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LOCAL DISTRIBUTION OF STRONG EARTHQUAKE GROUND MOTIONS

BY DONALD E. HUDSON

ABSTRACT

Twenty ground stations distributed over a 40-square-mile area in Pasadena recorded strong ground shaking during the San Fernando earthquake of February 9, 1971. Relative responses at 10 of these same stations as measured for small earthquakes by standard Wood-Anderson torsion seismometers are available for comparison from a study made by Gutenberg in the 1950's. Frequency spectra of strong ground motions as calculated for four sites having time-recording accelerographs assist in the interpretation of seismoscope results at the other stations. Attempts to correlate local distributions with known features of local geology such as thickness of alluvium, distance from known faults, etc., indicate that no single feature plays a dominant role in the resulting patterns. The implications of such complicated distributions for the preparation of seismic risk maps are discussed, and it is concluded that it would not be possible in the present state of knowledge to assess meaningful variations in the seismic risk throughout the Pasadena area.

INTRODUCTION

From the earliest days of earthquake studies, it has been observed that damage varies widely from point to point in the epicentral region, and much speculation has been devoted to possible causes. Some variation may, of course, be attributed to the different resistances of the damaged structures and to local soil and foundation failures, but, beyond this, there sometimes seem to be clear patterns of local variation in the amplitudes of ground shaking. This is, of course, not surprising, in view of the enormous complexity of the whole system involving the generation of seismic waves by an extended source and the propagation of the waves through a highly inhomogeneous medium to a site which may also be strongly influenced by an irregular surface topography.

These observed patterns of ground shaking have naturally directed thoughts to the possibilities of seismic zoning and the preparation of seismic risk maps. It would obviously be of great importance to know before an earthquake the particular regions likely to experience heavy shaking, and it would be hoped that ultimately these varying levels of excitation could be reflected in the requirements of building codes. This could, of course, be done only if such variations could be clearly correlated with local geological and soil conditions which could be conveniently delineated before the earthquake. To this end, numerous attempts have been made to correlate damage with such factors as depth of alluvium, character of foundation soil, distance from known faults, etc. What has been conspicuously lacking in all such investigations is the opportunity for actual case studies, in which predictions can be directly compared with measured strong earthquake ground motion.

The San Fernando earthquake of February 9, 1971 has provided one region for which such case studies can be carried out in some detail. This earthquake occurred near the center of the area most densely instrumented for strong-motion measurements of any region in the United States. The present investigation is concerned with one small subregion within the Los Angeles basin, the Pasadena area, for the following reasons:

1. The Earthquake Engineering Research Laboratory of the California Institute of Technology has been active for many years in the development of instrumentation for strong-motion studies, and the immediate vicinity of the campus in Pasadena is unusually well instrumented.

2. The area has been studied in great detail for small earthquake response (Gutenberg, 1957). Wood-Anderson seismometers were installed at a number of sites in sets of six, and simultaneously recorded many small earthquakes under a variety of site conditions. On the basis of the variations between the sites, certain principles for seismic zoning were proposed. Shortly after this investigation, strong-motion instruments were installed at most of the sites, with the idea that, if eventually a strong earthquake ground motion should occur, comparative studies would be possible.

This strong earthquake has now occurred, and the object of the present report is to indicate the type of information available, to give some quantitative results on the distributions of strong ground motion in this particular region, to suggest some comparisons with the results obtained previously by Dr. Gutenberg, and to assess the implications of these measurements for the basic problem of seismic risk zoning.

The Pasadena Strong-motion Network

The map of Figure 1 will show the locations of all stations, and the relationship between the area and the epicentral region of the earthquake. The distance of the earthquake from Pasadena is such that distance attenuation effects should be a minor factor in the variation of ground shaking throughout the area. Table 1 summarizes the instrumentation and site characteristics. The instrument types have been described in more detail in a previous summary of data from the San Fernando earthquake (Hudson, 1971).

There are four stations (JPL, SL, ML and ATH) at which time-recording strong-motion accelerographs are located, and, from these records, the complete spectral properties of the ground motion can be computed. Seismoscopes were located at 19 sites. Two of the accelerograph sites and ten of the seismoscope sites were those occupied by Dr. Gutenberg. The seismoscope is a simplified, nontime-recording device which records on a record plate the two-dimensional horizontal response of a pendulum having a natural period of 0.75 sec and 10 per cent critical damping (Hudson and Cloud, 1967). The seismoscope can be regarded as a dynamic model of a typical structure, and from its response, one point on the response spectrum curve can be determined. The amplitudes of the seismoscope records thus indicate the relative severity of the ground motion in the period range of typical structures.

The straight-line segments centered on the various stations have a length proportional to the maximum relative displacement spectrum, and the direction is that of the maximum horizontal response (Hudson and Cloud, 1967). Sites showing two segments have two seismoscopes close together, as at the crest and abutment of a dam. Numerical values of the maximum relative velocity-response spectrum measurements will be found in the previously referenced data summary report (Hudson, 1971).

At three of the sites, seismoscopes and accelerographs were mounted side by side and were, thus, exposed to the same ground excitation. This provides a means of evaluating the overall accuracy of the seismoscope, because from the recorded acceleration-time curve the seismoscope response can be calculated and directly compared with the seismoscope record plate. Figure 2 indicates the results of this comparison. On the left are

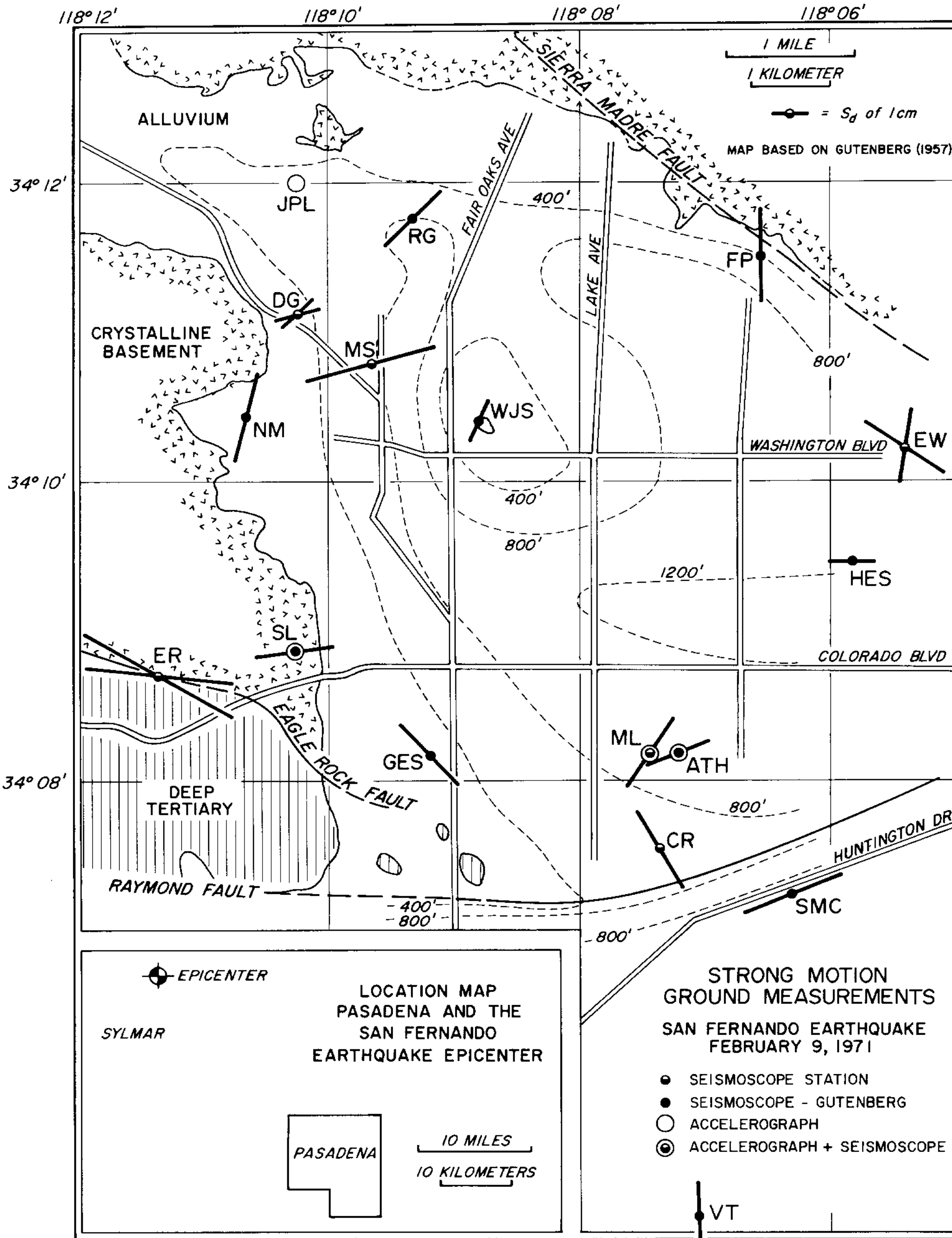


FIG. 1. Location map and maximum relative velocity response values.

reproductions of the seismoscope plates, and on the right are the computer plots calculated from the two measured horizontal components of the ground motion. The agreement of the patterns is most satisfactory and indicates that the seismoscope, in spite of its simplicity, is portraying the main features of the motion. The unidirectional character of the record on the rock at (SL) is clearly shown in the figure, as well as the fact that the maximum responses on the rock at (SL) are about the same as on some 900 ft of alluvium at (ATH).

TABLE 1

INSTRUMENTATION AND SITE CHARACTERISTICS

Site No.	Station	Location	Instrument*	Remarks
1	ATH	Caltech Athenaeum	SMA–1, 124	900 ft alluv. Bsmt. of $2\frac{1}{2}$-storey r.c. bldg.
2	CR	San Marino residence	SS 615	600 ft alluv.
3	DG	Devils Gate Reservoir (bank)	SS 568	400 ft alluv.
4	DG	Devils Gate Reservoir (crest)	SS 566	Concrete gravity dam
5	ER	Eagle Rock Reservoir (abut.)	SS 208	Cryst. rock/deep tertiary
6	ER	Eagle Rock Reservoir (crest)	SS 209	Earth filled dam
7	EW	Eaton, Wash. Reservoir (base)	SS 508	800 ft alluv.
8	EW	Eaton, Wash. Reservoir (crest)	SS 517	Earth filled dam
9	FP	Altadena residence	SS 117	400 ft alluv.
10	GES	Garfield Elementary School	SS 124	300 ft alluv.
11	HES	Hale Elementary School	SS 128	1000 ft alluv.
12	JPL	Jet Propulsion Lab.	RFT–250, 195†	400 ft alluv. Bsmt. of 9-story steel frame bldg.
13	ML	Caltech Millikan Library	RFT–250, 198†	900 ft alluv. Bsmt. of 9-story r.c. bldg.
14	MS	Muir High School	SS 108	800 ft alluv.
15	NM	Pasadena residence	SS 151	100 ft alluv.
16	RG	Altadena residence	SS 133	800 ft alluv.
17	SL	Caltech Seismological Lab.	RFT–250, 193†	Granite crystalline rock
18	SMC	San Marino City Hall	SS 115	1200 ft alluv.
19	VT	Alhambra residence	SS 110	1000 ft old sed. over tertiary
20	WJS	Washington Jr. High School	SS 100	Crystalline rock outcrop

* Numbers are instrument serial numbers. SMA–1 and RFT–250 are time-recording accelerographs; SS = seismoscope.
† Interconnected network for common start.

