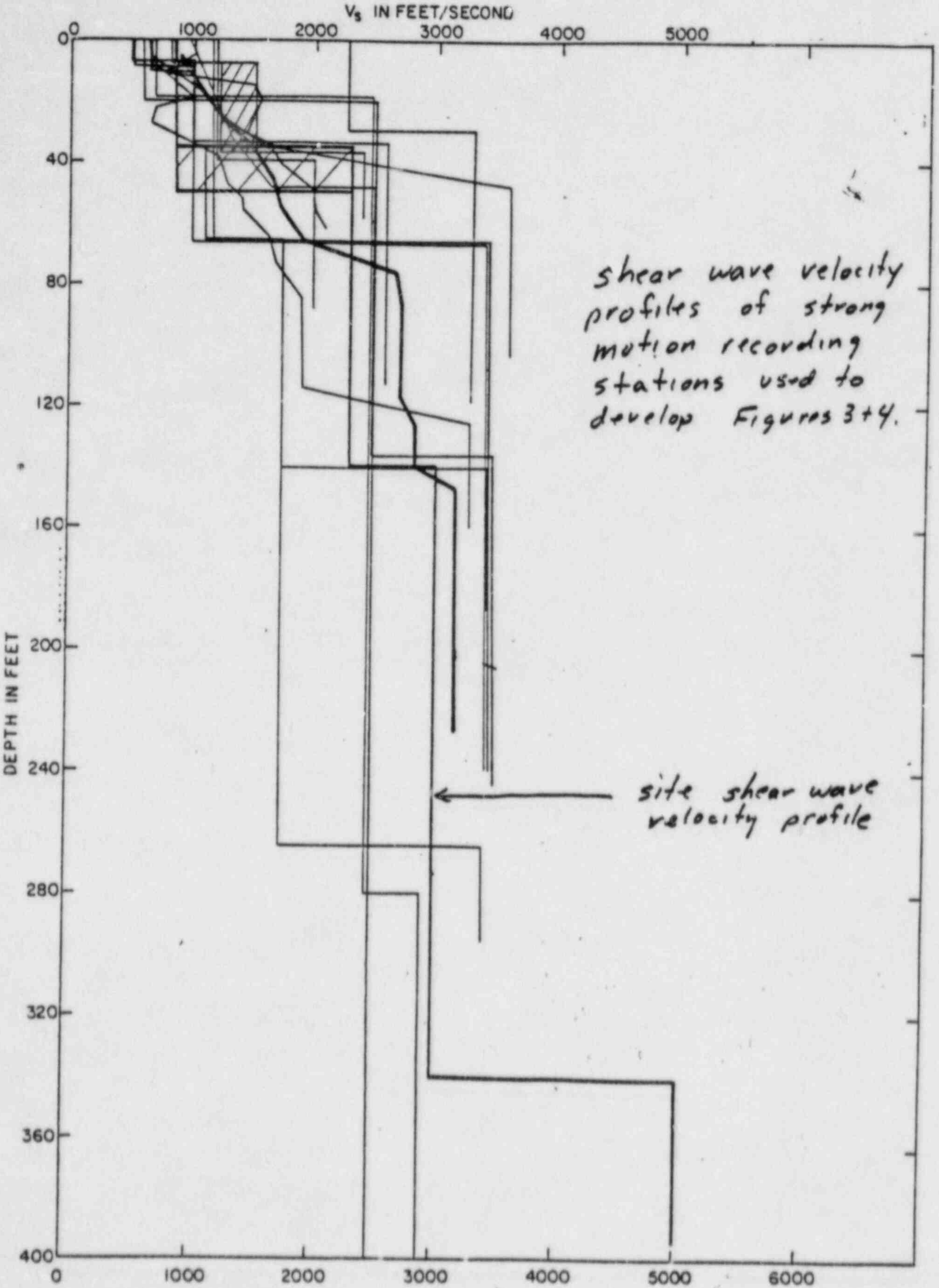
Geophysical



shear wave velocity profiles of strong motion recording stations used to develop Figures 3+4.

