

## ANALYSIS OF ACCELEROGRAMS—PARKFIELD EARTHQUAKE

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### ABSTRACT

Integrated velocities and displacements show that near the fault at Cholame the surface motion exhibited a transient horizontal displacement pulse of approximately ten inches amplitude and one and one-half seconds duration, normal to the fault. Although 50 per cent of  $g$  ground acceleration was recorded at the fault, the ground motion attenuated rapidly with distance and at ten miles from the fault the maximum acceleration was reduced to one-tenth of its near-fault value. The ground motion also changed its character with distance, losing its pulse-like directional characteristic and becoming isotropic. Computed response spectra are presented and the large spectrum ordinates for this shock of relatively small magnitude and moderate destructiveness indicate that in an engineering sense the Parkfield ground motion is in a different class from such large destructive ground motions as El Centro 1940, Tehachapi 1952, and Olympia 1949.

### INTRODUCTION

The ground motion of the magnitude 5.6 Parkfield earthquake of June 27, 1966 was recorded by an array of five strong-motion accelerographs and fifteen seismoscopes across the San Andreas fault at Cholame. Hence, the instrumental coverage of this earthquake was much more extensive than that of any other. The maximum recorded ground acceleration of the fault was 50 per cent of gravity, which is stronger than has been recorded for any other earthquake. On the other hand, the ground motion caused little damage to structures, presumably because of its very short duration. The impulsive strong motion at the fault near Cholame had a large component transverse to the fault which consisted essentially of a single north-easterly displacement pulse of 10 inches amplitude and 1.5 seconds duration. The instrument at the fault near Cholame was near the end of the surface cracking which extended some 20 miles northwesterly along the San Andreas fault beyond Parkfield. The original accelerograph recordings (Cloud and Perez, 1967), the seismoscope recordings (Hudson and Cloud, 1967), and the damage caused by the earthquake (Cloud, 1967) are described in companion papers.

The array, shown in Figure 1, had been installed only shortly before the earthquake as a cooperative venture of the California Department of Water Resources and the U. S. Coast and Geodetic Survey. The DWR project to bring water from the Feather River to southern California involves the construction of facilities close to known active faults, in particular, the San Andreas fault, which is crossed by the aqueduct several times. The design of these facilities, as well as the planning of nuclear reactor power plants in California, raised questions as to the nature of the ground motion immediately adjacent to the causative fault and how it changes with distance out to approximately ten miles from the fault. It was recommended by one of the authors (GWH) that arrays of accelerographs be placed across the San

Andreas fault at several locations, with one array across the fault somewhere between the southerly end of the fault slip of the 1906 San Francisco earthquake and the northerly end of the fault slip of the 1857 Fort Tejon earthquake. The most

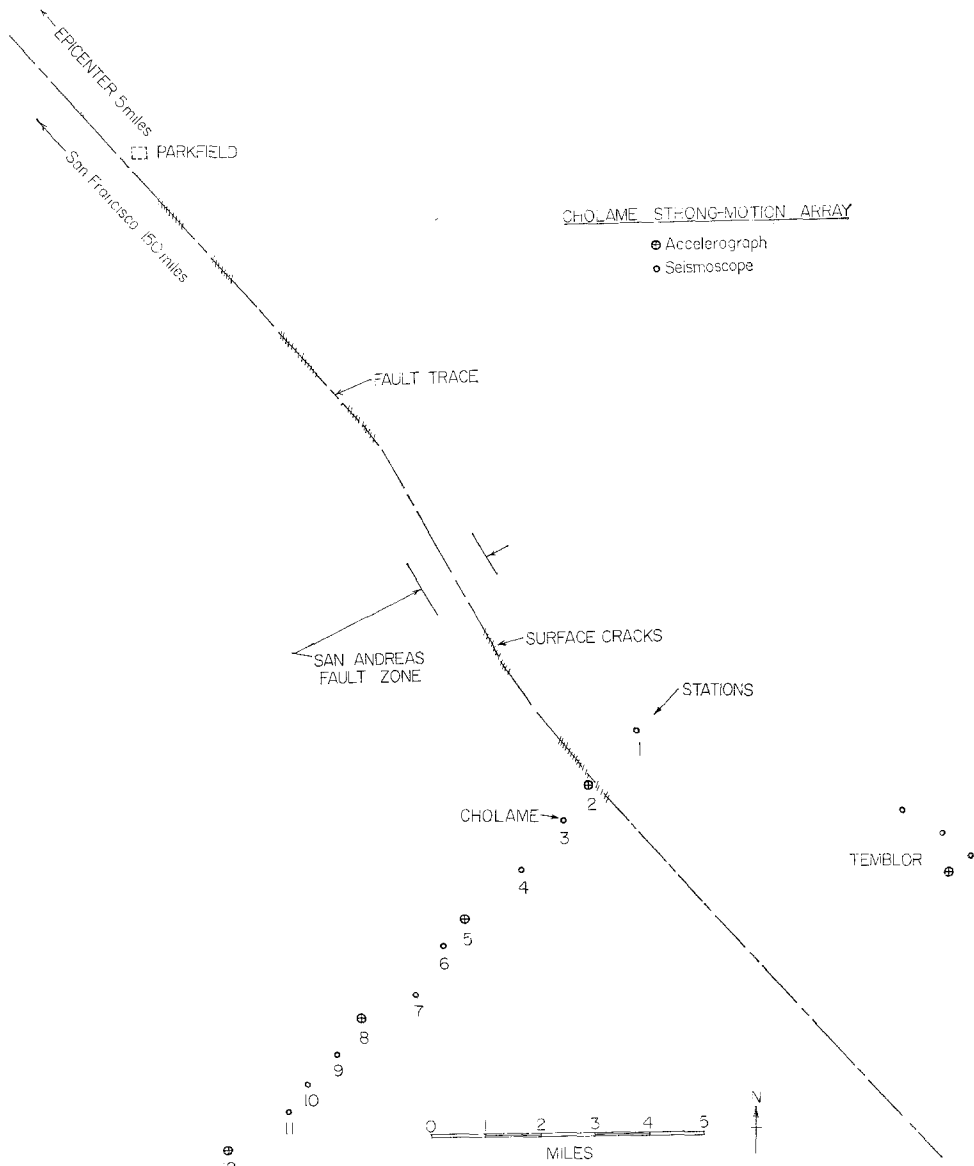


FIG. 1. Strong-Motion Array at Cholame. Five accelerographs and fifteen seismoscopes.

accessible line was along the highway through Cholame. The northerly end of the 1857 slip is thought to have been not far distant. A second array has been installed across the San Andreas fault in the Lake Hughes area just north of Los Angeles.

The accelerographs are UED AR-240's which record one vertical and two hori-

zontal components of motion. The instruments have a natural frequency of approximately 18 cps, and have approximately 65 per cent of critical damping. These instruments record essentially the true ground acceleration. Unfortunately, there was a malfunction of the instrument at Station 2 so that the component parallel to the fault did not record.