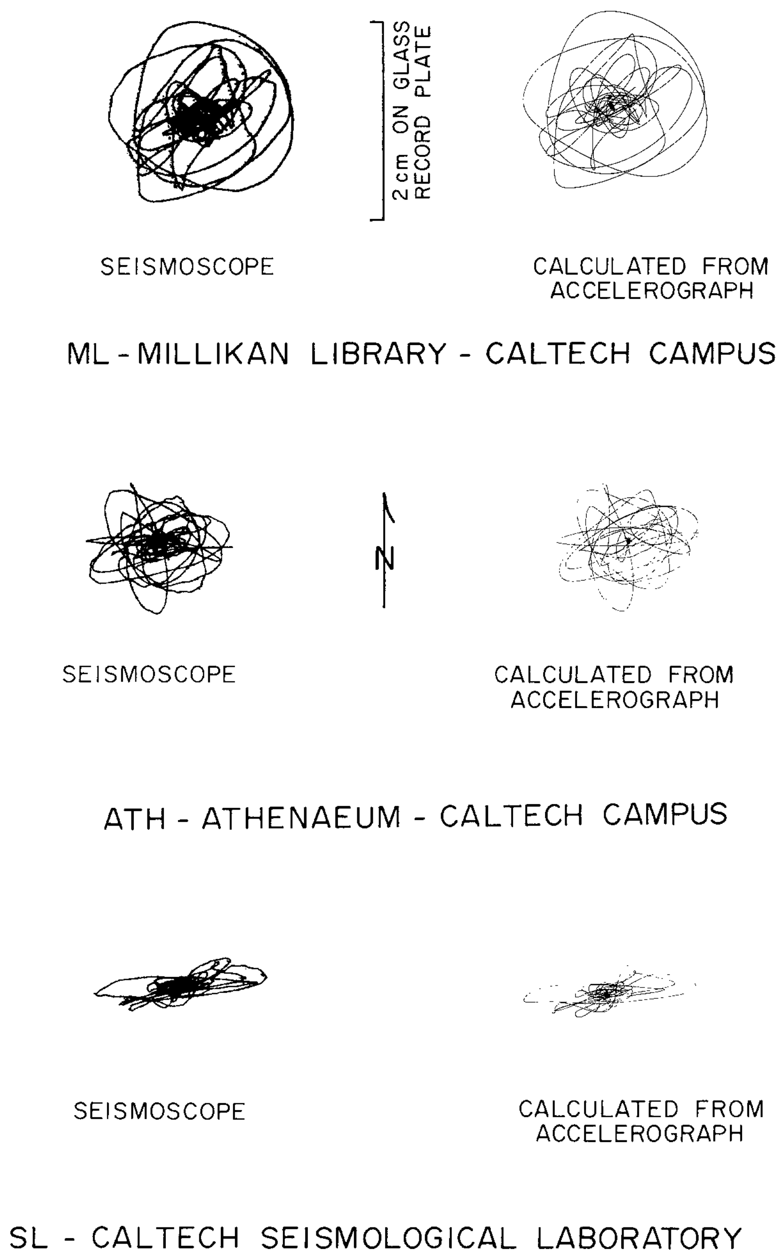
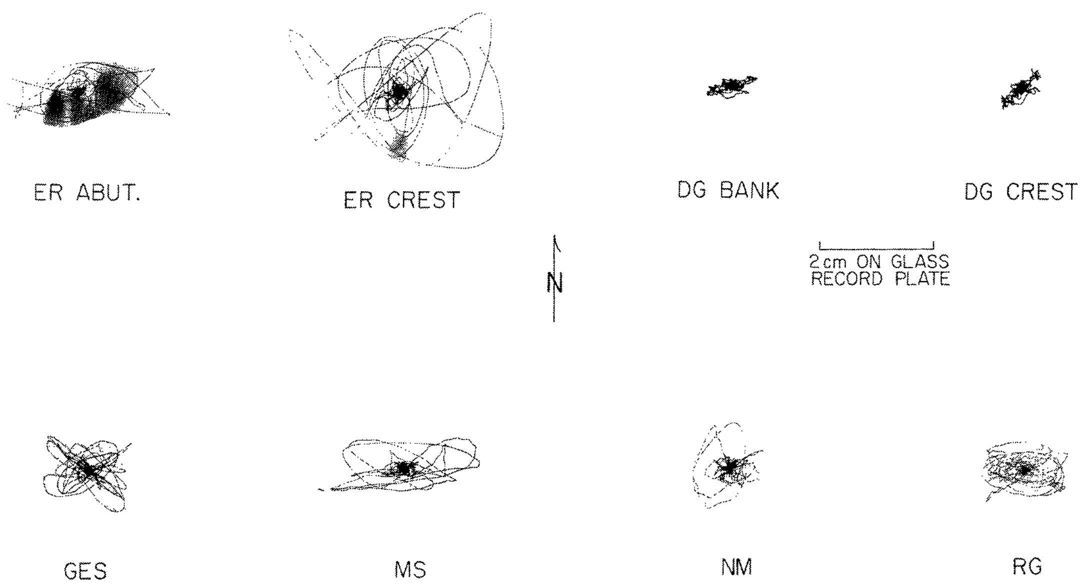


FIG. 2. Computed and measured seismoscope responses. San Fernando earthquake of February 9, 1971.

(A)



(B)

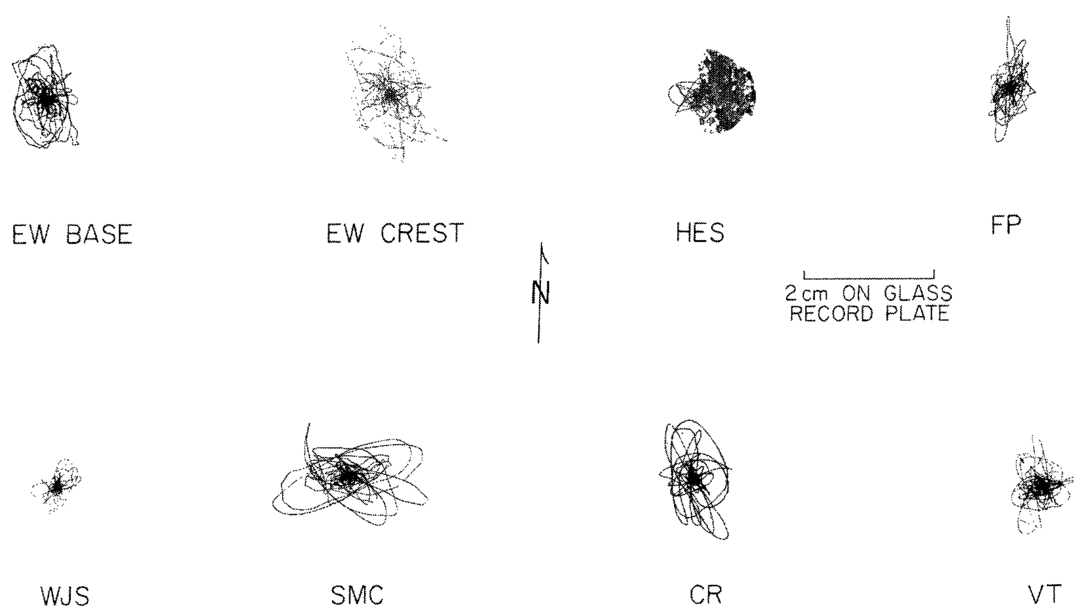


FIG. 3 Seismoscope records of the San Fernando earthquake of February 9, 1971. (A) Pasadena area I, (B) Pasadena area II.

In Figure 3A and B, the remaining seismoscope records are shown, illustrating the great variety of ground motions encountered over this relatively small area (Hudson, 1971).

The accelerograms obtained at four of the sites are shown in Figure 4, along with integrated ground velocity and displacement curves. These integrated curves have been corrected for instrument transducer characteristics, and base-line adjustments have been made by digital filtering so that accurate information is retained over the frequency range 0.06 to 25 Hz (Trifunac, 1971, 1972).

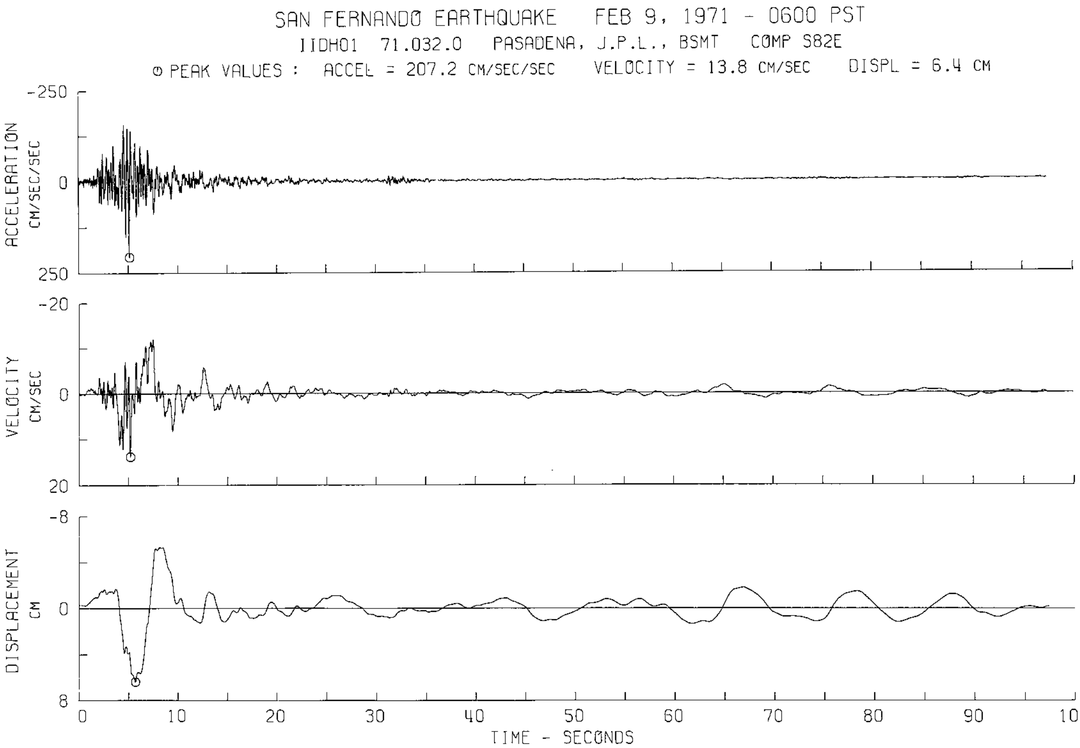


FIG. 4A-1

FIG. 4A, 1–3. Ground acceleration, velocity, and displacement, Jet Propulsion Laboratory.