site shear wave velocity profile

Figure 2

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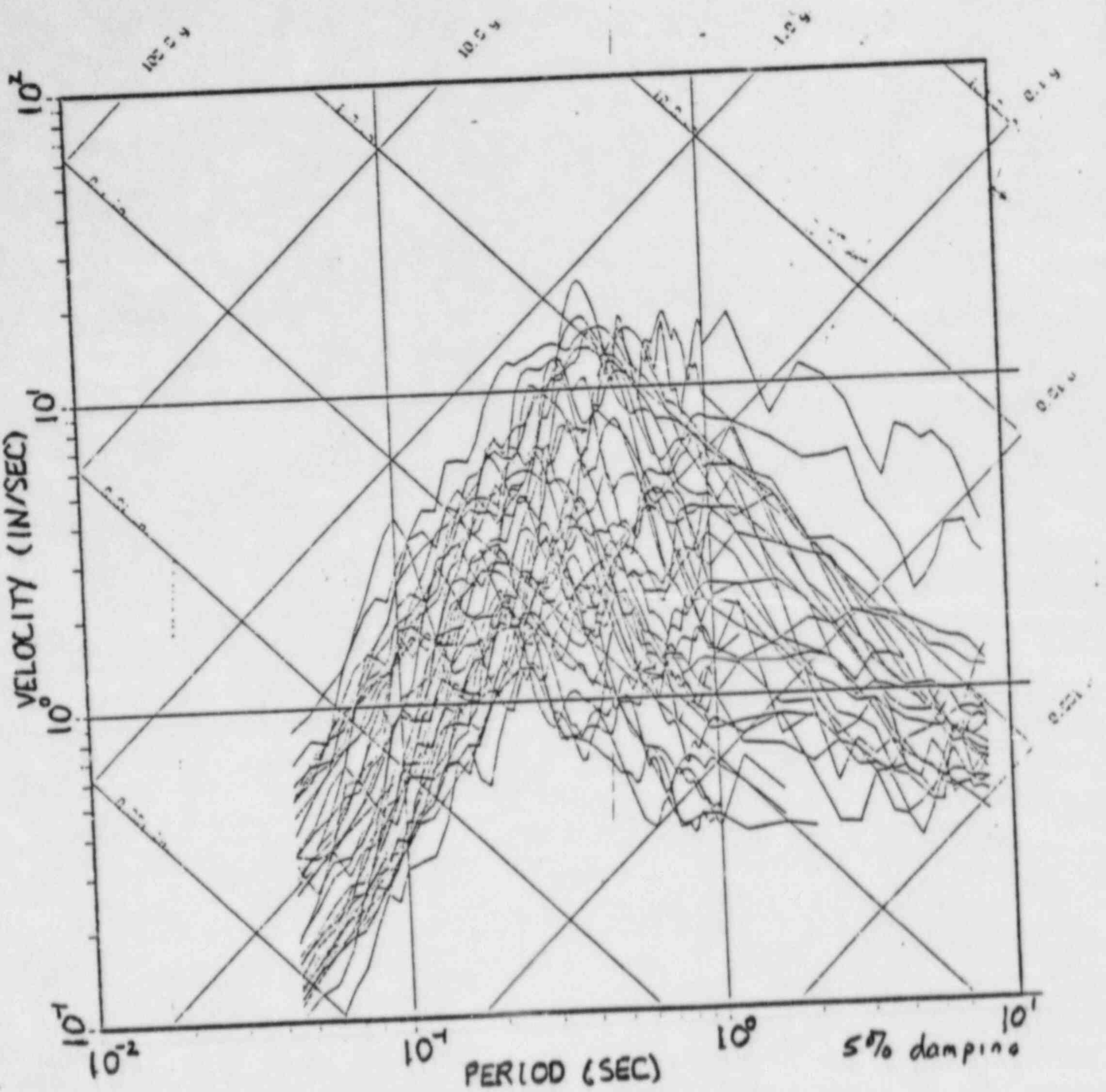
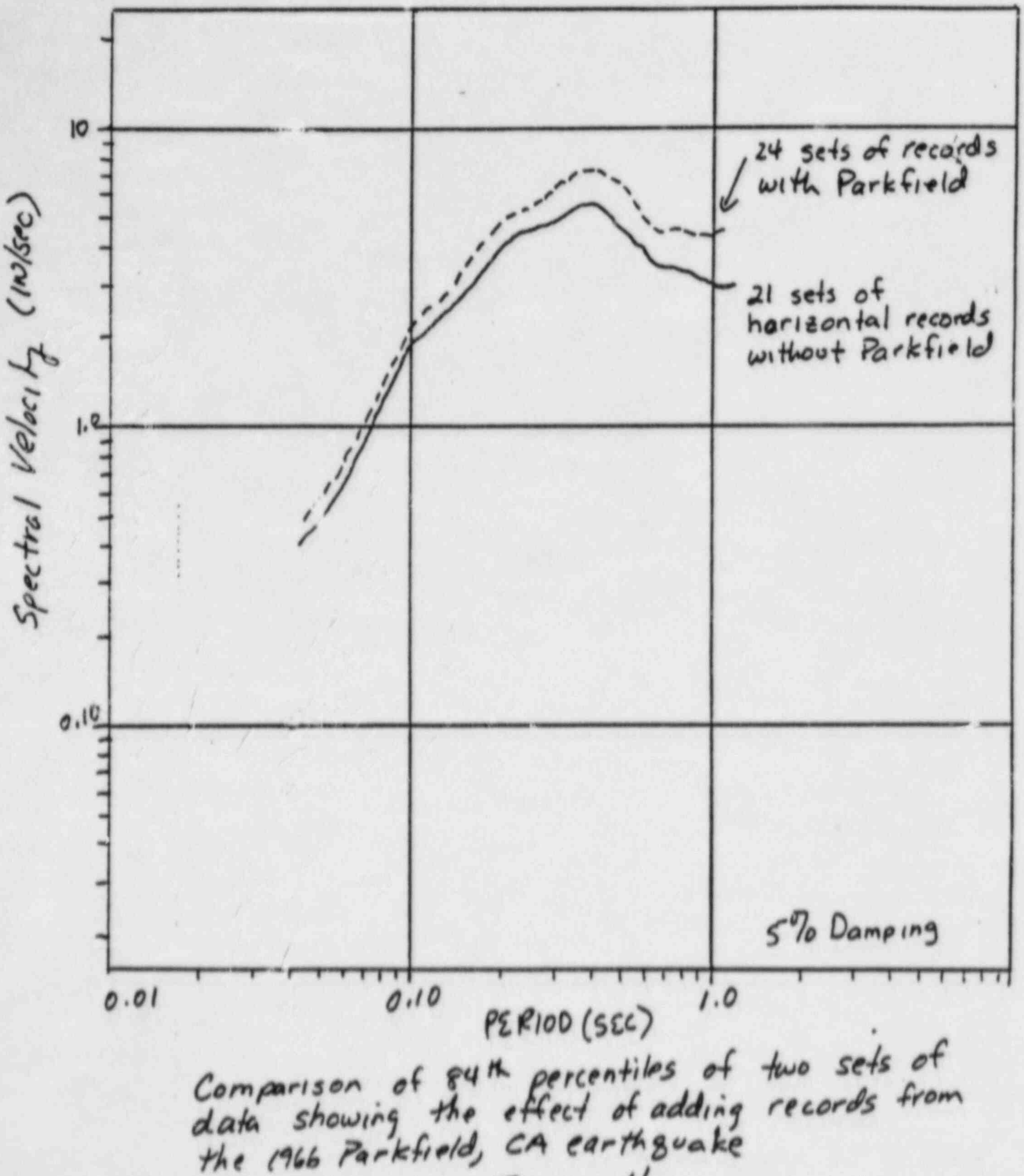


OVERPLOT OF RESPONSE SPECTRA used to develop site specific spectrum in Figure 4

Weston Geophysical

Figure 3



Comparison of 84th percentiles of two sets of data showing the effect of adding records from the 1966 Parkfield, CA earthquake