The epicenter of the magnitude 5.6 Parkfield shock was located on the San Andreas fault approximately 20 miles northwest of Cholame. This shock was preceded

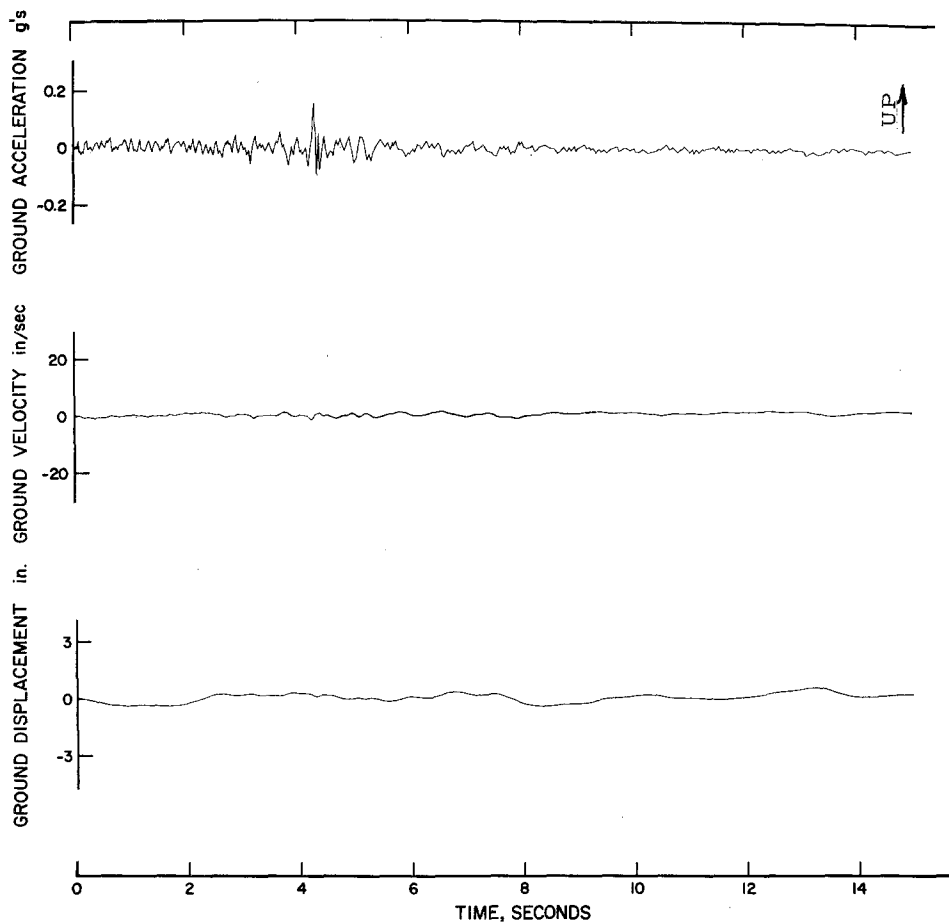


FIG. 2. Temblor Station Vertical Motion.

by a magnitude 5.1 earthquake whose epicenter had approximately the same location. The earlier shock triggered the accelerographs at Stations 2, 5 and 8 which recorded maximum horizontal accelerations of slightly less than 2 per cent of  $g$ , which is about triggering sensitivity. Accelerographs at Stations 12 and Temblor were not triggered by the smaller shock.

There was surface cracking along the fault from about the epicenter to just south of Station 2. Hence, a slipped length of fault of some 20 miles was indicated.

## THE RECORDED GROUND MOTIONS

As shown in Figure 1, there is an offset in the fault trace of about one mile between Cholame and Parkfield. The valley between Cholame and Parkfield appears to be a

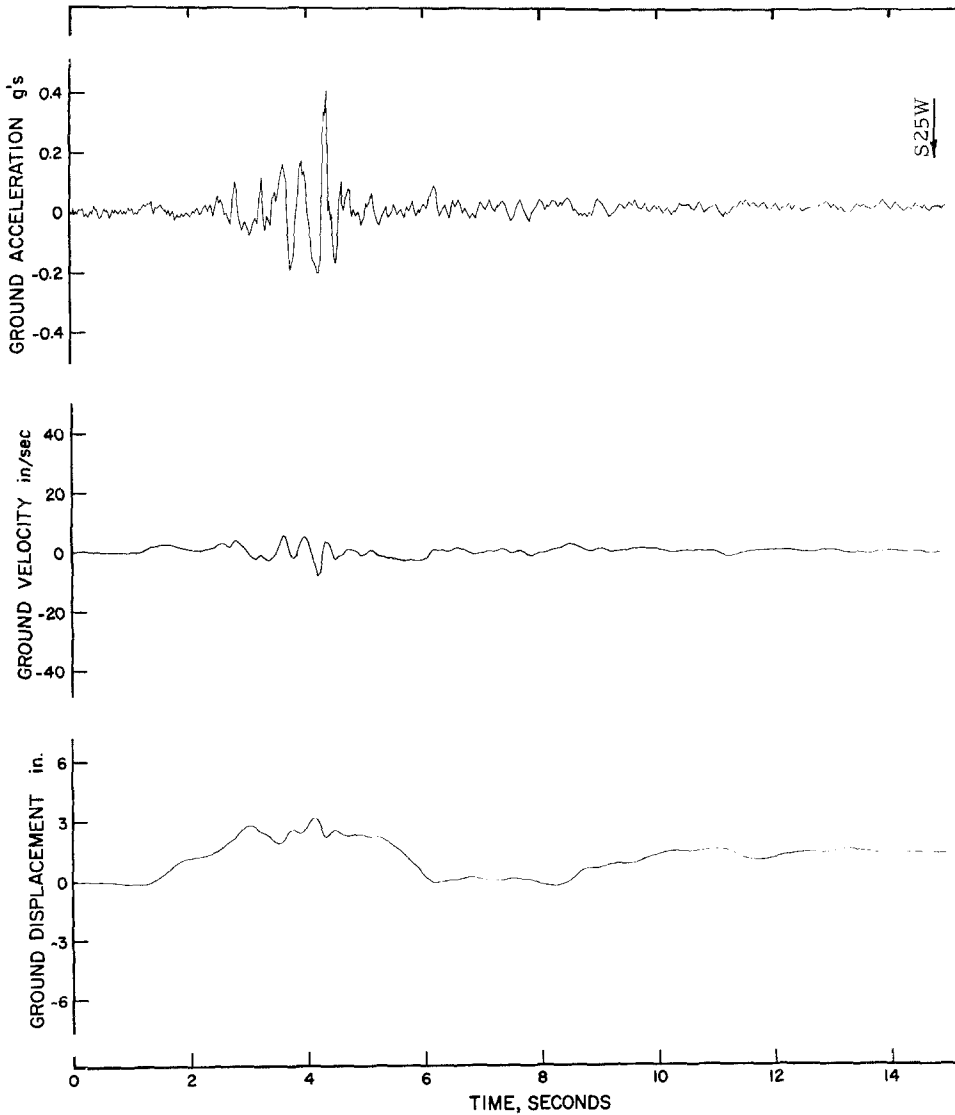


FIG. 3. Temblor Station S25W Motion.

fault zone of about a mile in width. It is not known what influence, if any, this offset had upon the recorded ground motions.

The analysis of the ground motions was done at Caltech using digitized accelerations provided by the Seismographic Field Station of the USC&GS. As a check, several of the accelerograms were independently digitized at Caltech and compared

with the USC&GS digitized data and good agreement was found. A fifteen-second long section of each accelerogram was selected for analysis. A cubic-curve baseline was fitted to each ground motion by a least squares fit on the velocity (Housner and