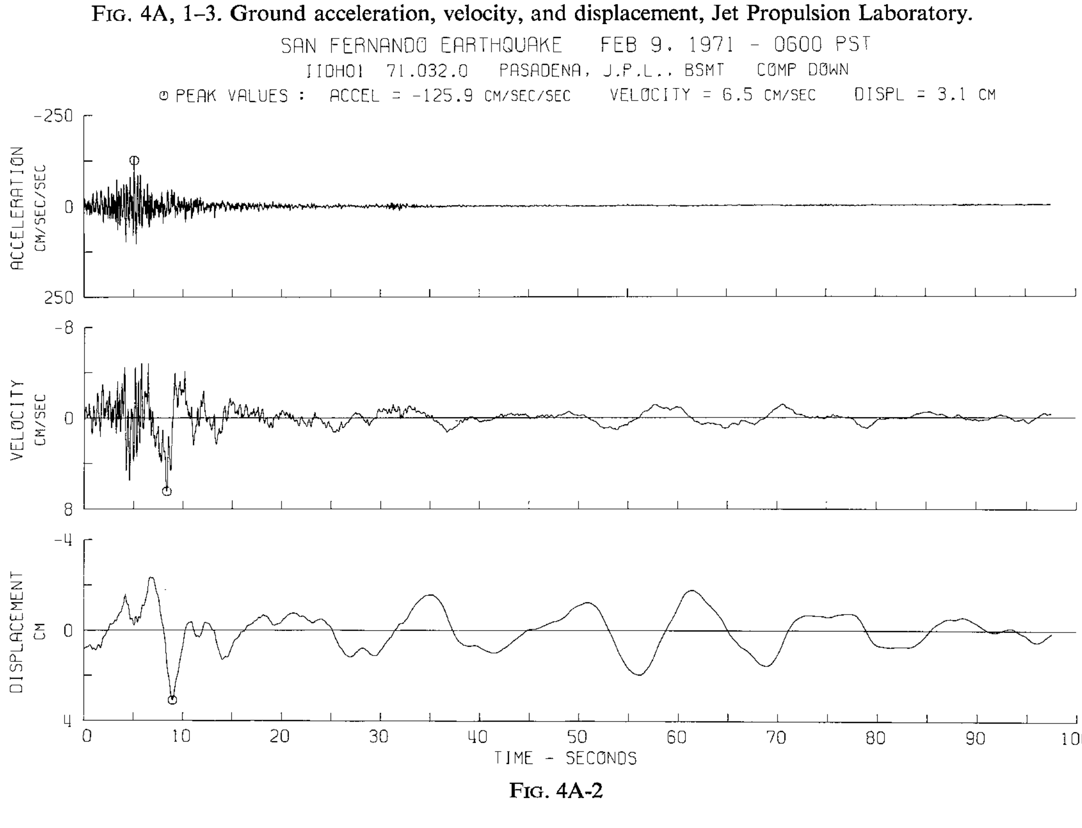


FIG. 4A-2

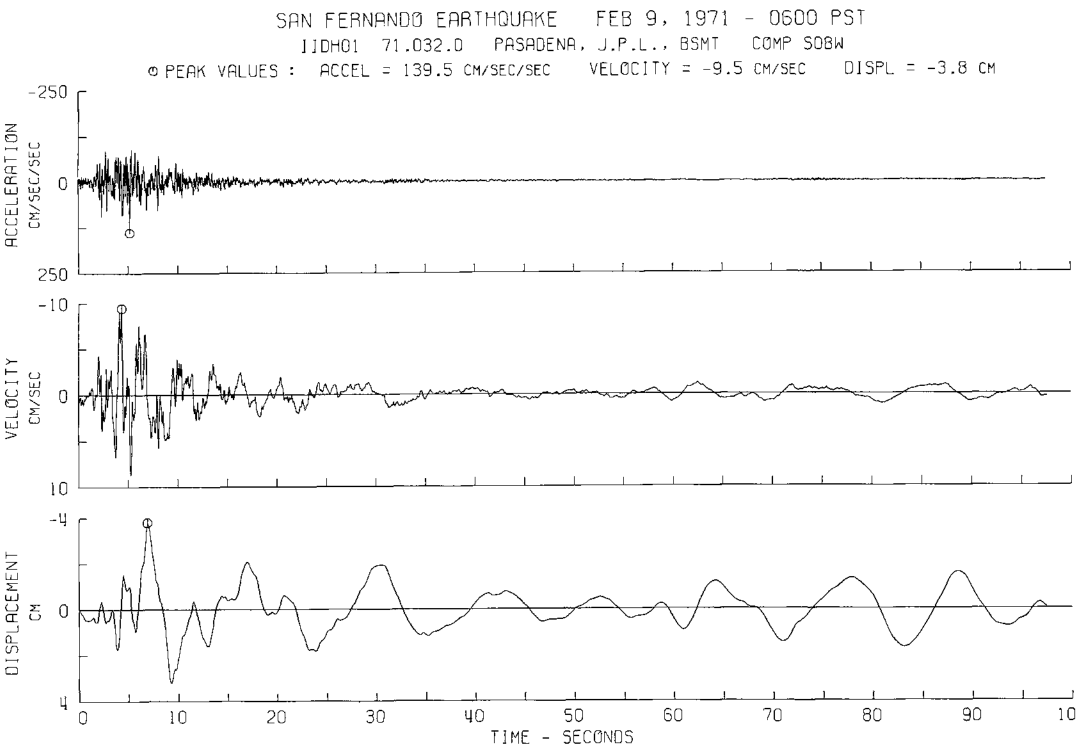


FIG. 4A-3

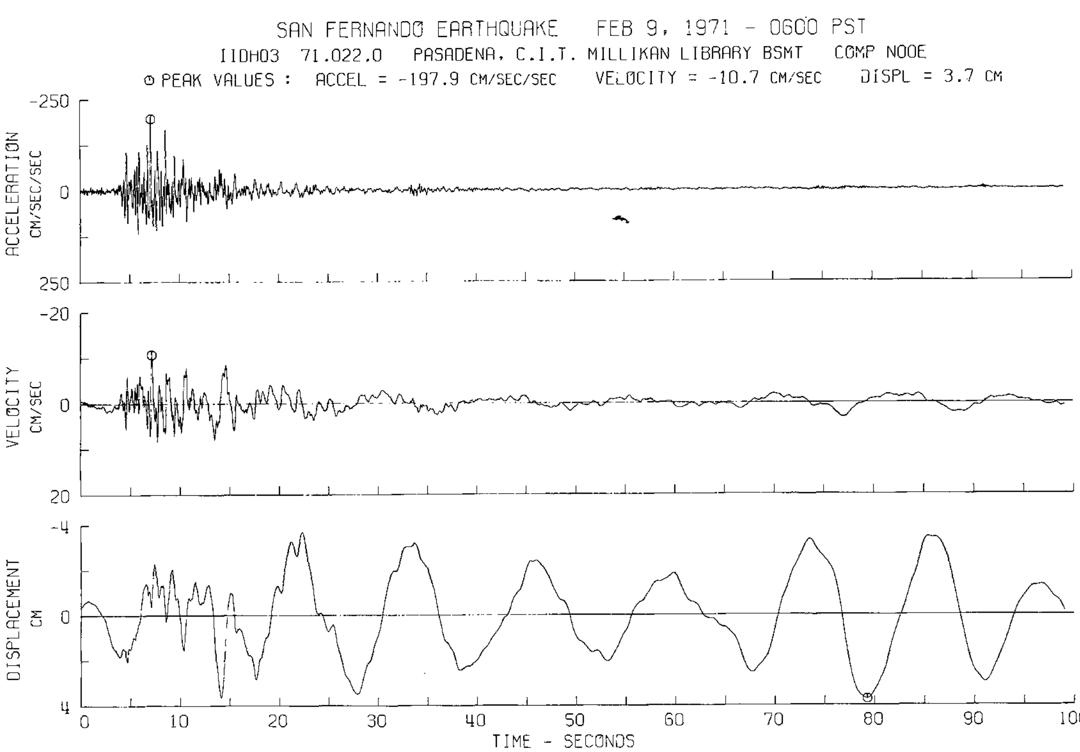


FIG. 4B-1

FIG. 4B, 1-3. Ground acceleration, velocity, and displacement, Caltech Millikan Library.