FIGURE 4

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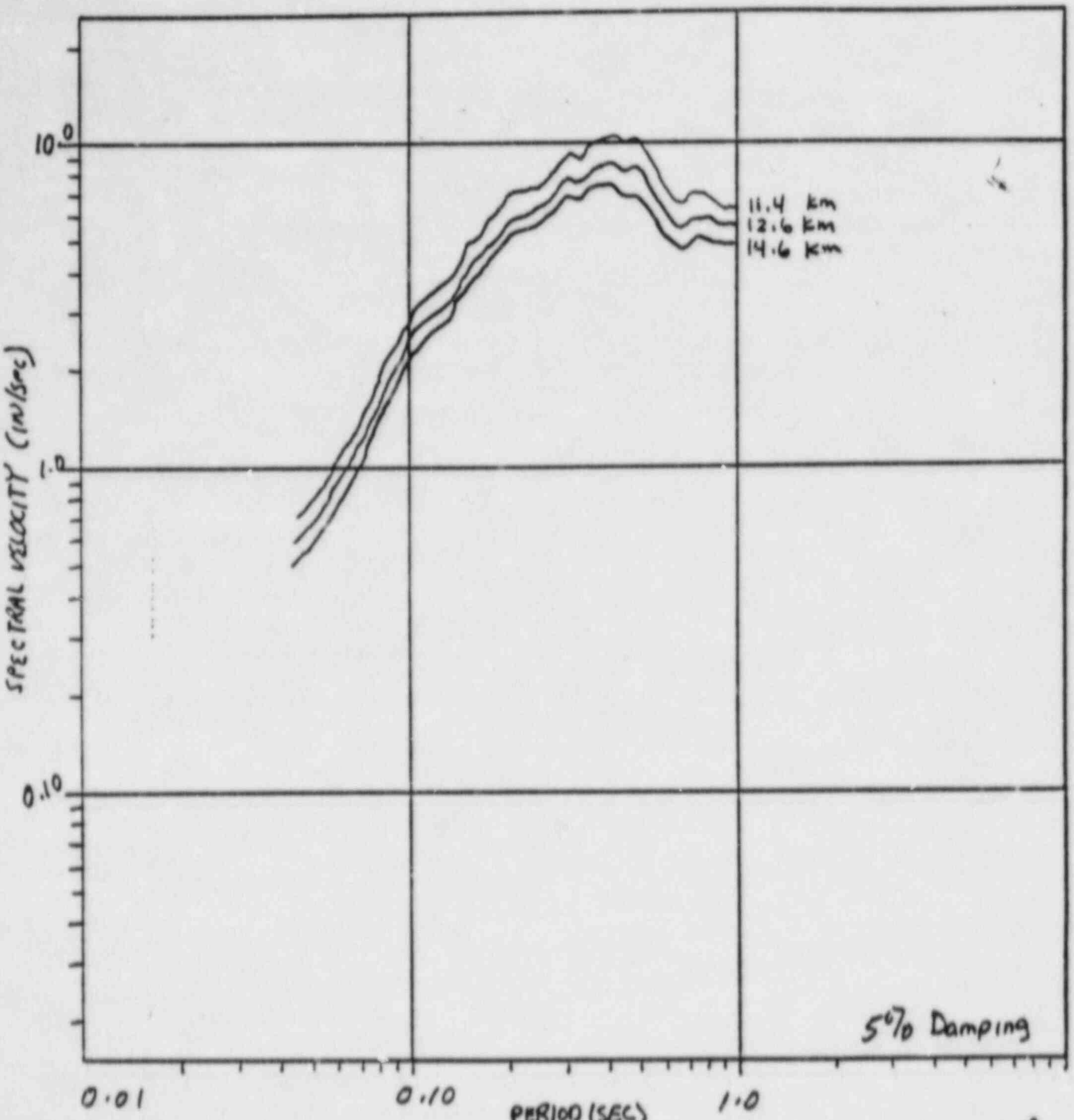

Comparison of the 84th percentiles of the site specific spectra with Parkfield data in Figure 4, as the source distance of the strong motion data is systematically restricted.

Figure 5

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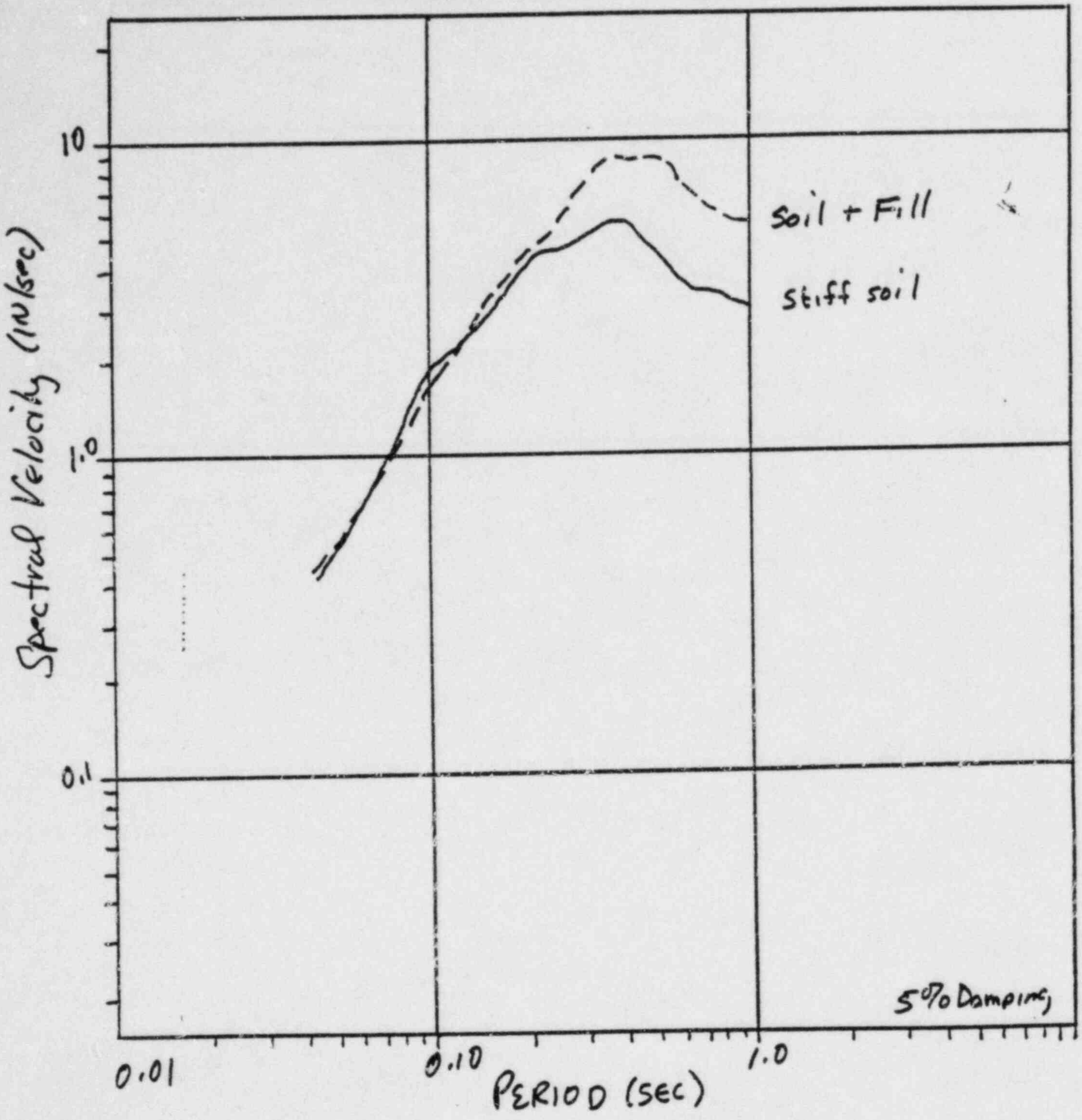