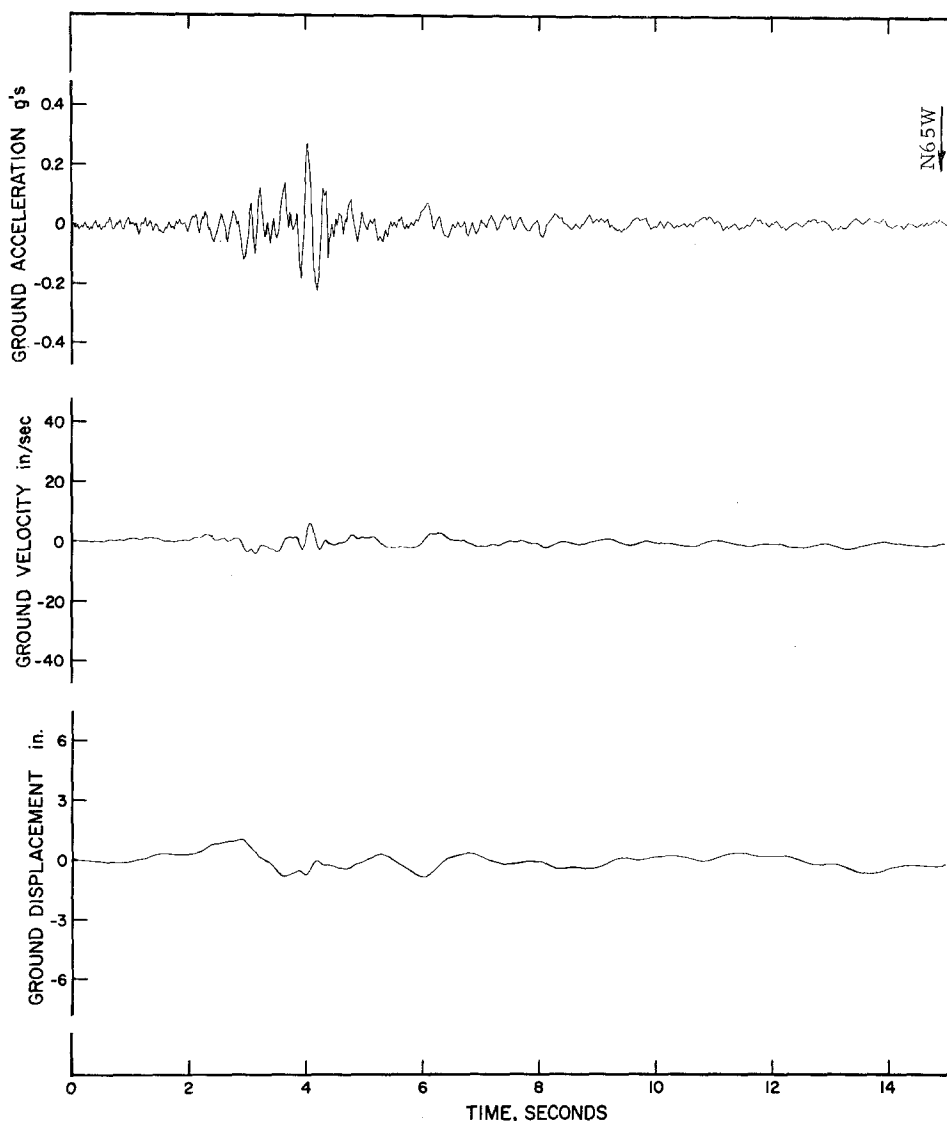


FIG. 4. Temblor Station N65W Motion.

Berg, 1961). The resulting acceleration, velocity and displacement represented by the processed digitized data is shown for each recorded component of each accelerogram in Figures 2-15, as drawn by the computer.

It is seen in Figure 6 that at Station 2 the transverse component had a maximum acceleration of 50 per cent of  $g$ . Figures 3 and 8 show that the maximum acceleration

exceeded 40 per cent of  $g$  out to a distance of about 3.5 miles each side of the fault. At Station 8 the maximum acceleration was 27 per cent of  $g$ , and at Station 12 it was reduced to 5 per cent of  $g$ . This rapid attenuation with distance from the fault indicates a relatively shallow depth of slipped fault as the origin of this motion.

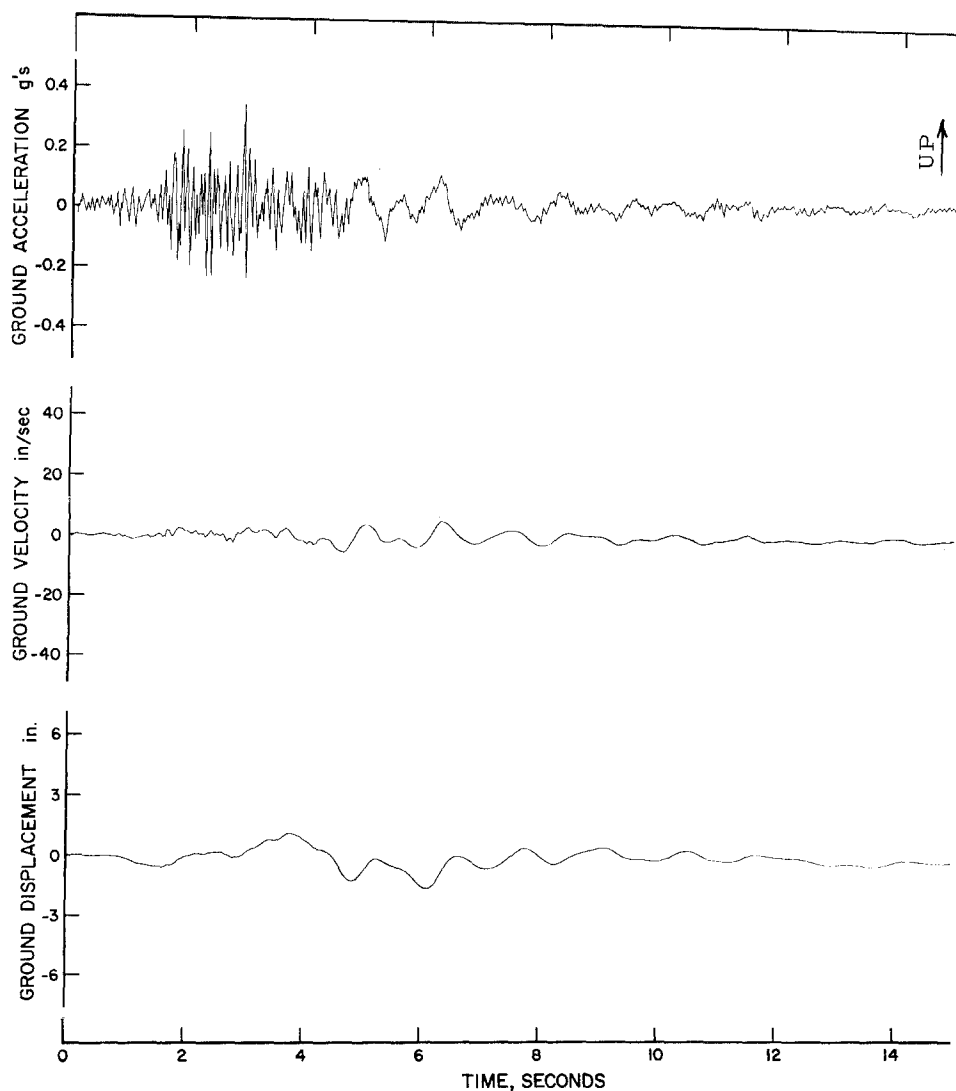


FIG. 5. Station 2 Vertical Motion.

Figure 6 shows the maximum ground velocity at Station 2 to be 27 inches per second. It also shows the displacement to be essentially a single pulse of approximately 10 inches amplitude and 1.5 seconds duration. This is followed by motion having about an inch or less amplitude and about one second predominant period.

Figures 8 and 9 show that at Station 5 the horizontal ground acceleration has

already become essentially isotropic and the ground displacement does not appear as a single pulse, but has a shape similar to that of more orthodox ground motions such as Taft, 21 July 1952 and Olympia, 13 April 1949. At Stations 8 and 12 the ground displacement curves become more smooth with increasing distance from the fault.