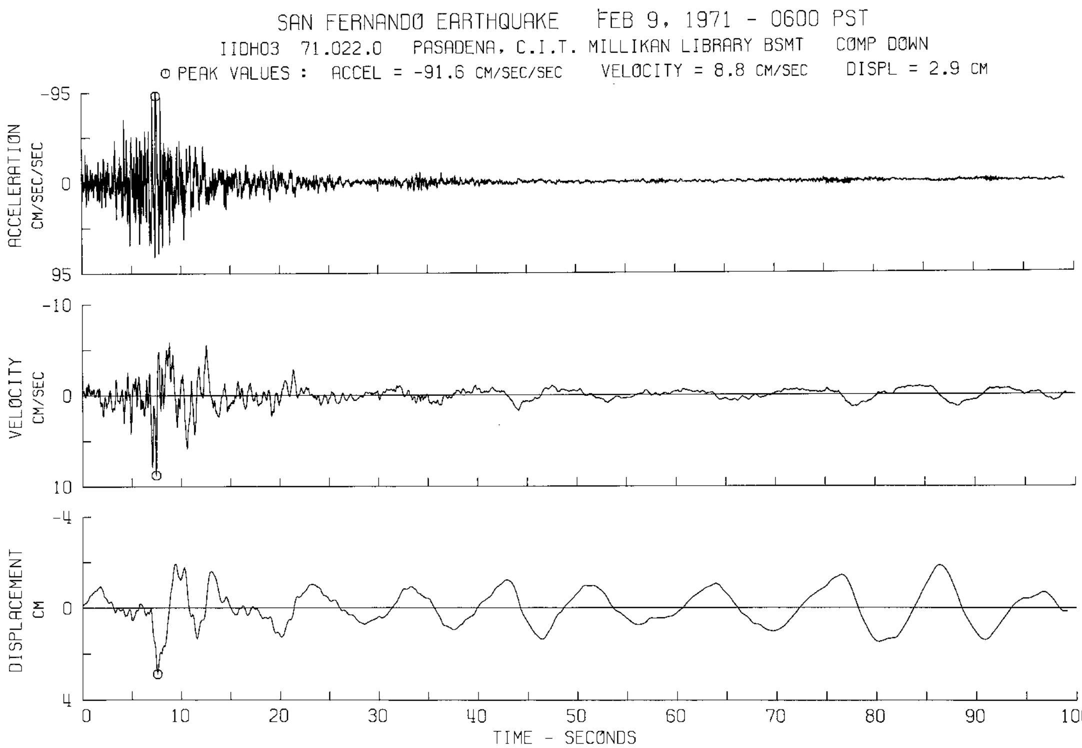


FIG. 4B-2

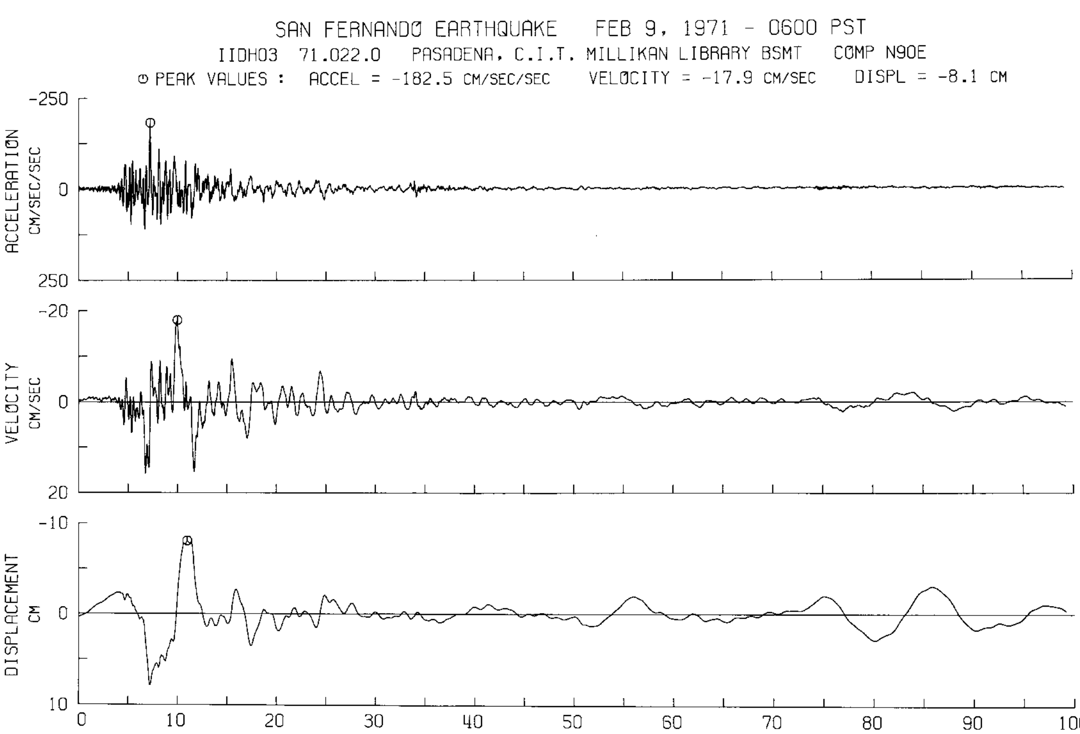


FIG. 4B-3

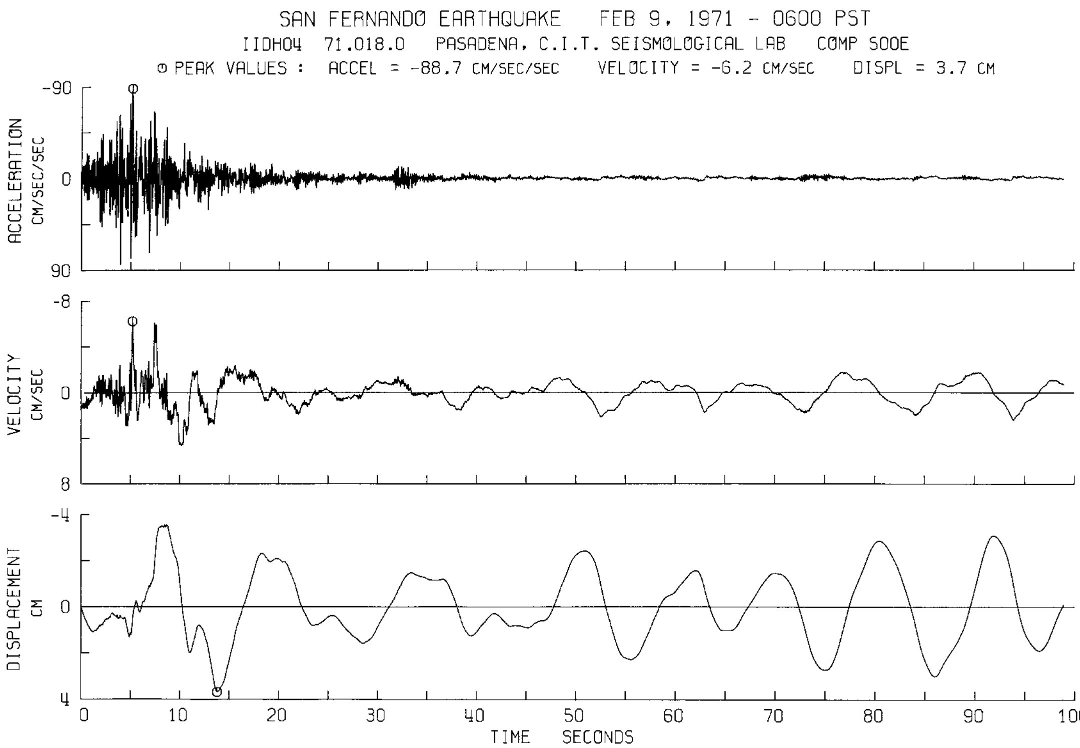


FIG. 4C-1

FIG. 4C, 1-3. Ground acceleration, velocity and displacement, Caltech Seismological Laboratory.