Comparison of 84th percentile of site specific spectra on top of stiff soil and on top of stiff soil plus fill material

Figure 6

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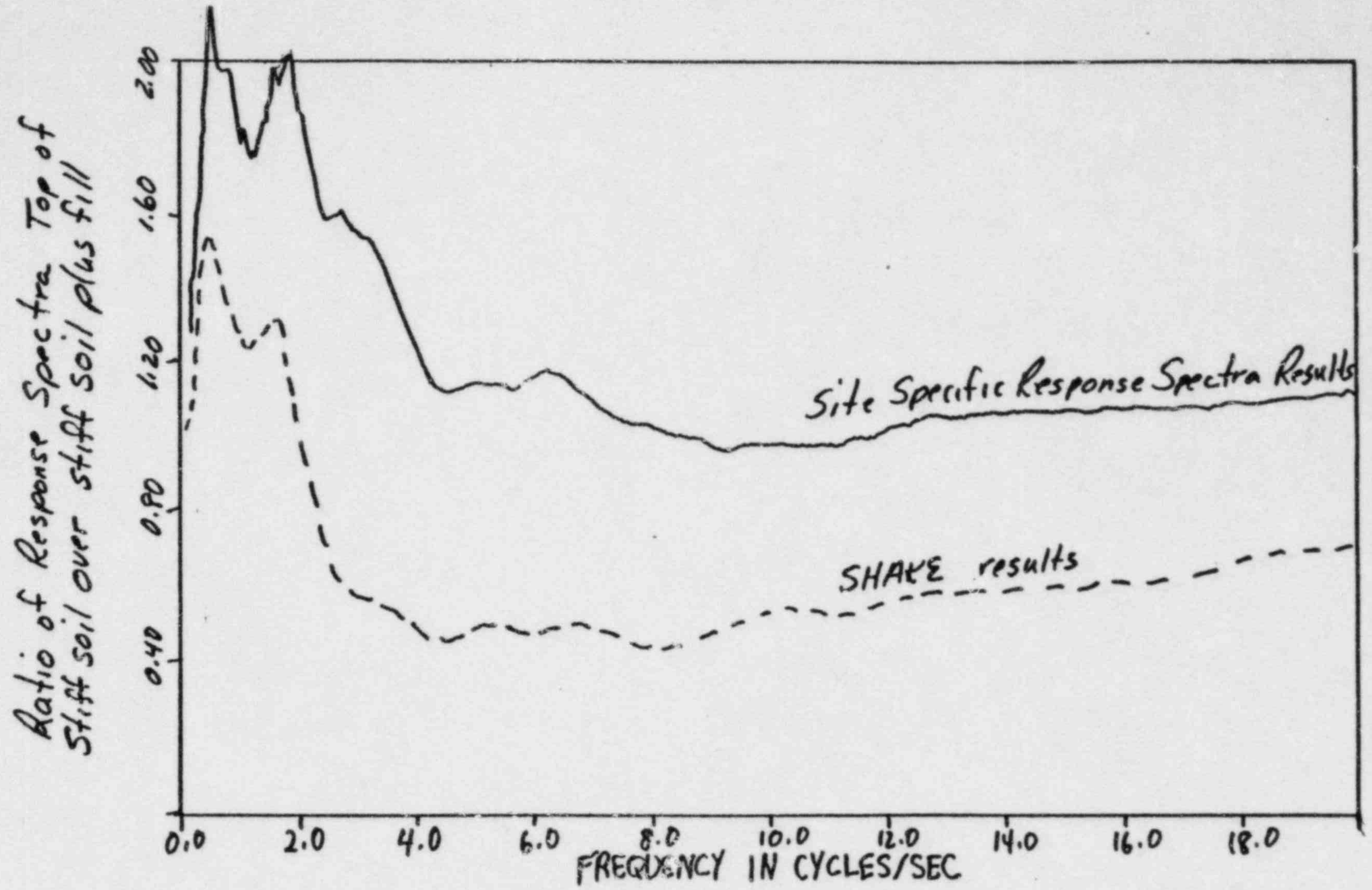