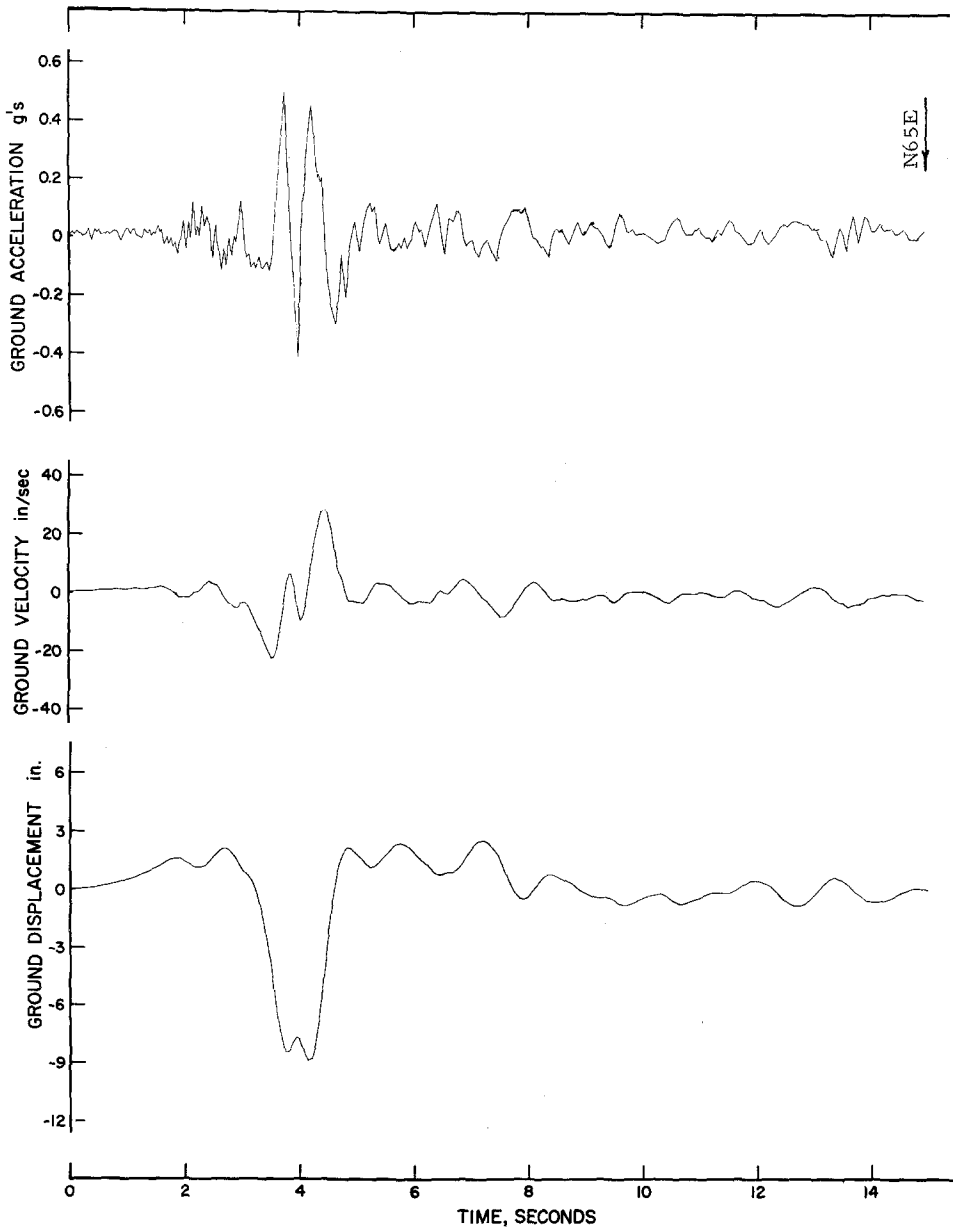


FIG. 6. Station 2 N65E Motion.

Figures 3 and 4 show that at the Temblor Station the motions were similar to, but somewhat less strong than those at Station 5. On the Temblor side of the fault basement granite at a depth of 2.6 miles is overlain by four sedimentary layers and

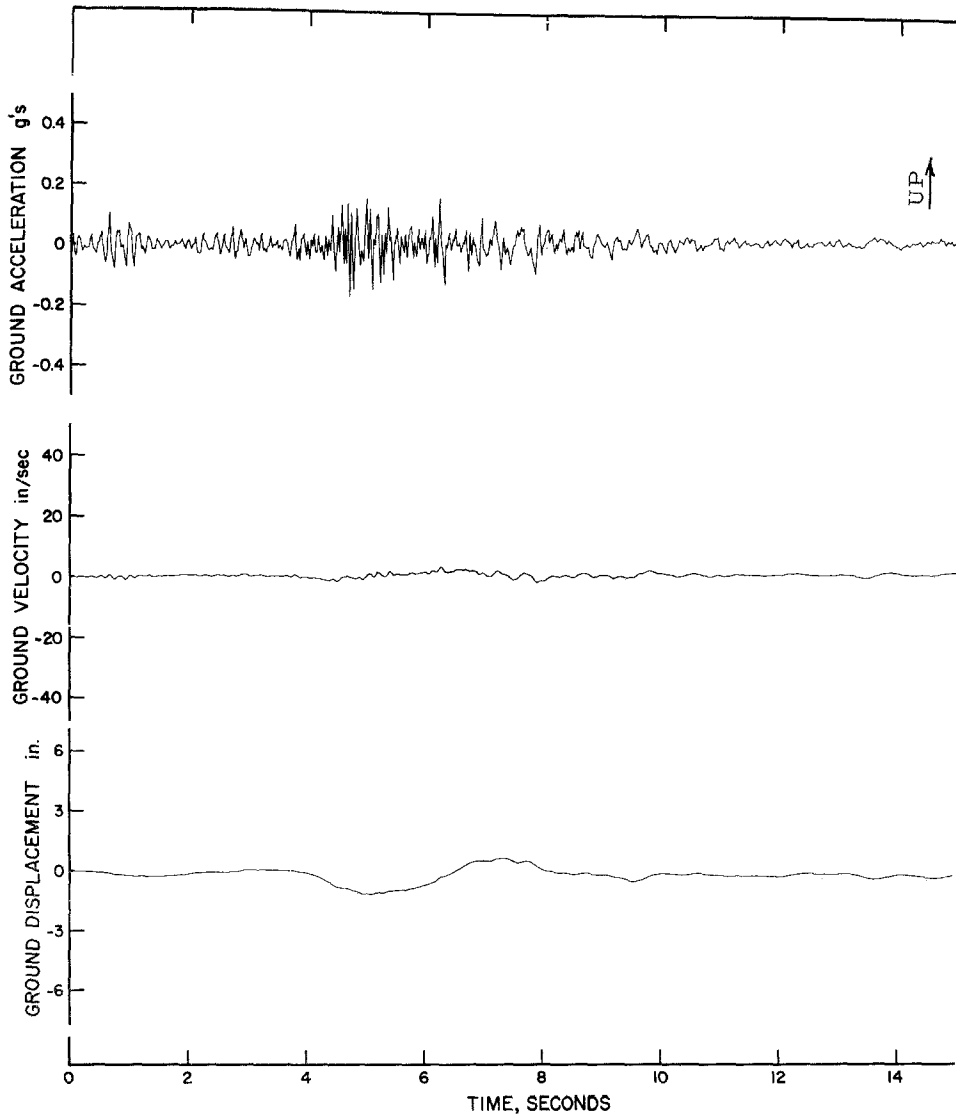


FIG. 7. Station 5 Vertical Motion.

on the southwestern side granite at 2.2 miles depth is overlain by three sedimentary layers (M. E. O'Neill, private communication) as shown in Table 1. In addition there is a shallow surface layer of alluvium at Stations 5, 8 and 12. Station 2 is directly on the fault zone.

The vertical acceleration at Station 2, shown in Figure 5, has a maximum value



of 35 per cent of  $g$ . The appearance of the accelerogram differs markedly from that of the horizontal motion, Figure 6. There is a three-second long segment of relatively high frequency motion whose amplitude becomes very small about five seconds after