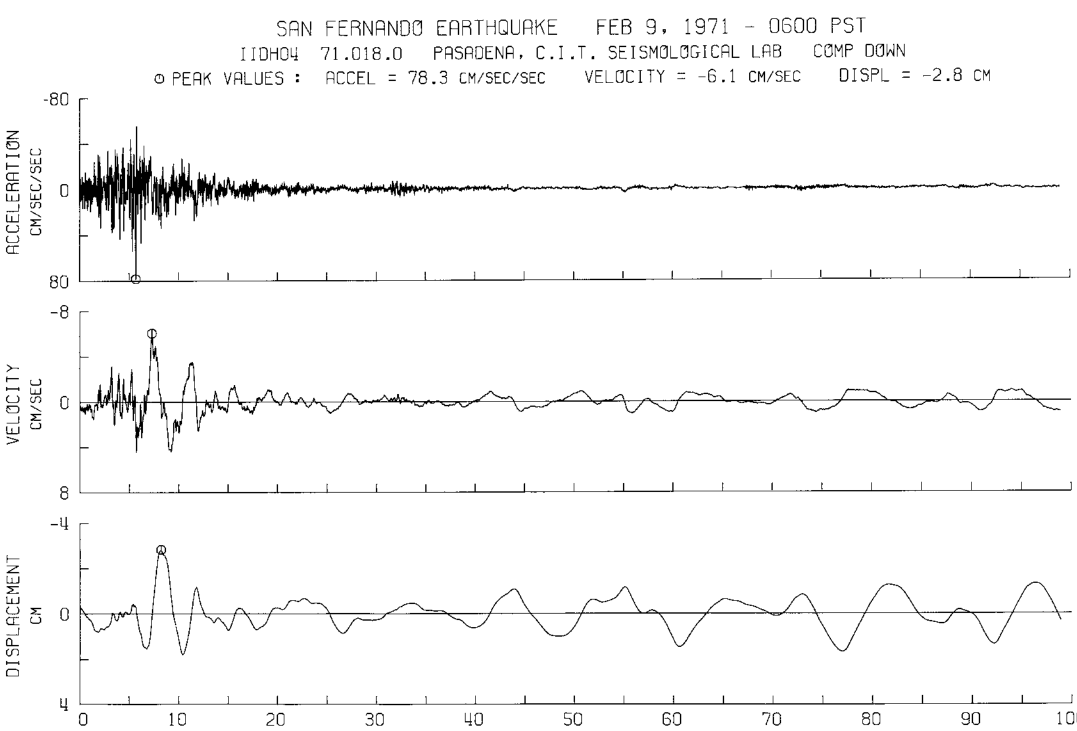


FIG. 4C-2

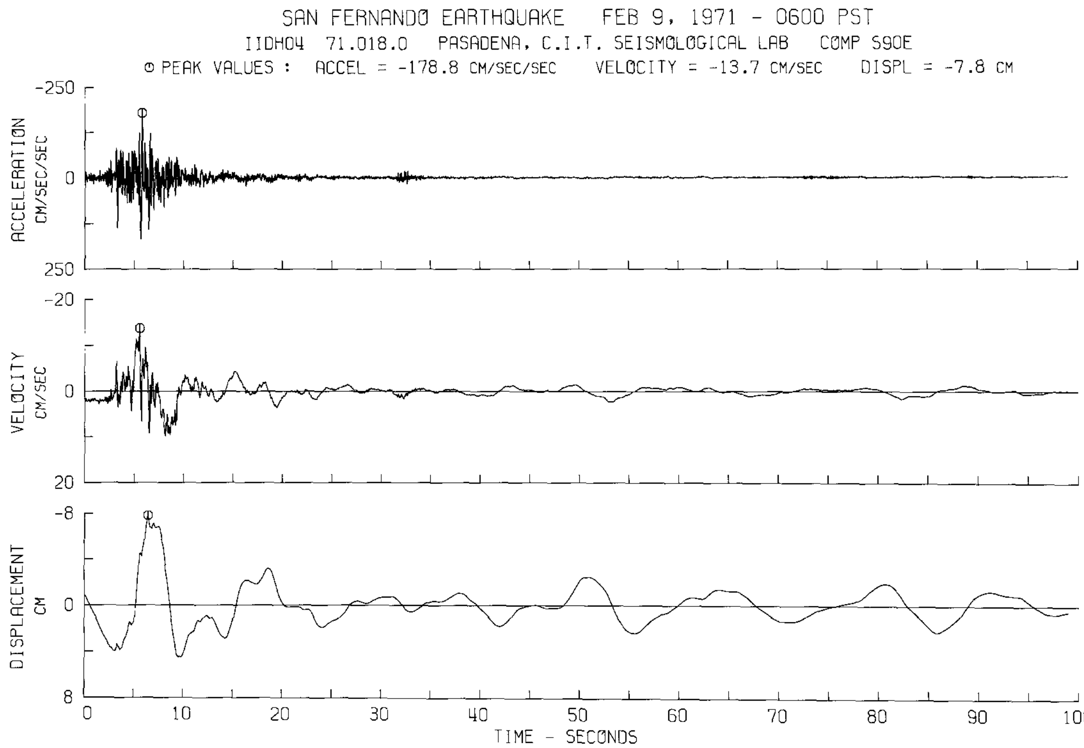


FIG. 4C-3

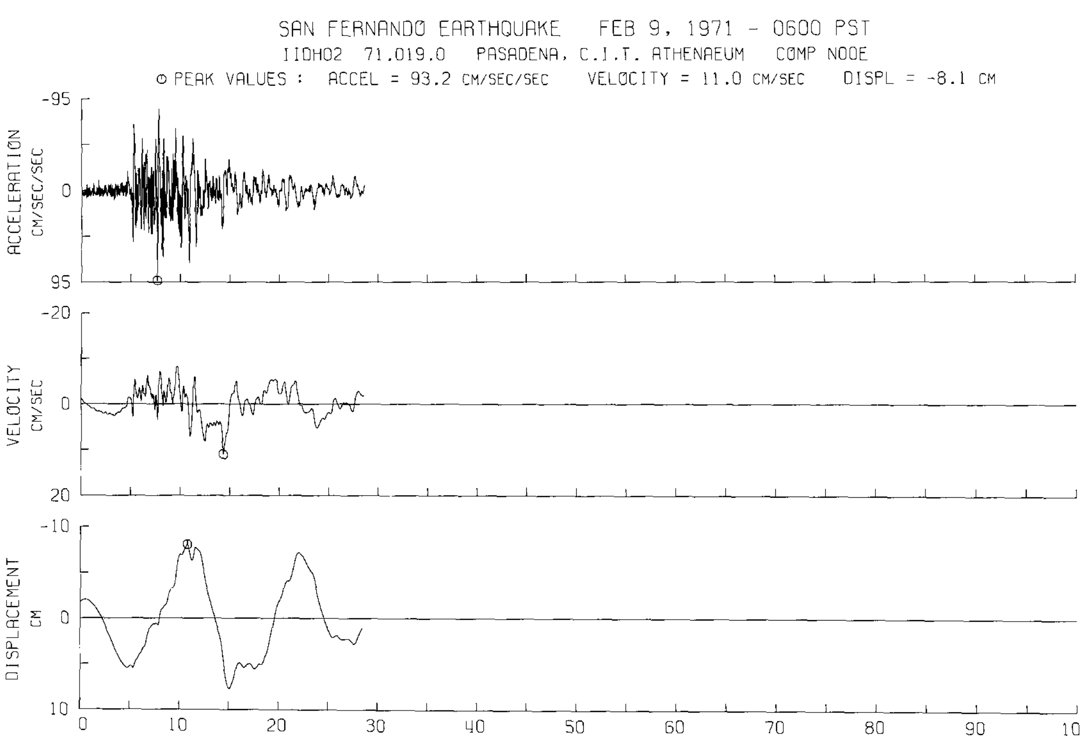


FIG. 4D-1

FIG. 4D, 1-3. Ground acceleration, velocity, and displacement, Caltech Athenaeum.

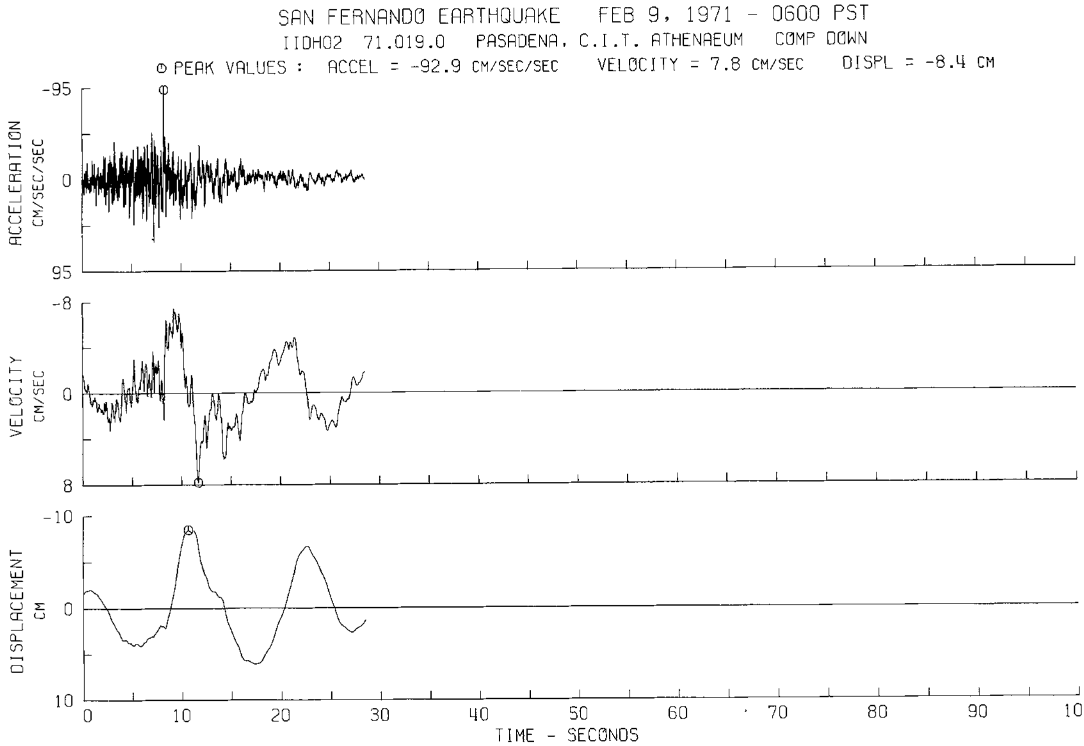


Fig. 4D-2

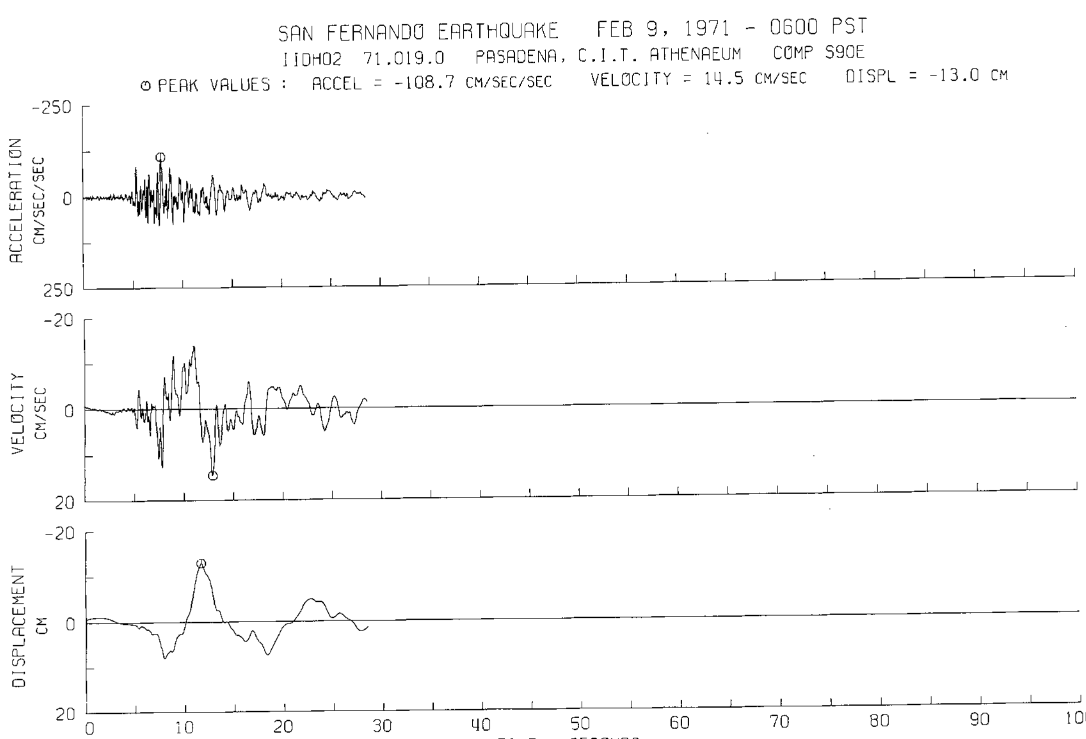


Fig 4D-3

Ground-Motion Frequency Analysis

From the accelerograph recordings at the four sites, a complete frequency analysis can be made to reveal further details of the motions. Figure 5 shows relative velocity-response curves calculated from the corrected accelerograms, which permit accurate calculations over the frequency range 0.06 to 25 Hz (Nigam and Jennings, 1969). It has been found that the damped response spectrum curves have some advantage over smoothed Fourier spectra in that the damped response-spectrum curves naturally involve the type of smoothing which has a direct physical significance in terms of the behavior of structures.

Shown on the same response-spectrum curves of Figure 5B, C, and D are the single response points obtained from the seismoscope mounted next to the accelerographs. This gives a quantitative evaluation of the accuracy of the seismoscope, which is seen to be reasonably satisfactory, indicating proper performance of the instrumentation and of the data processing.

In order to compare the ground motions at the accelerograph sites, the 10 per cent damped velocity-response curves have been superimposed in sets of two for various site combinations, as shown in Figure 6. Figure 6A shows the spectra for the two campus sites, (ML and ATH), less than $\frac{1}{2}$ km apart. The (ML) site is located in the basement of a 9-story reinforced concrete building, whereas the (ATH) site is in the basement of a $2\frac{1}{2}$-story reinforced concrete building. The spectra show no evidence of predominant building periods to suggest a building-soil interaction. Figure 6B shows the comparison between the rock site (SL) and the campus site on 900 ft of alluvium (ATH). It is clear that over most of the frequency range of structural significance, the maximum response at the rock site is greater than on the alluvium site.

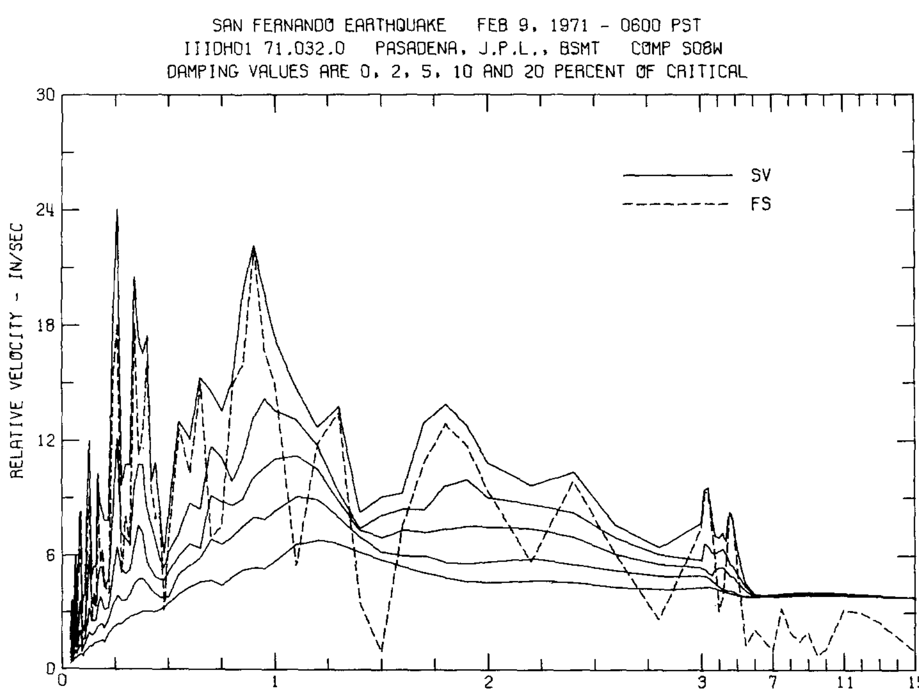


Fig. 5A-1

Fig. 5A, 1-3. Relative velocity response spectra, Jet Propulsion Laboratory.