Comparison of Amplification from Site Specific Response Spectra to that of SHAKE

Figure 7

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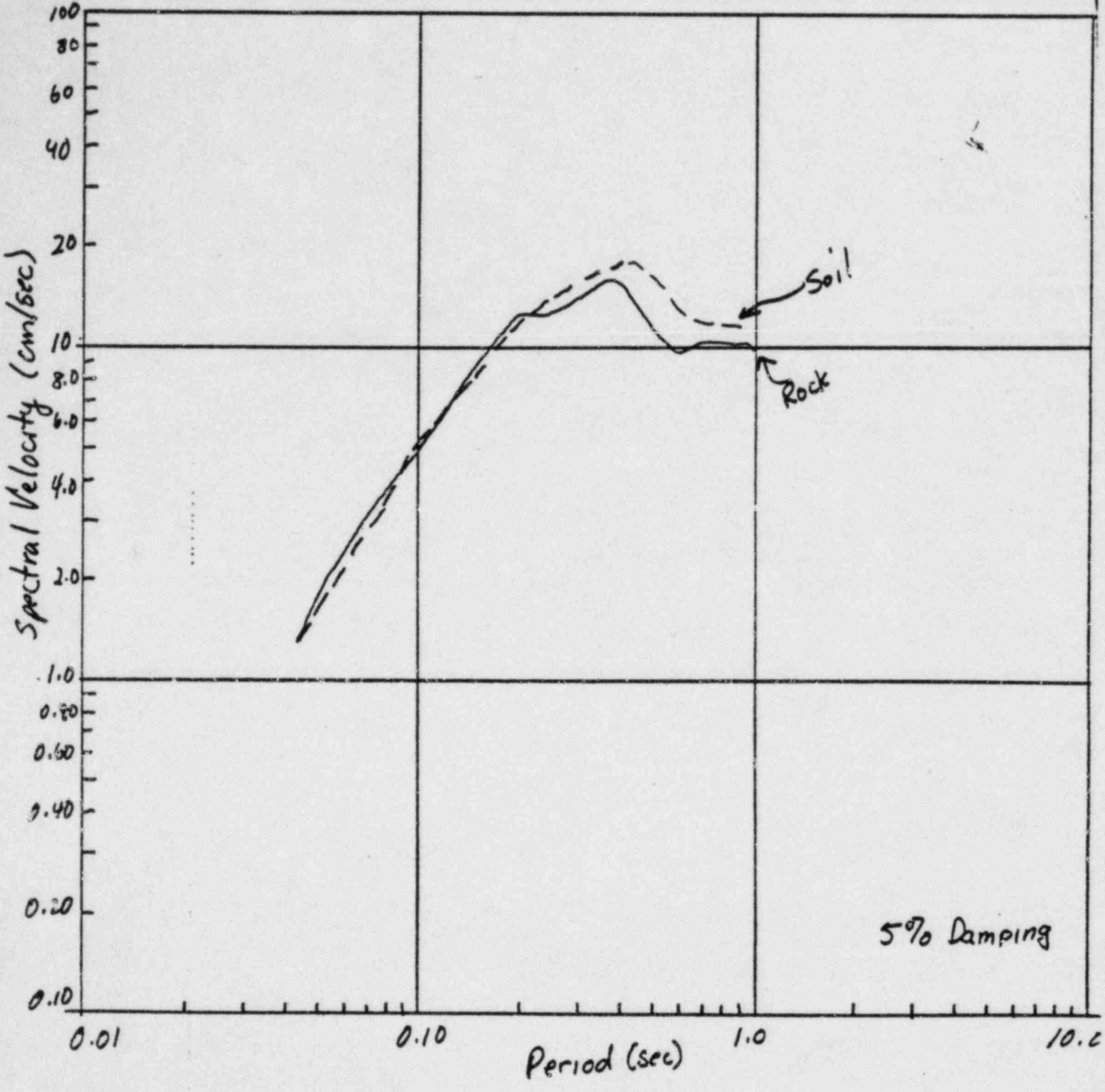
Geophysical



Comparison of 84th percentiles of $M_L = 5.3$ soil and rock site specific spectra