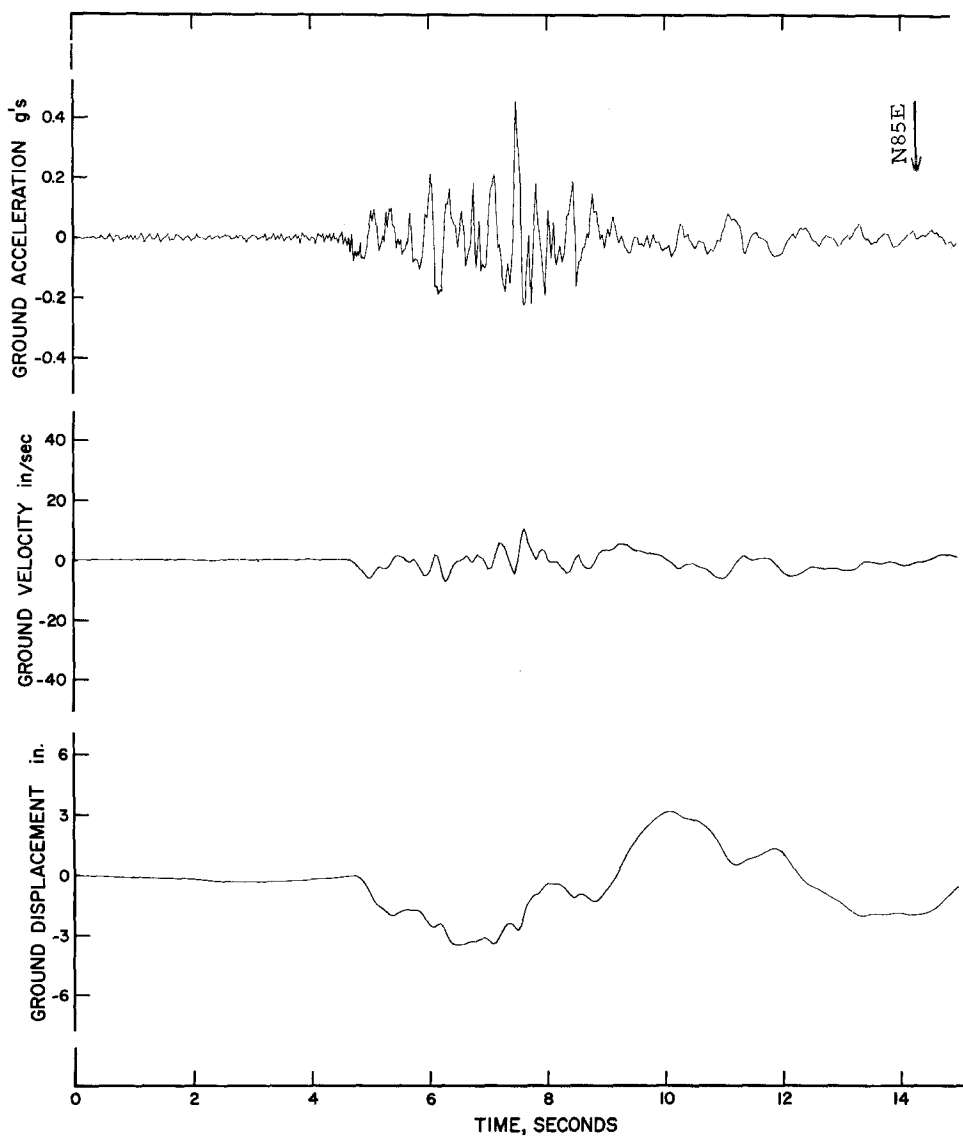


FIG. 8. Station 5 N85E Motion.

the start of the record. There is also visible a longer period component, approximately one second period, that has about 5 per cent of  $g$  amplitude out to six seconds after the beginning of the accelerogram, and then gradually dies away. This longer period component shows clearly in the vertical ground displacement. The

vertical ground motion attenuates with distance from the fault even more rapidly than does the horizontal motion. At Stations 8 and 12 the vertical motion is very much attenuated and even at Station 5 and at Temblor Station, only about 3.5 miles from Station 2, the vertical motion is much reduced.

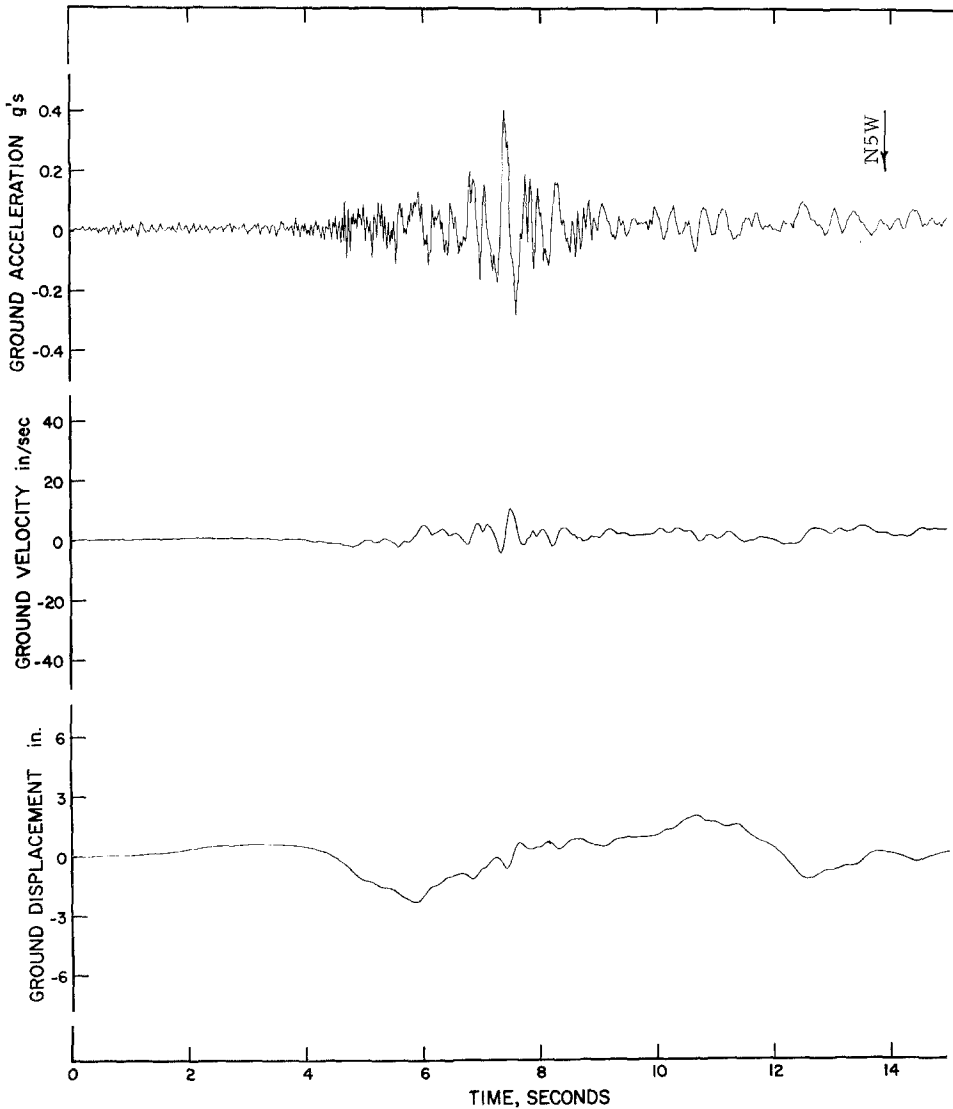


FIG. 9. Station 5 N5W Motion.

#### RESPONSE SPECTRA

The computed response spectra are presented in Figures 16-29. In each figure the four curves are the velocity response spectra for 0, 2, 5 and 10 per cent of critical damping. It may be noted that the zero damped response spectrum curve is a fair representation of the Fourier amplitude spectrum of the accelerogram.