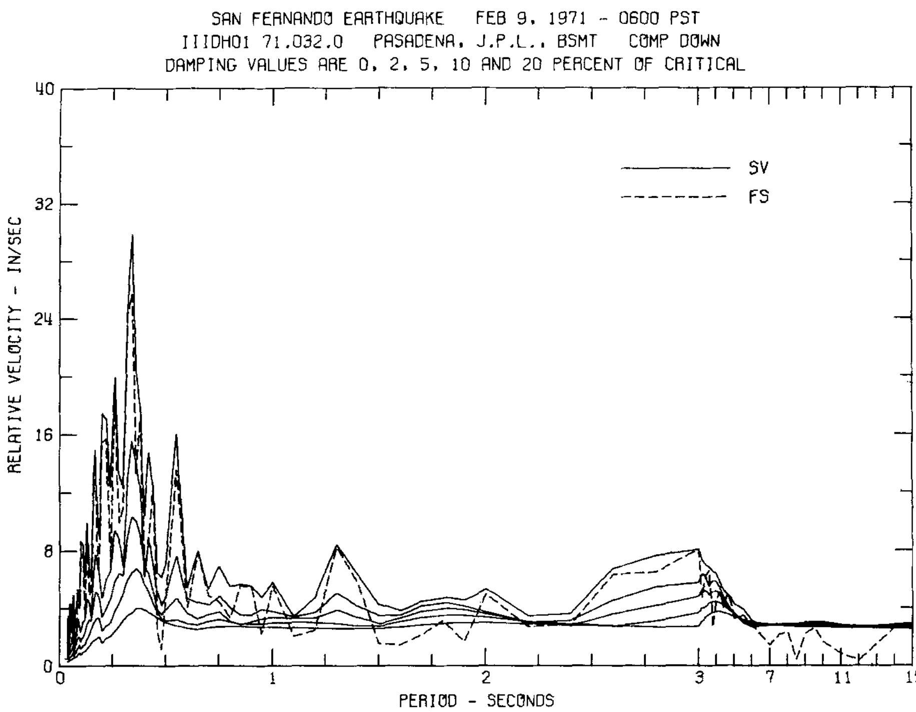


FIG. 5A-2

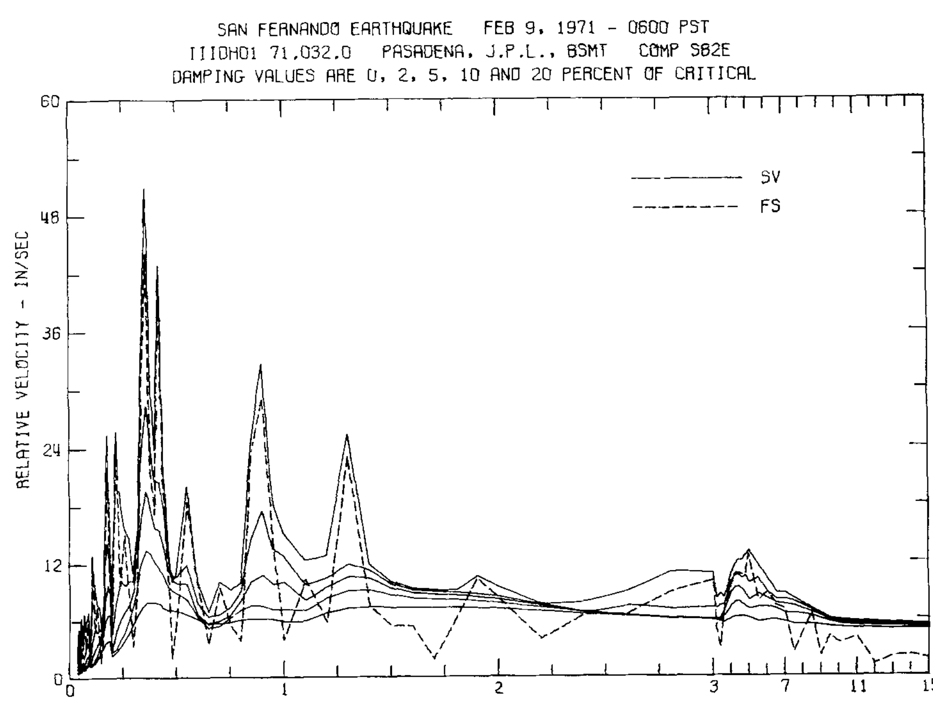


FIG. 5A-3

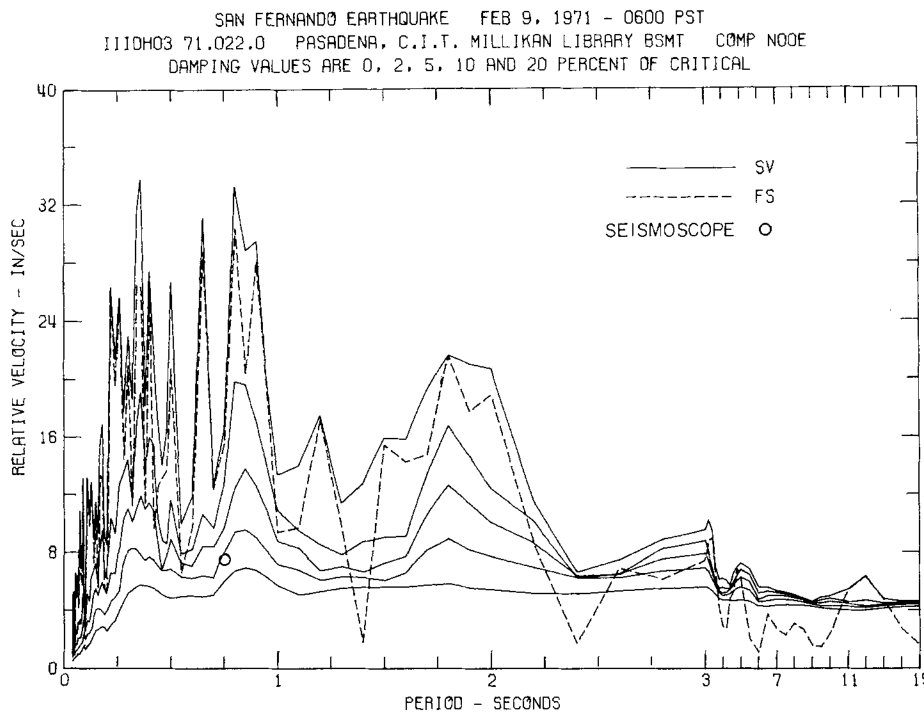


FIG. 5B-1

FIG. 5B, 1-3. Relative velocity response spectra, Caltech Millikan Library.

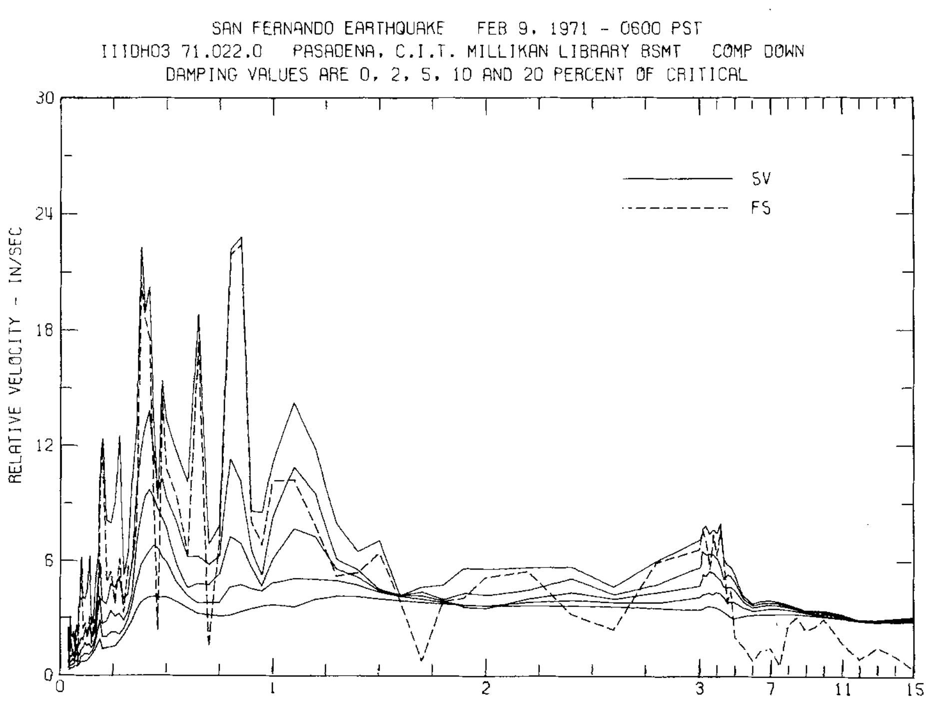


FIG. 5B-2

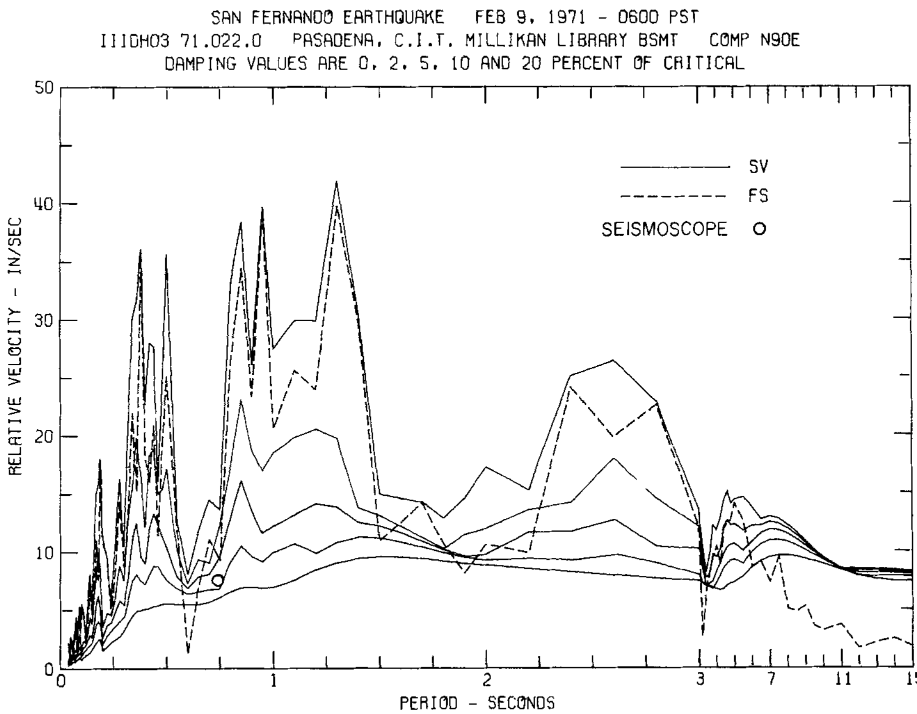


Fig. 5B-3

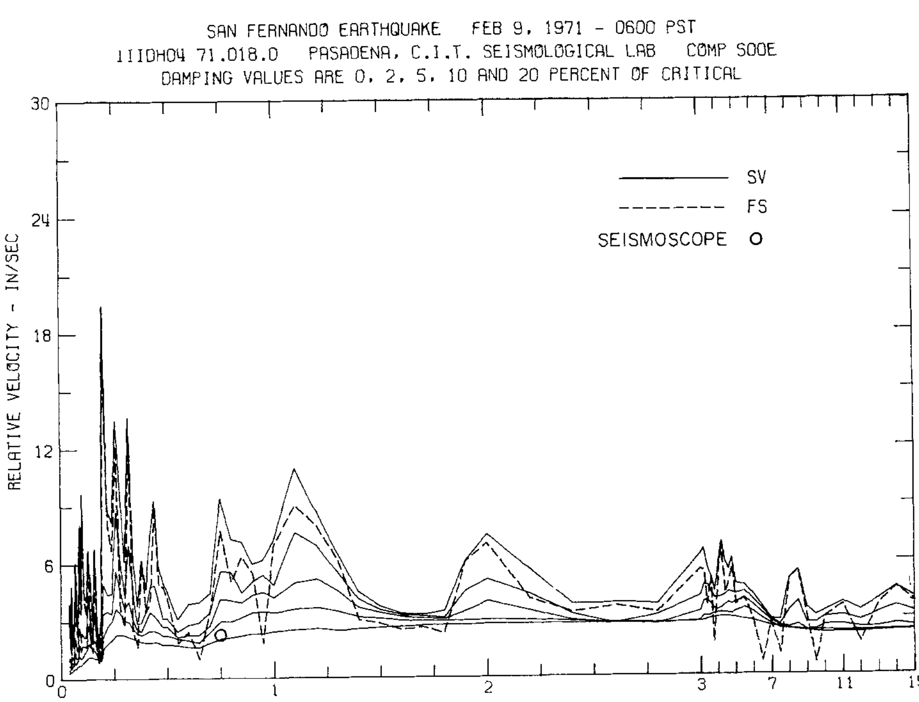


Fig. 5C-1

Fig 5C, 1-3. Relative velocity response spectra. Caltech Seismological Laboratory.