Figure 8

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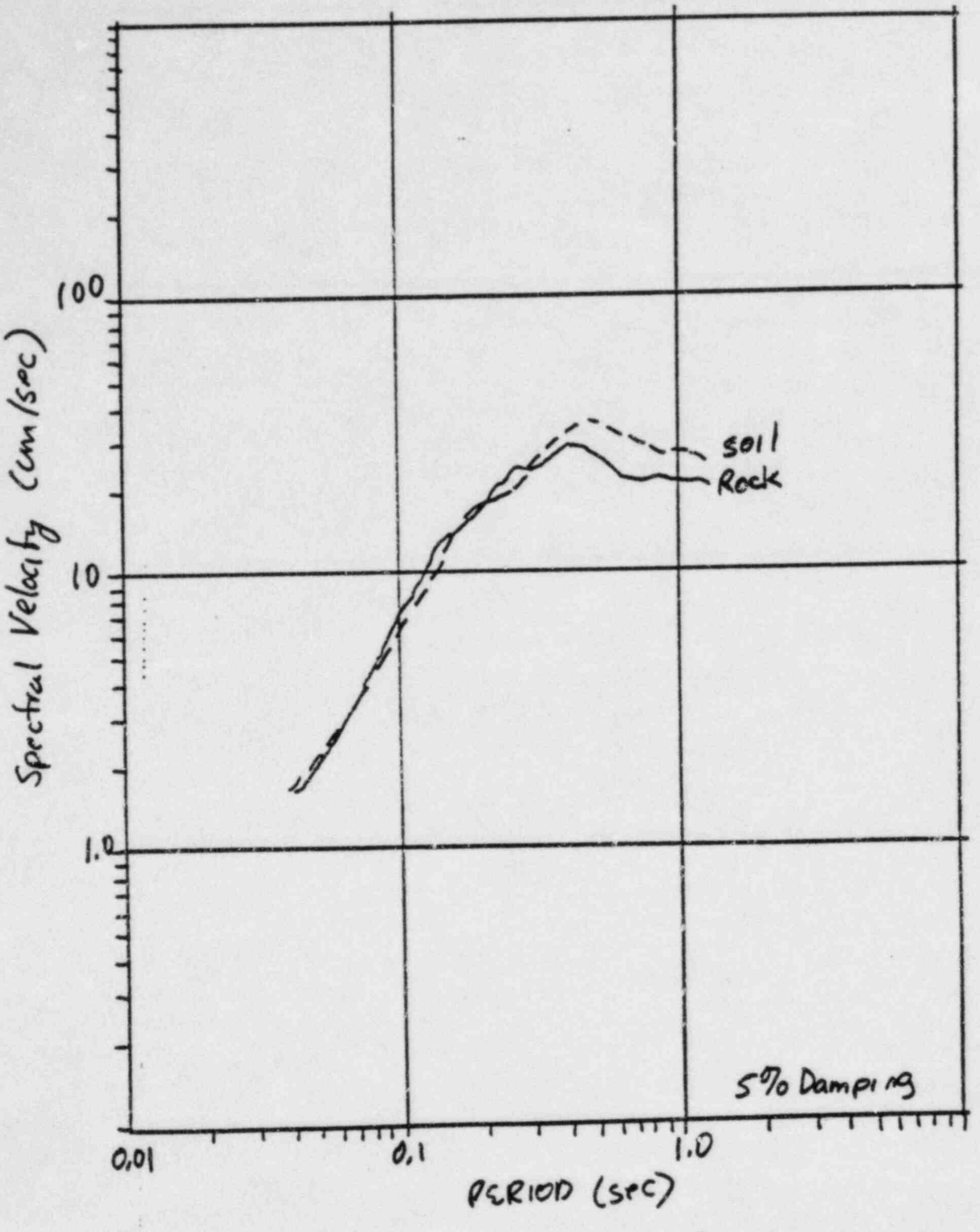
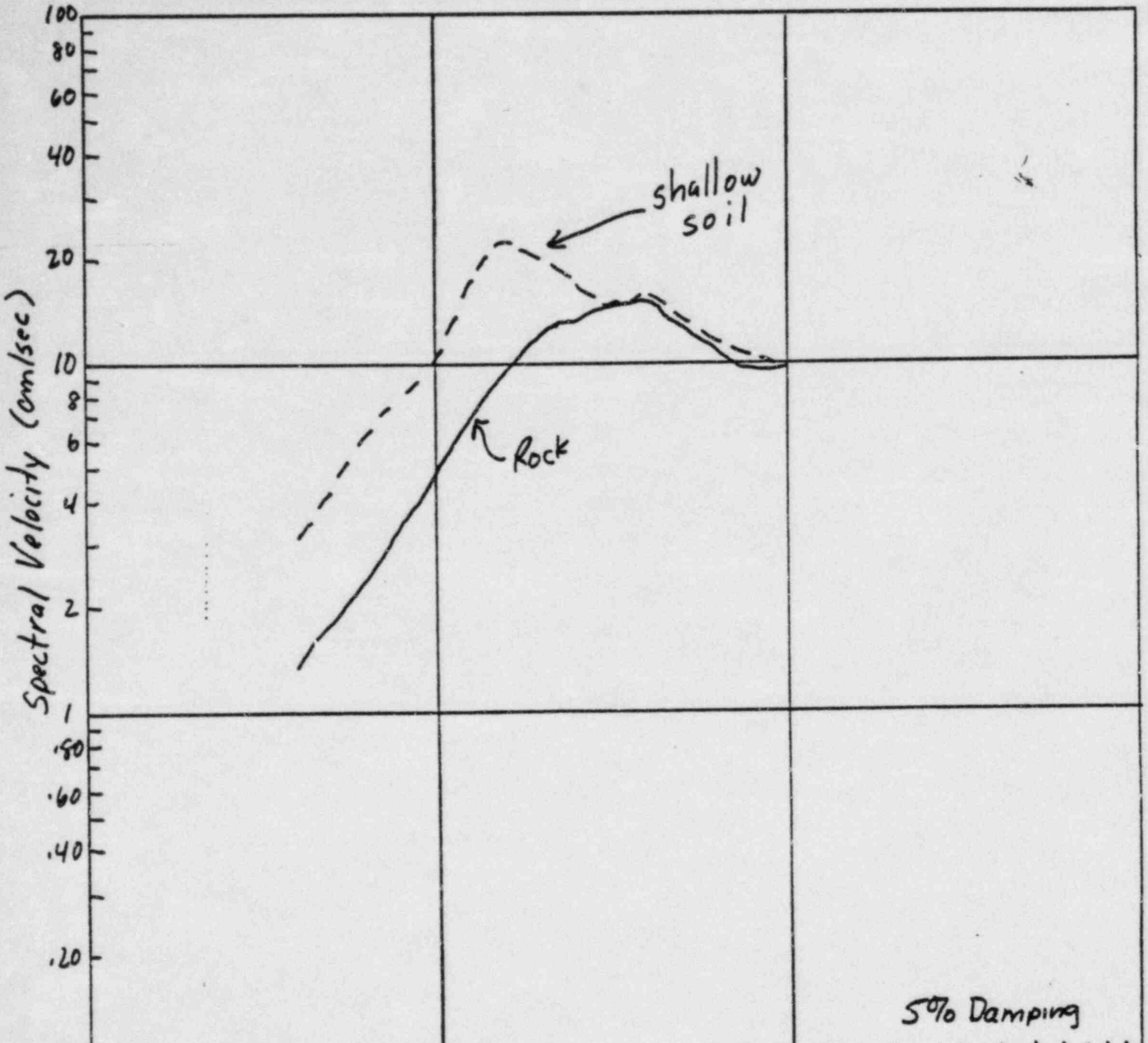
Geophysical



Comparison of 84th percentiles of a $M_L=5.8$ soil and rock site specific spectra