Figure 20 shows the spectrum of the transverse motion at Station 2. The spectrum has a pronounced peak at about 0.75 seconds period which is produced by the few large peaks on the accelerogram. There is a lesser peak at 1.25 seconds period and a

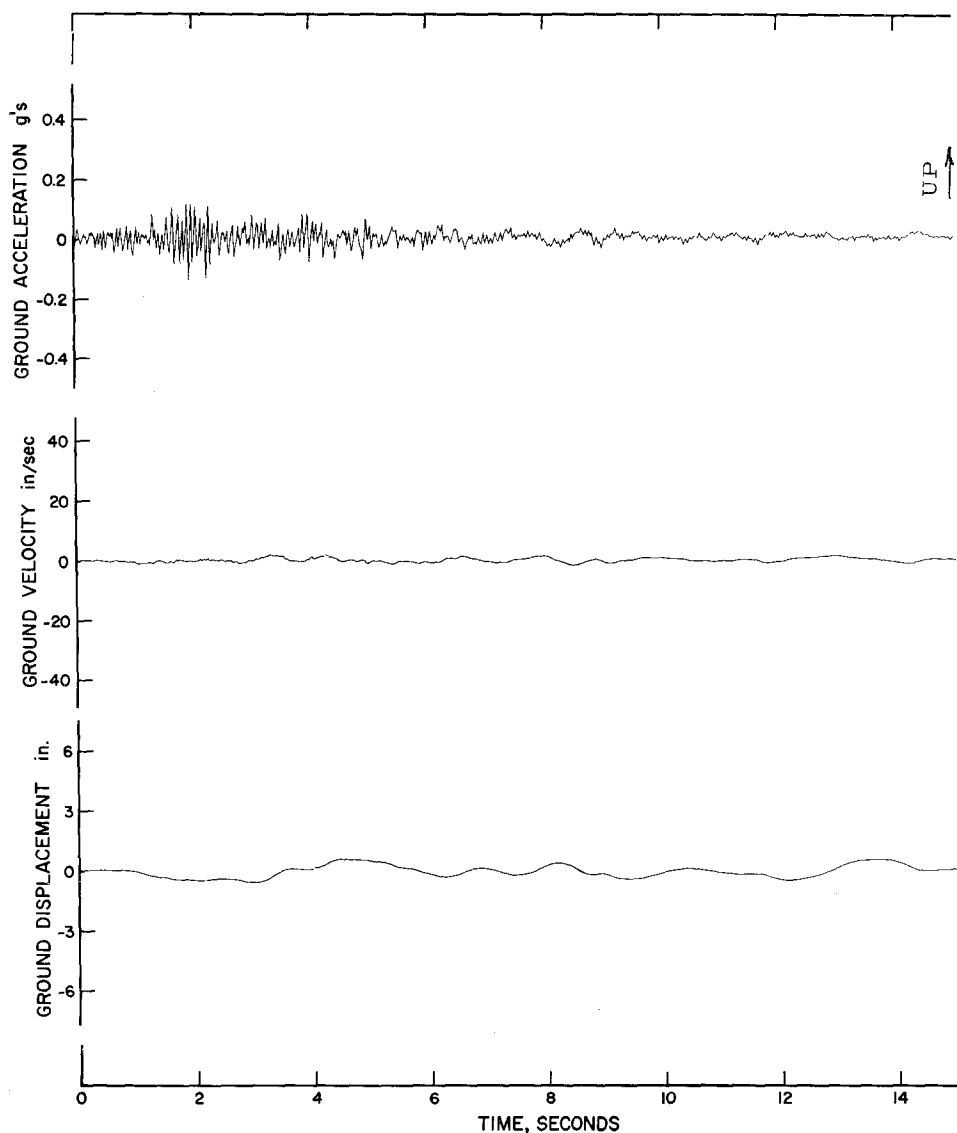


FIG. 10. Station 8 Vertical Motion.

broad hump at about 1.5 seconds period. It should be noted also that the spectrum curves drop off rapidly at the short period end, being already very low at a period of 0.2 seconds. The spectra at Station 5 show that the horizontal components have higher frequencies than at Station 2 for there is a pronounced peak at about 0.4 seconds period. In the N 85 E spectrum at Station 5 there are two pronounced peaks, at

1.25 and 2.0 seconds respectively, that do not appear on the N5W component. These velocity spectra at Station 5 with sharp peaks at 0.4 seconds period are not too dissimilar from those calculated for other small earthquakes recorded relatively

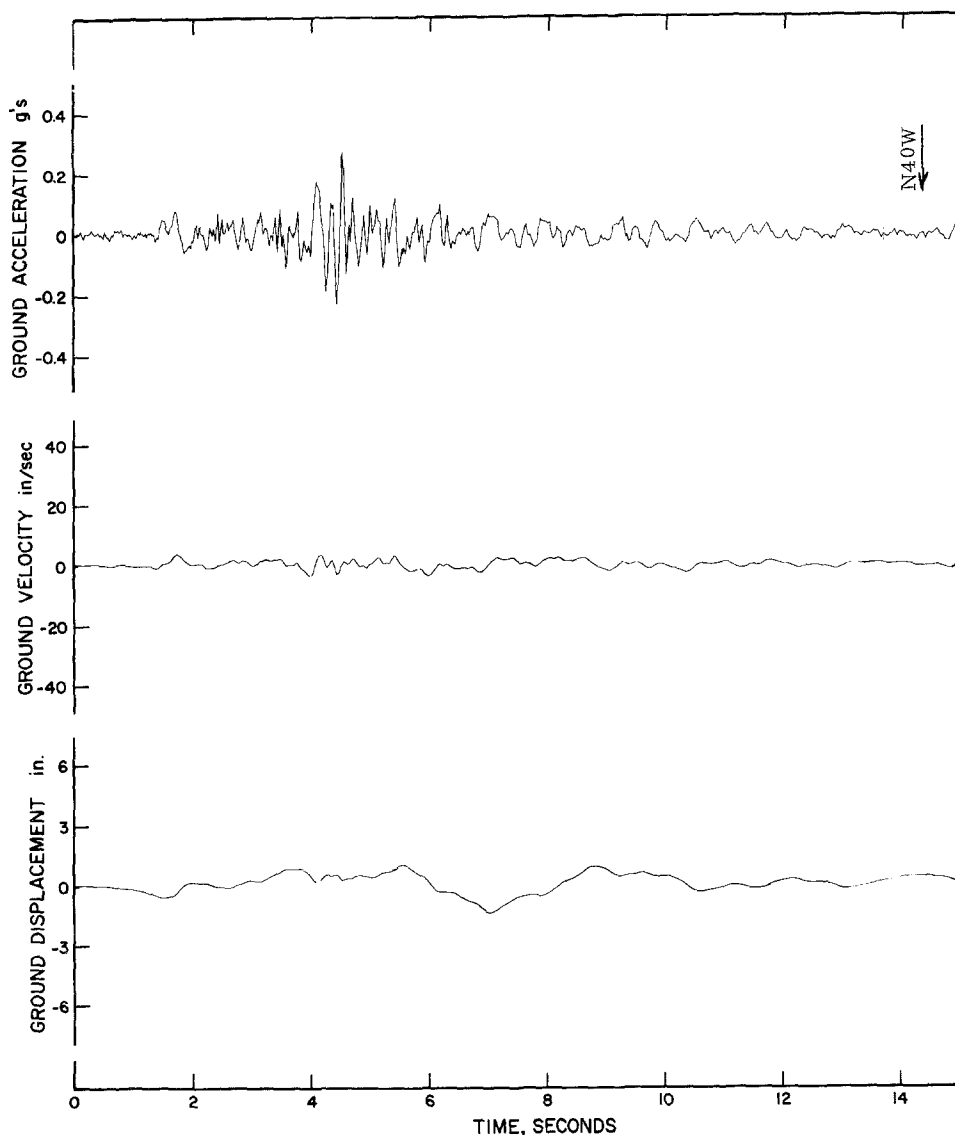


FIG. 11. Station 8 N40W Motion.

close to epicenters as, for example, the Golden Gate Park record for the March 22, 1957 San Francisco shock ( $M = 5.3$ ).

The spectrum curves for Station 8 do not exhibit the marked peak at 0.4 seconds period that the Station 5 spectra showed. This difference in shape of spectra is presumably due to the greater distance from the fault of Station 8. So far as is

known, there is no significant difference in geology at the two stations which are less than three miles apart.