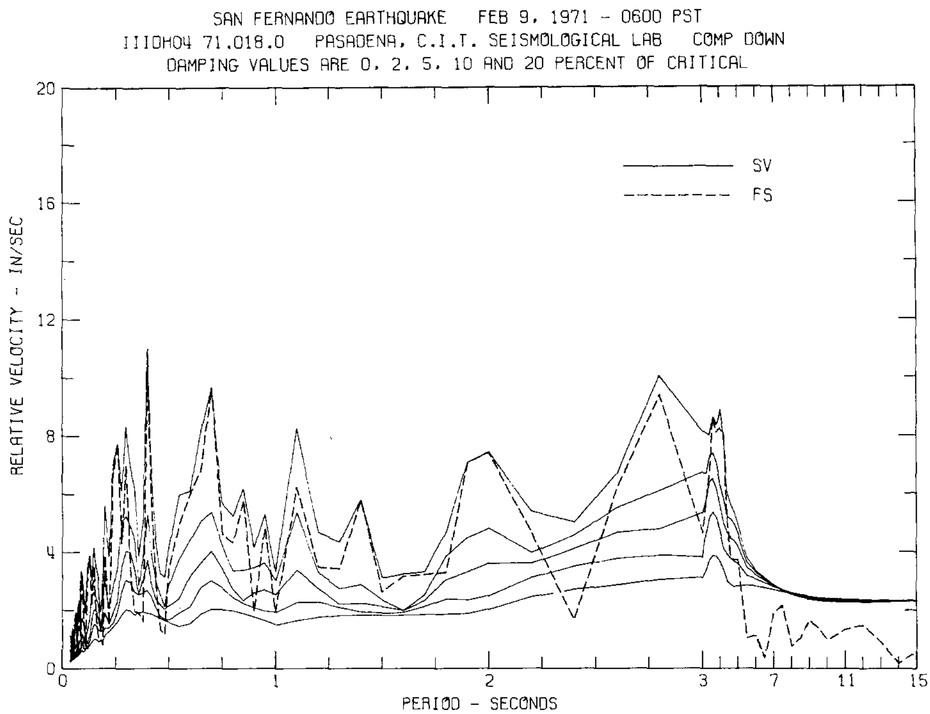


FIG. 5C-2

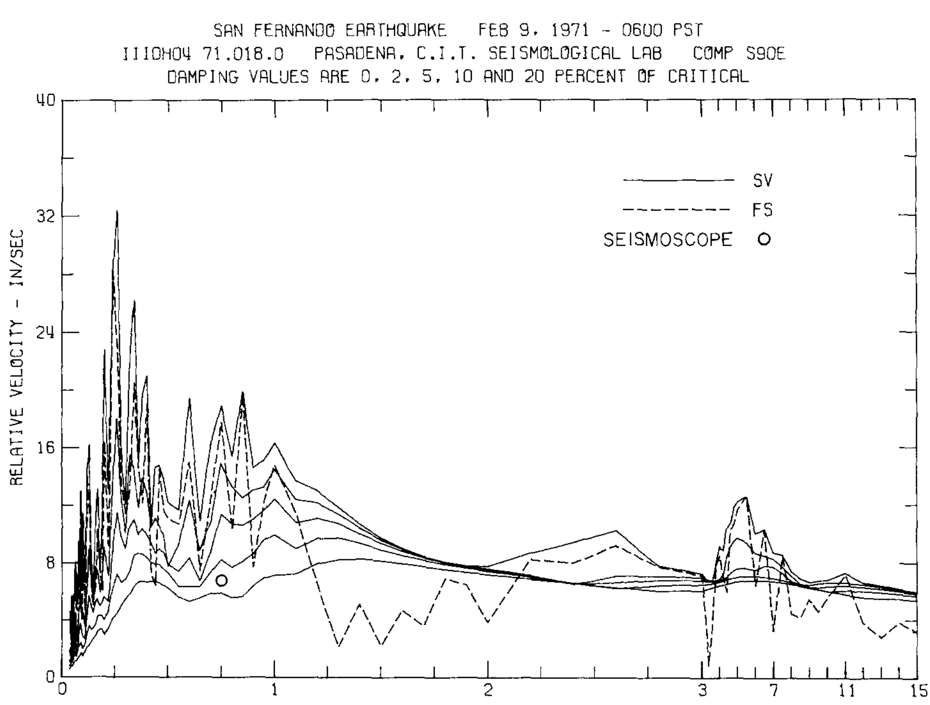


FIG. 5C-3

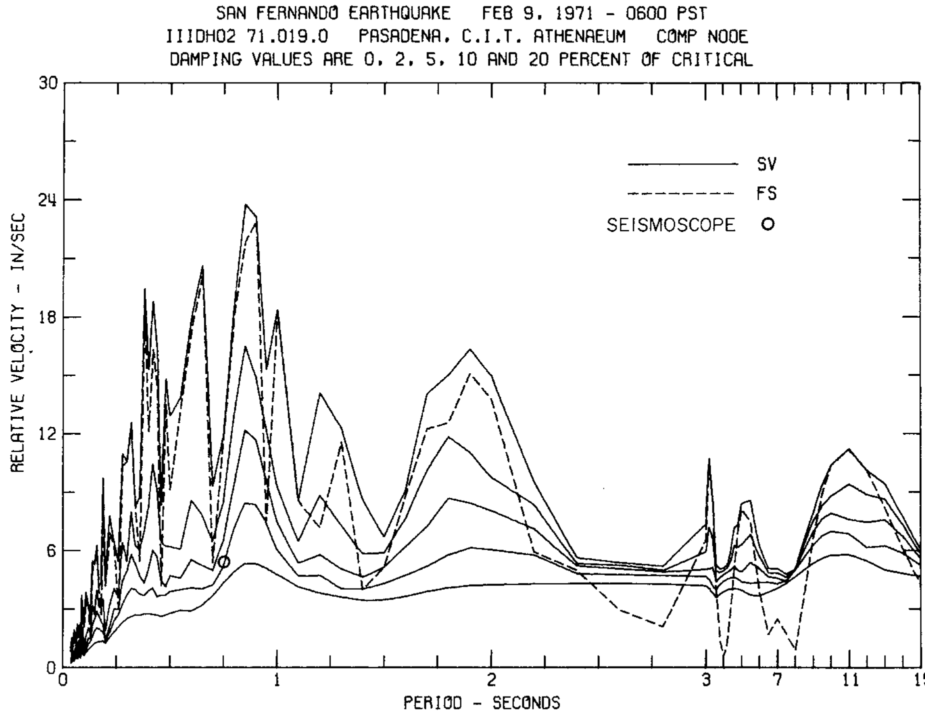


FIG. 5D-1

FIG. 5D, 1-3. Relative velocity response spectra, Caltech Athenaeum.