Figure 9

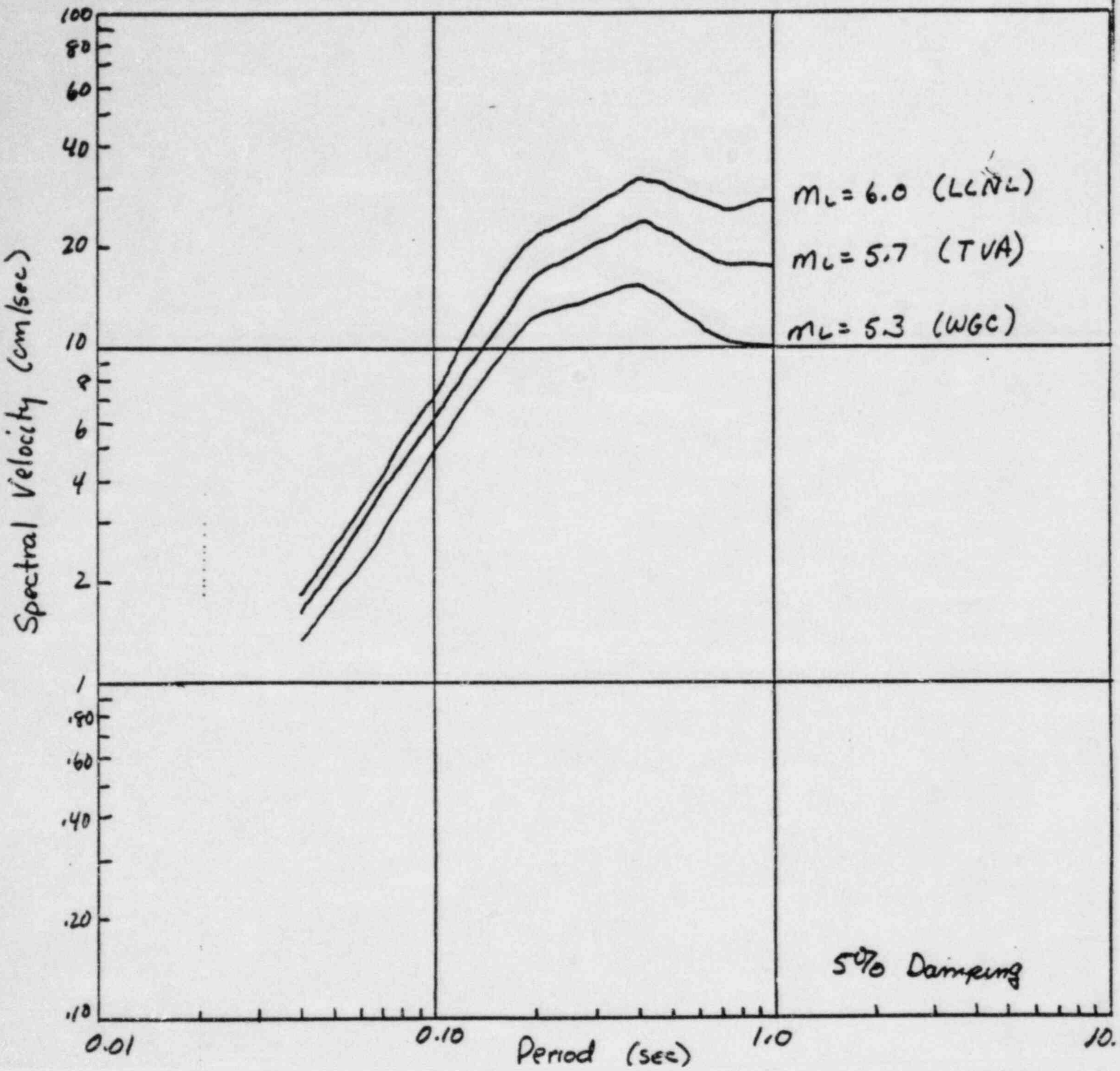
Lawrence
Livermore
National Lab



Comparison of 84th percentiles of $M_L = 5.3$ shallow soil and rock site specific spectra

Lawrence
Livermore
National Lab

Figure 10



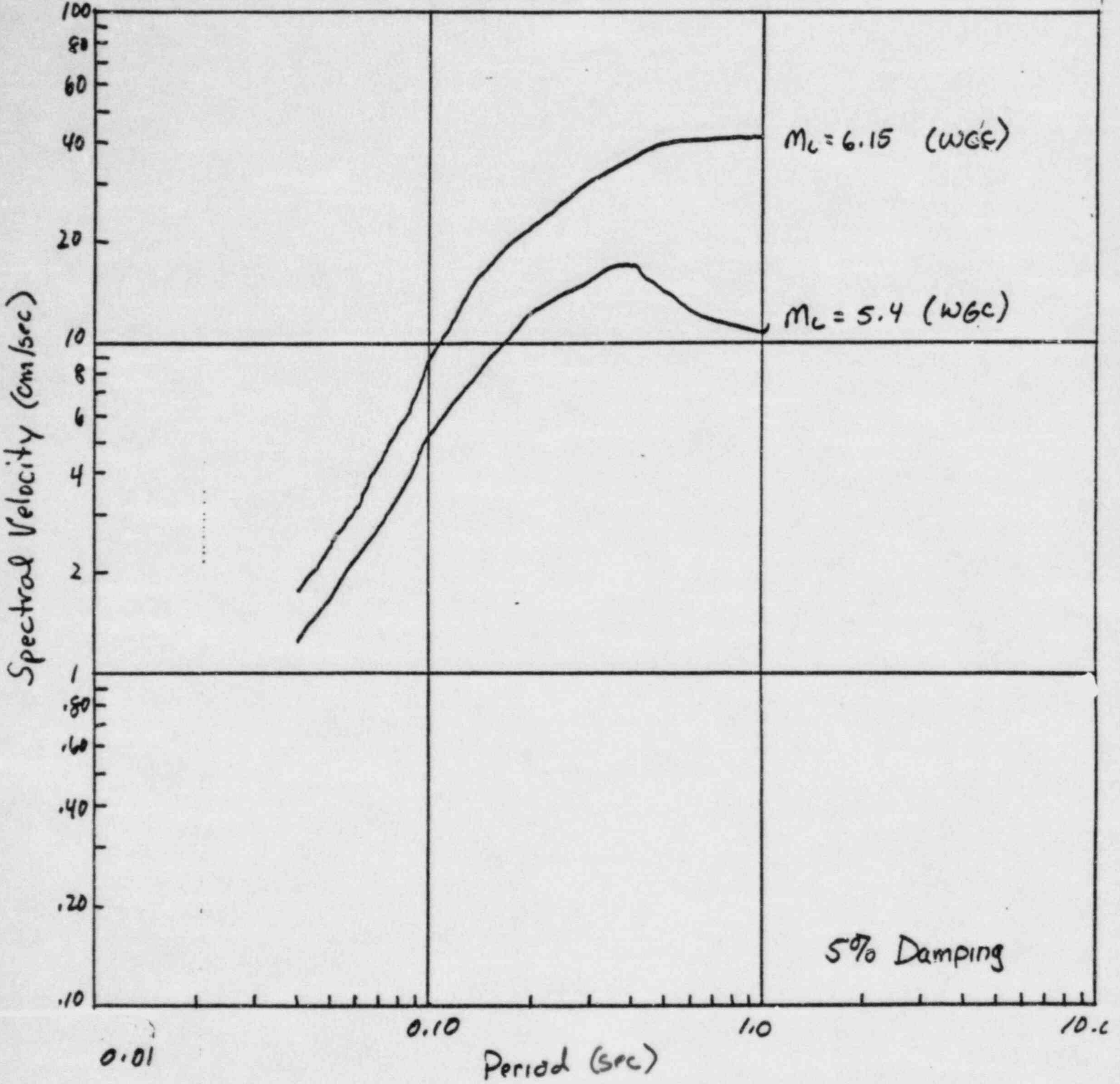
Comparison of 84th Percentile of $m_L = 5.3, 5.7, 6.0$ rock site specific spectra.