The spectrum curves for horizontal motion at Station 12 show some pronounced

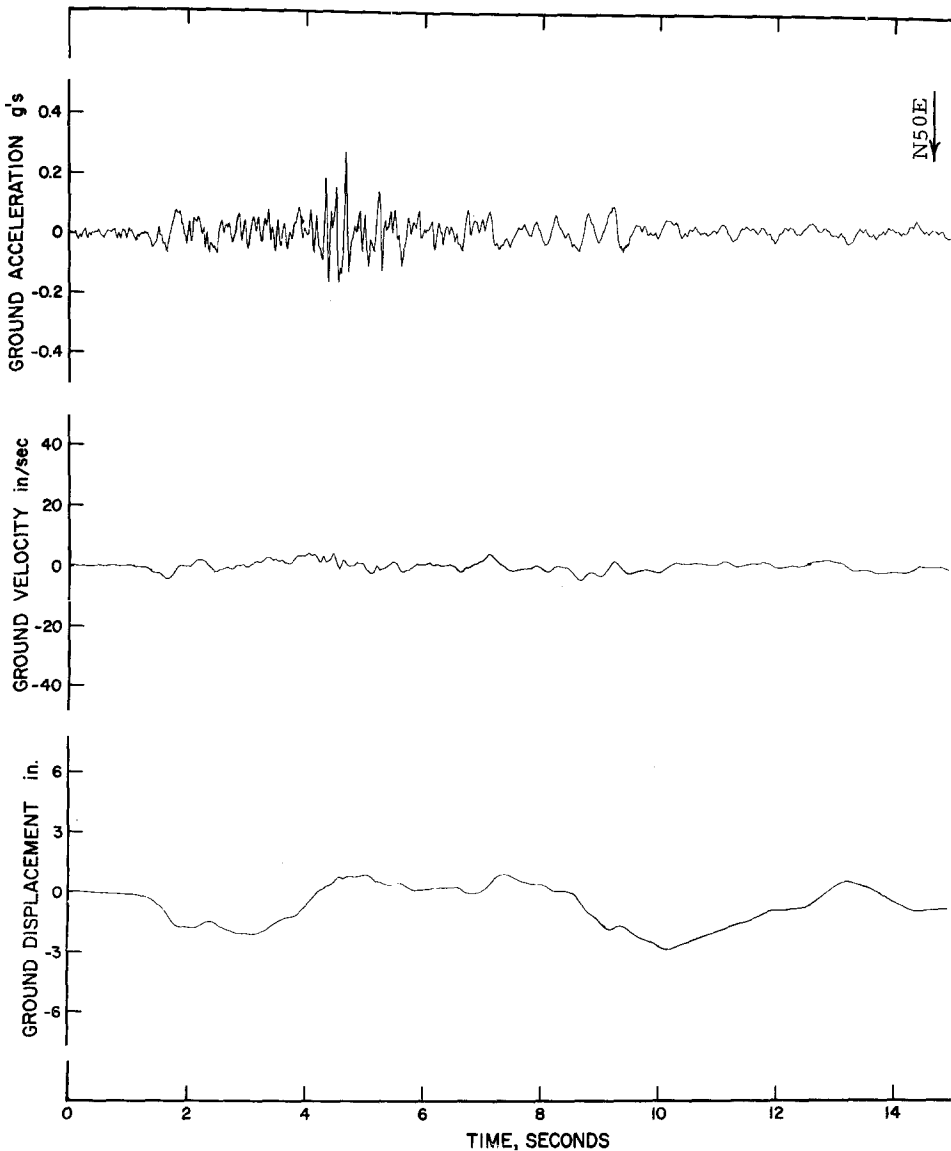


FIG. 12. Station 8 N50E Motion.

humps at 1.4 and 2.2 seconds period that did not appear at Station 8, although similar humps appeared in the N85E component at Station 5.

The Temblor horizontal spectra are similar to those of Station 5 but the large hump at 2 seconds in the N85E component at Station 5 does not appear at Temblor.

The vertical component spectrum for Station 2 shows peaks at 0.75 and 1.5

seconds similar to the horizontal component spectrum. The vertical components at Stations 5, 8, 12 and Temblor do not show any pronounced frequency components.

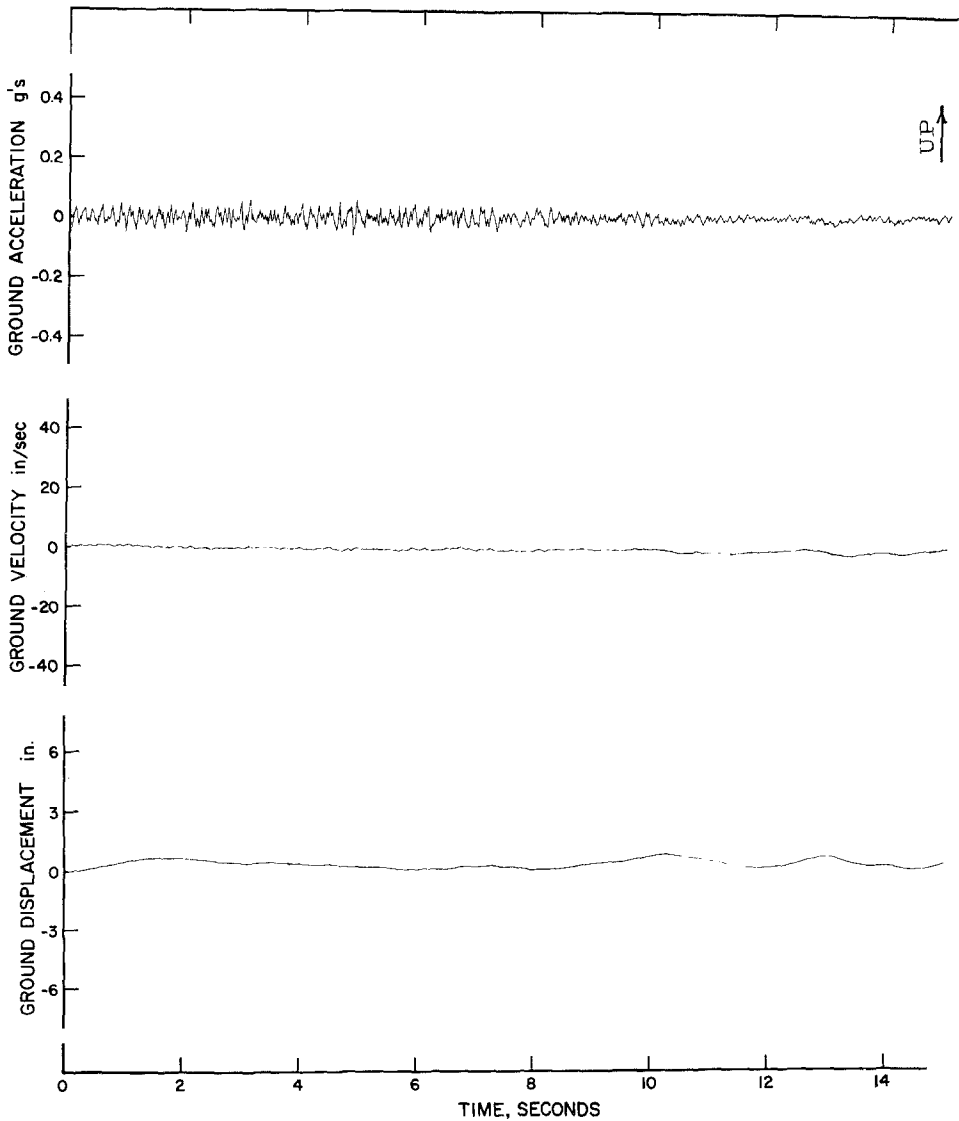


FIG. 13. Station 12 Vertical Motion.