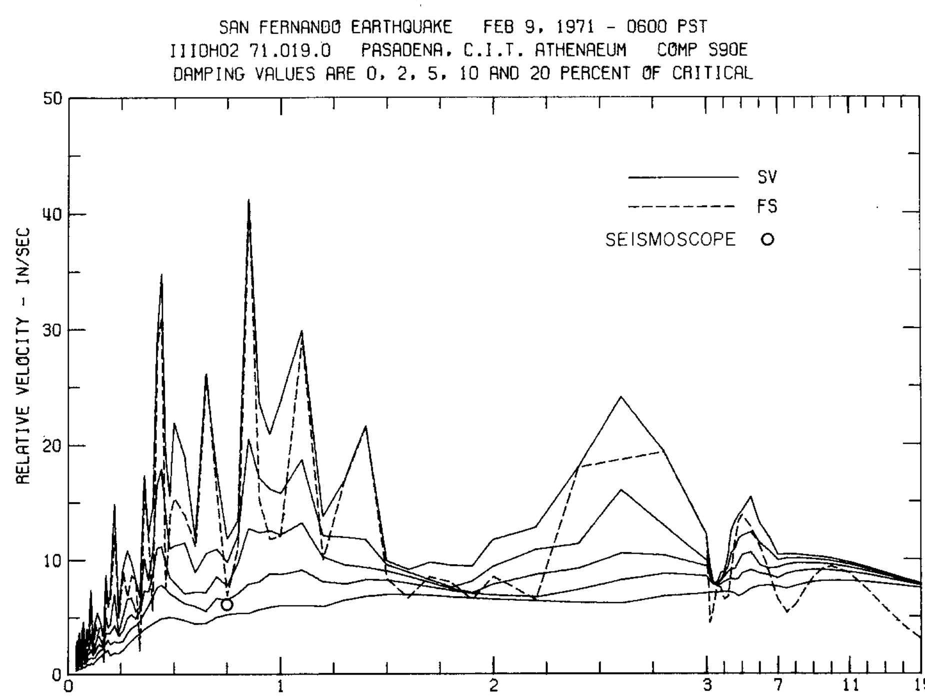


FIG. 5D-2

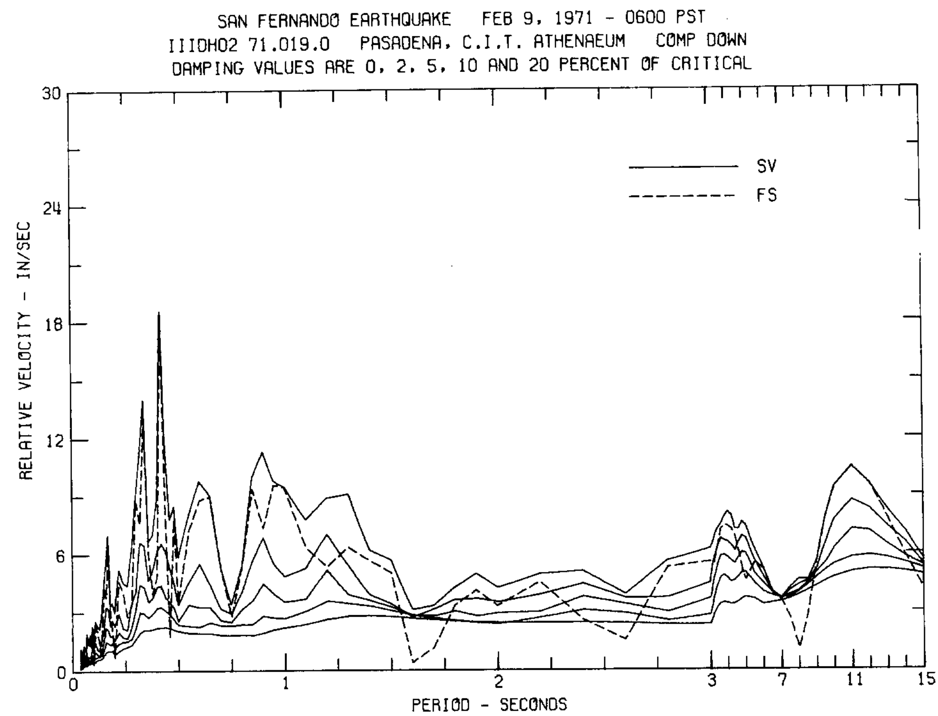


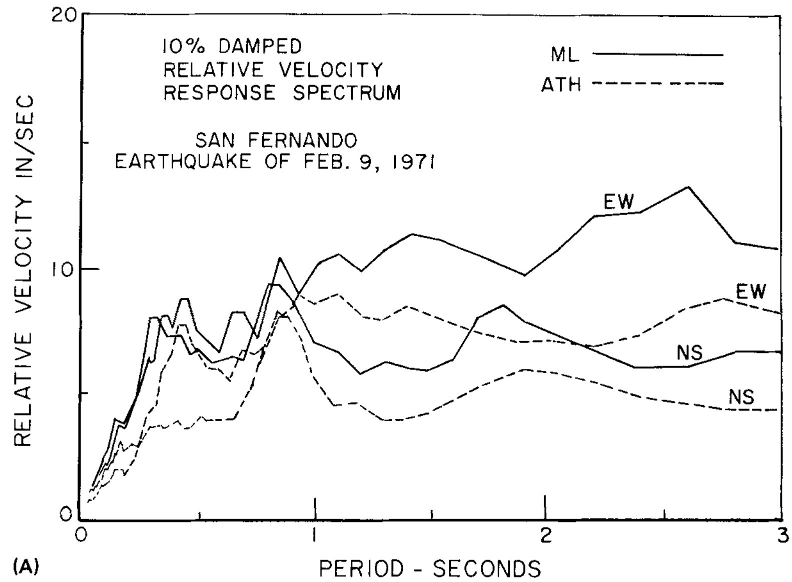
FIG. 5D-3

The comparison of these two sites is of special interest because of the extensive measurements at these same two stations reported by Gutenberg. The results given by Gutenberg for the ratio of the motions at the two sites versus period indicate, first, a wide scatter of amplitude ratios at any one period of as much as a factor of 4 or 5, and, second, a rough average result of ground motion amplitudes at the campus site of 3 to 4 times the amplitudes at the Seismological Laboratory (Gutenberg, 1957). These previous results indicated clearly that, although there is a wide scatter of results, on the basis of any kind of average, the motions on the alluvium would be expected to be considerably greater than on the rock. For the San Fernando eathquake, however, it has been seen above that the strong ground motions were larger on the rock than on the alluvium.

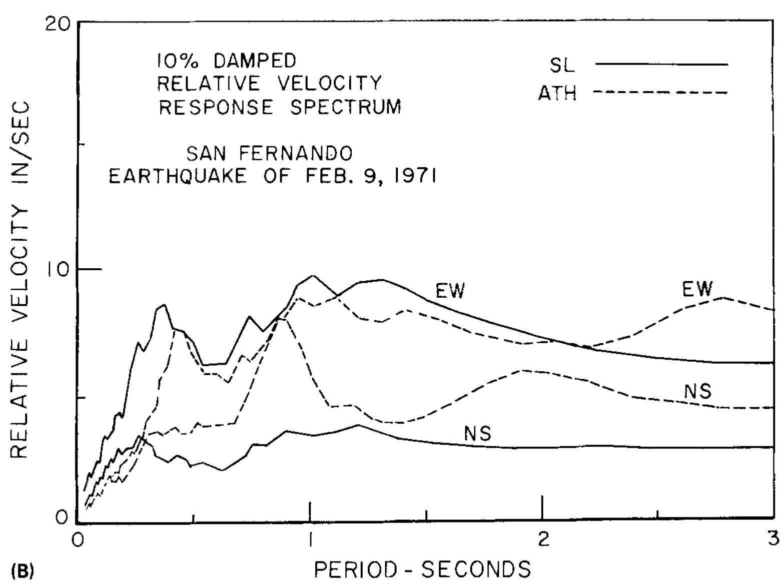
In explanation of this significant difference in results between Dr. Gutenberg's investigations and the San Fernando earthquake measurements, it may be noted first that Dr. Gutenberg's measured ground motions were considerably smaller than those during the San Fernando earthquake. Second, there may have been differences between the San Fernando earthquake and many of the earthquakes measured by Dr. Gutenberg in the location of the earthquake with respect to the sites and the effects of transmission path, surface topography, etc., on the shaking. Dr. Gutenberg states, however, that he found no systematic differences as a function of the azimuth of the arriving waves.

DISCUSSION

The general picture that emerges from a study of the distribution of the instrumental readings is one of considerable complexity. Some stations on rock (SL) have relatively large values, whereas some on alluvium (HES) have small values. On the Caltech campus, for example, two sites less than $\frac{1}{2}$ km apart have significantly different values. Similarly,



(A)

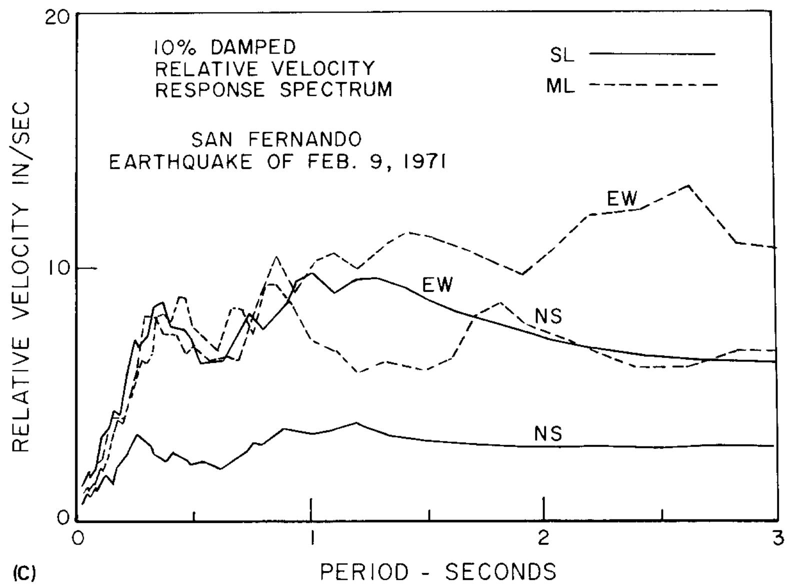


(B)

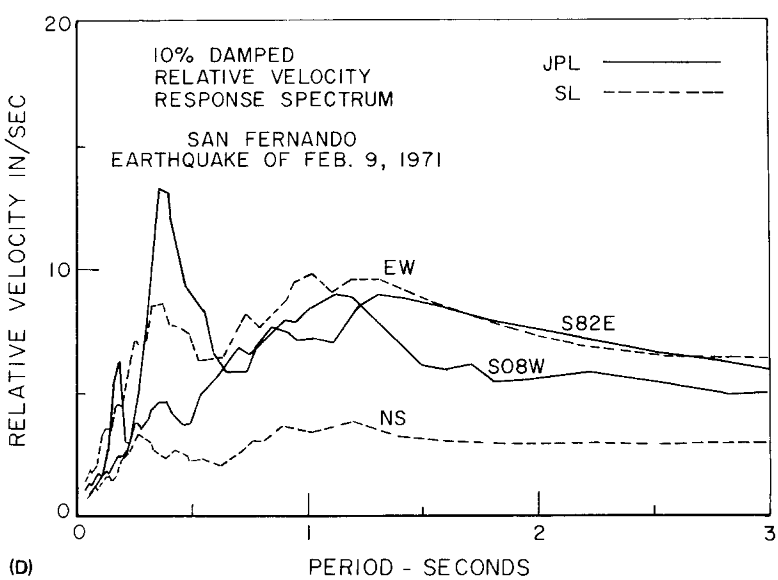
FIG. 6. Comparison of velocity spectra. (A) Millikan Library and Athenaeum, (B) Seismological Laboratory and Athenaeum, (C) Seismological Laboratory and Millikan Library, and (D) Jet Propulsion Laboratory and Seismological Laboratory.

the two sites (MS) and (RG), which are on approximately the same depth of alluvium, show considerably different values. The site at (WJS), which is on a small outcrop of crystalline rock similar to the (SL) site, shows a smaller value than some adjacent alluvium sites.

Probably not much significance should be attached to the directions of the seismoscope maxima shown, because most of the responses had approximately the same values in all directions. The (SL) site showed a prominent undirectional response, and the sites (FP), (MS), and (DG) have a similar tendency. No explanations suggest themselves for these specific variations in pattern.



(C)



(D)

FIG. 6, C and D

Recent studies have shown that patterns of surface motion may be influenced in a major way by surface topography (Boore, 1972), and by nonuniform subsurface configurations (Trifunac, 1971b). Such effects would be expected to be quite different for various travel paths and might overshadow the influence of local site conditions. It may well be that, if another earthquake the size and distance of the San Fernando earthquake should occur, but in a different direction from Pasadena, the distribution throughout the Pasadena area might be equally complicated but quite different in detail at any particular site. Perhaps by the time the local distributions of a number of large earthquakes are superimposed, the "average" conditions will be considerably smoothed out, and the seismic zoning map may approach a one-zone pattern. This can be considered to be the main conclusion of the investigation so far. It seems that the local distribution of ground shaking predicted on the basis of the simultaneous measurement at a number of sites of many small earthquakes may not, in fact, correspond very well with the distribution occurring during a damaging earthquake. At least, this is what has happened for the Pasadena area and the San Fernando earthquake. It is, thus, clear that considerable caution must be used in the preparation of detailed local seismic risk maps. It must always be kept in mind that considerations of long-term average conditions may be of small comfort to the engineer whose building was destroyed by an earthquake which happened to depart from the average. The significance of average conditions becomes vague when it is considered that most structures will probably be exposed to only one damaging earthquake during their lifetimes.

An important reason for increasing the amount of strong-motion instrumentation in seismic regions is that studies of the above type can be made for other earthquakes and other regions. Only when much more data of this kind are available can the preparation of more detailed seismic risk maps proceed with confidence.

Acknowledgment

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Earthquake Engineering Research Laboratory
California Institute of Technology
Pasadena, California

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