Figure 11

Lawrence Livermore National Lab

Weston Geophysical

Tennessee Valley Authority



Comparison of 84th Percentile of $M_L = 6.15, 5.4$ soil site specific spectra

Woodward-Clyde Consultants

Figure 12

Weston Geophysical

COMPARISON OF COMPUTED HIGH STRESS AREAS WITH RECORDED CRACKED A

WEST CENTER WALL

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NSWC Figure	Computed High Stress Areas	Period of Measured Settlement	Observations ~~[illegible]~~ of J. Kon ~~Comments~~, in Comparison of Cracked Areas with High Stress Area			Conclusions on Comparison
			Fig 14-2 Mapping December 1978	Figs 28-2 and 28-3 Mapping Dec 1978, Sept. 1979 to ~~[illegible]~~ Jan. 1980	~~Fig 28-3 Mapping~~ Fig 49 Mapping July 1981	
31	On south side ① below El 650	3/28/78 to 8/15/78 (Presurcharge)	* No cracks shown ~~recorded~~ on 12/78 Map	Crack observed in 9/79 is recorded in this area and is identified as crack due to structural displacement	Same crack observed in 9/79 is again recorded in 7/81	Cracks do appear in all NSWC identified areas of high stress when incremental settlements for a given time frame are imposed and the latest crack mapping (July 1981) is used. If comparison is limited to available maps closest to dates of measured settlement then cracks appear in 4 out of the 6 locations (shown by asterisks) of high stresses. The fact that cracks were observed in 12/78, not observed in 9/79 but reappear in some locations in 7/81 could mean, the cracks were also missed in 9/79
32	On north side ② below El 650	3/28/78 to 8/15/78 (Presurcharge)	* Crack shown in 12/78 Map ~~[illegible]~~	No cracks shown on 9/79 Map	Cracks shown in 7/81 Mapping	
33	On north side ③ above El 634	8/78 to 1/79 (Presurcharge)	* Cracks shown in 12/78 Map	No cracks shown on 9/79 Map	Cracks shown in 7/81 Mapping and slight extension of 12/78 ~~mapping~~ mapped cracks	
35	On north side ② below El 650	8/78 to 1/79 (Presurcharge)	* Cracks shown in 12/78 Map	No cracks shown on 9/79 Map	Cracks shown in 7/81 Mapping	
37	On north side ③ above El 634	1/79 to 8/79 (Surcharge Period)	Fig 14-2 Mapping not applicable as it predates this period of settlement	* No cracks shown on 9/79 Map	Cracks shown in 7/81 Mapping and slightly extend 12/78 mapped cracks	
39	On south side ④ above El 634	1/79 to 8/79 (Surcharge Period)	Fig 14-2 Mapping not applicable.	* Crack shown in 9/79 Map and is identified as structural displacement crack	Same crack observed in 9/79 is again recorded in 7/81	

10/8/83
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COMPARISON OF COMPUTED HIGH STRESS AREAS WITH RECORDED CRACKED AREAS

CENTER WALL

NSWC Figure	Computed High Stress Areas	Period of Measured Settlement	Observations of J. Kane in Comparison of Cracked Areas With High Stress Areas			Comparison Conclusions
			Fig 14-2 Mapping December 1978	Figs 28-2 and 28-3 Mapping Dec 1978; Sept '79 to Jan '80	Fig 49 Mapping July 1981	
31	On north side ① above El. 634	3/28/78 to 8/15/78 (Presurcharge)	Cracks shown in 12/78 Map	Cracks shown and increase ~~in number~~ from 12/78 to 9/79	Cracks shown in 7/81 Mapping	Cracks do appear in 5 out of the 6 locations where NSWC has computed areas of high stress and on crack maps with dates closest to the periods of measured settlements
32	On north side ② below El. 650	3/28/78 to 8/15/78 (Presurcharge)	Cracks shown in 12/78 Map	Cracks shown and increase from 12/78 to 9/79	Cracks shown in 7/81 Mapping	
33	On north side ① above El. 634	8/78 to 1/79 (Presurcharge)	Cracks shown in 12/78 Map	Cracks shown and increase ~~in number~~ from 12/78 to 9/79	Cracks shown in 7/81 Mapping	
35	On north side ① above El. 634	8/78 to 1/79 (Presurcharge)	Cracks shown in 12/78 Map	Cracks shown and increase ~~in number~~ from 12/78 to 9/79	Cracks shown in 7/81 Mapping	
37	On north side ① above El. 634	1/79 to 8/79 (Surcharge Period)	Fig 14-2 Mapping not applicable as it predates this period of settlement	Cracks shown and increase ~~in number~~ from 12/78 to 9/79	Cracks shown in 7/81 Mapping	
39	On south side ③ above El. 634	1/79 to 8/79 (Surcharge Period)	Fig 14-2 Mapping not applicable	No cracks shown on 9/79 Map	No cracks shown on 7/81 Map	

COMPARISON OF COMPUTED HIGH STRESS AREAS WITH RECORDED CRACKED AREAS

10/8/83
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EAST CENTER WALL

NSWC Figure	Computed High Stress Areas	Period of Measured Settlements	Observations of J. Kane in Comparison of Cracked Areas With High Stress Areas			Comparison Conclusions
			Fig 14-2 Mapping December 1978	Figs 28-2 & 28-3 Mapping Dec 78; Sept '79 to Jan '80	Fig. 49 Mapping July 1981	
31	On south side below El. 663 (Not reasonable since wall is built only to El. 656 at this time					Location of high stress is unreasonable for this stage of construction. No comparison therefore can be made.
32	On north side ① below El 650	3/28/78 to 8/15/78 (Presurcharge)	* Cracks shown in 12/78 Map	* No cracks shown in 9/79 Map	Cracks shown in 7/81 Mapping	Cracks do appear in all NSWC identified areas of high stress when incremental settlements for a given time frame are imposed and the latest crack mapping (July 1981) is used.
33	On north side ② above El. 634	8/78 to 1/79 (Presurcharge)	* Cracks shown in 12/78 Map	No cracks shown in 9/79 Map	Cracks shown in 7/81 Mapping	
35	On ~~[illegible]~~ south side ③ ~~[illegible]~~ above El. 640	8/78 to 1/79 (Presurcharge)	* Cracks appear very close to this location in 12/78 Map	Crack shown in 12/78 Map	Crack shown in 7/81 Mapping	If comparison is limited to available maps closest to dates of measured settlements, then cracks appear in 3 out of the 5 locations (shown by asterisks) of high stresses.
37	On north side ④ above El. ~~[illegible]~~ 646	1/79 to 8/79 (Surcharge Period)	Fig 14-2 Mapping not applicable as it predates this period of settlement	* No cracks shown in 9/79 Map	Cracks shown in 7/81 Mapping	
39	On south side ⑤ above El. 634	1/79 to 8/79 (Surcharge Period)	Fig 14-2 Mapping not applicable.	* Crack shown in 12/78 Map but not in 9/79 Map	Crack shown in 7/81 Mapping	