#### THE NATURE OF THE MOTION AT STATION 2

Station 2 was located about 200 feet westerly of the line of fault slip that passed through the asphalt road near Cholame. The recorded motion transverse to the fault showed a maximum acceleration of 50 per cent of  $g$  corresponding to a displacement pulse of about 10 inches amplitude and 1.5 seconds duration. The

direction of this pulse was towards the northeast. As the component longitudinal to the fault was not recorded, it is of interest to see what can be deduced about this motion. Figure 30 shows the retouched seismoscope record at Station 2. The

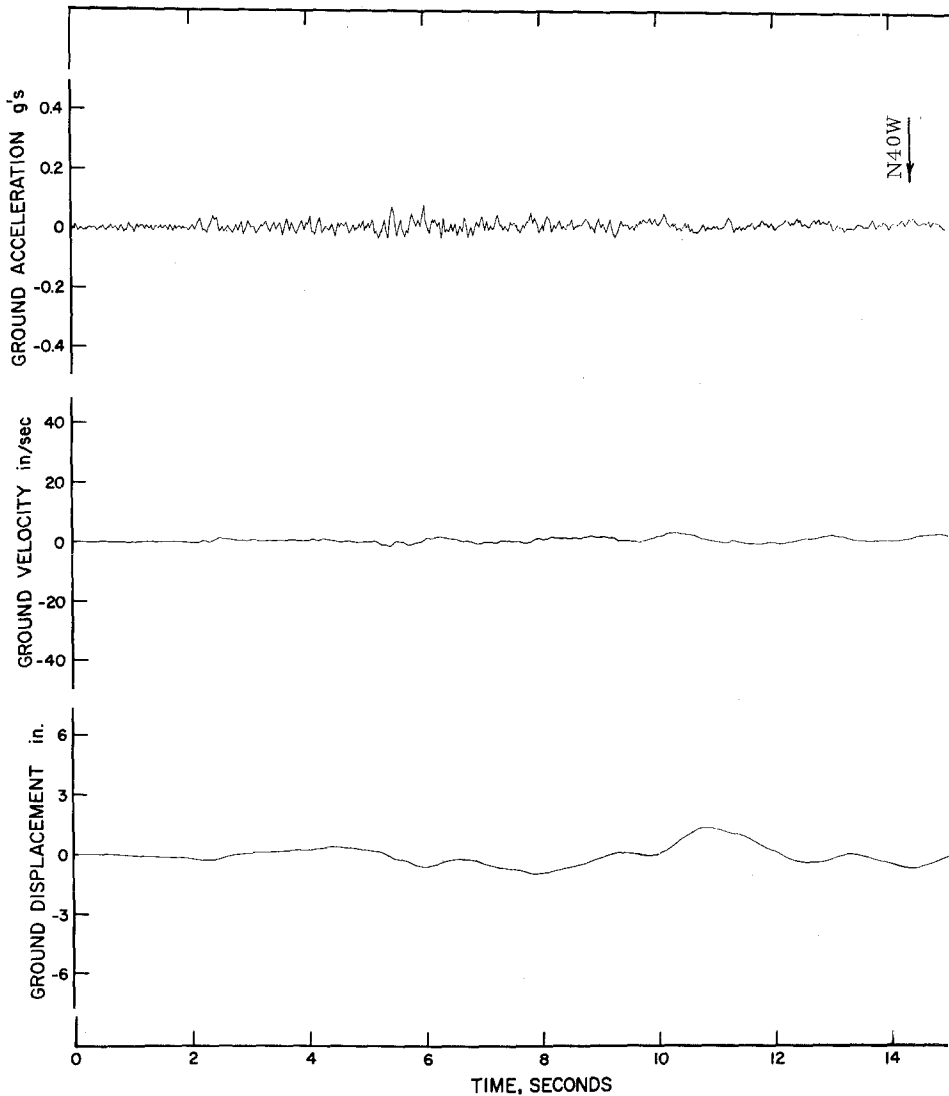


FIG. 14. Station 12 N40W Motion.

solid line portion of the record is reliably recorded, and the dotted line indicates that the recording needle skipped, went off the edge and then returned onto the smoked watch-glass, touched the edge again and shortly thereafter the glass was dislodged and dropped on the floor. The following check was made of the reliability of the seismoscope record: The response of the seismoscope, which had 0.78 seconds period and 8.5 per cent damping, was calculated using the recorded

transverse component of acceleration as input. This computed response agreed very closely with the projection of the seismoscope record on a plane transverse to the fault, including both the solid and the dotted lines shown in Figure 30.

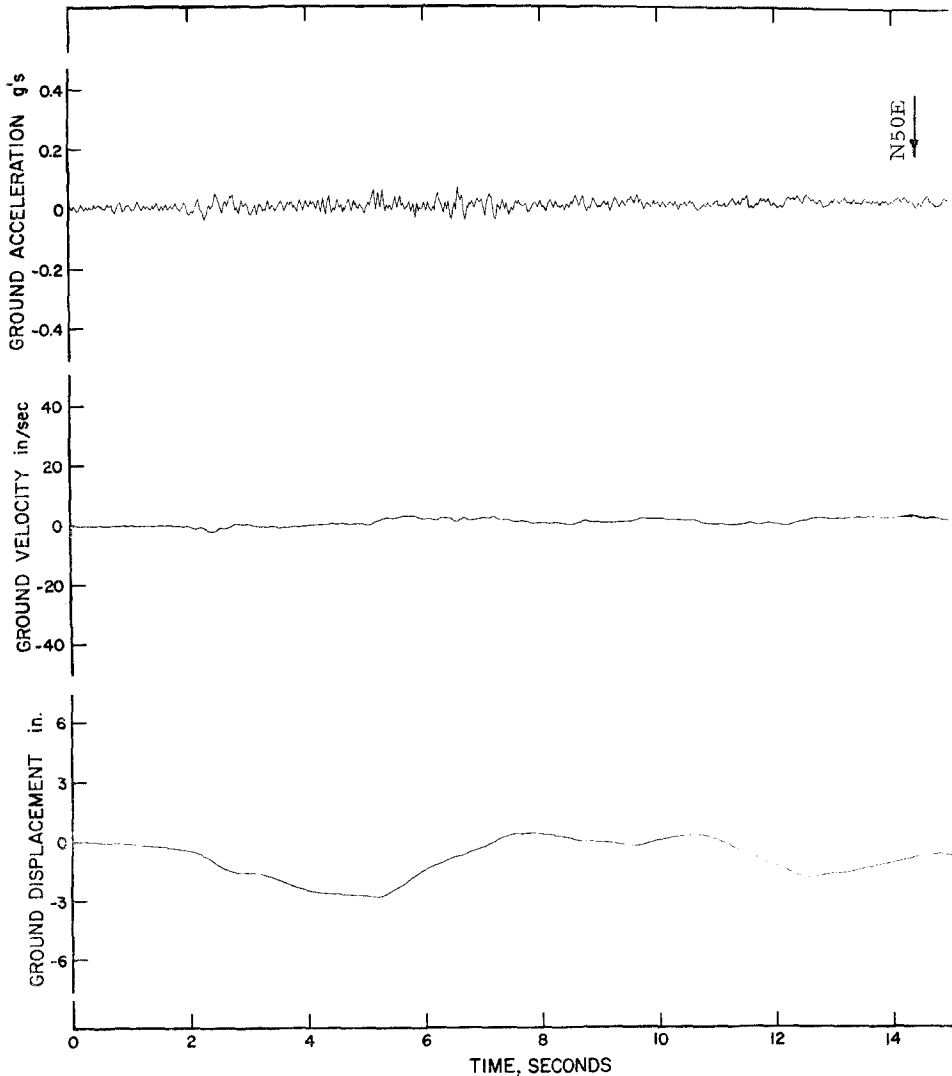


FIG. 15. Station 12 N50E Motion.

This covers the initial portion of the accelerogram up to the 50 per cent  $g$  pip. The seismoscope record thus shows that during the initial portion of the ground motion the transverse component was much stronger than the longitudinal component. Similar indications have been deduced from seismoscope records from other shocks (Cloud, 1967b).

Figure 31 shows the seismoscope record at Station 1 which was about one mile easterly of the fault. Although the sequence of motion cannot be deciphered, it is



clear that the transverse motion was much stronger than the longitudinal component of motion. Figure 32 shows the seismoscope record for Station 3 about one mile westerly of the fault. Recalling that the dotted lines in Figure 30 take the record just up to the 50 per cent of g pulse, it may be concluded that the effective

TABLE 1  
GENERALIZED P-WAVE VELOCITY STRUCTURE

Velocity (ft per sec)	Thickness of Layer (ft)
<i>A. Southwest of San Andreas Fault Zone Near Cholame</i>	
5,400	900
8,900	4000
16,000	7000
19,000	—
<i>B. Northeast of San Andreas Fault Zone Near Cholame</i>	
7,500	570
10,500	3300
14,500	4900
18,000	5300
19,000	—

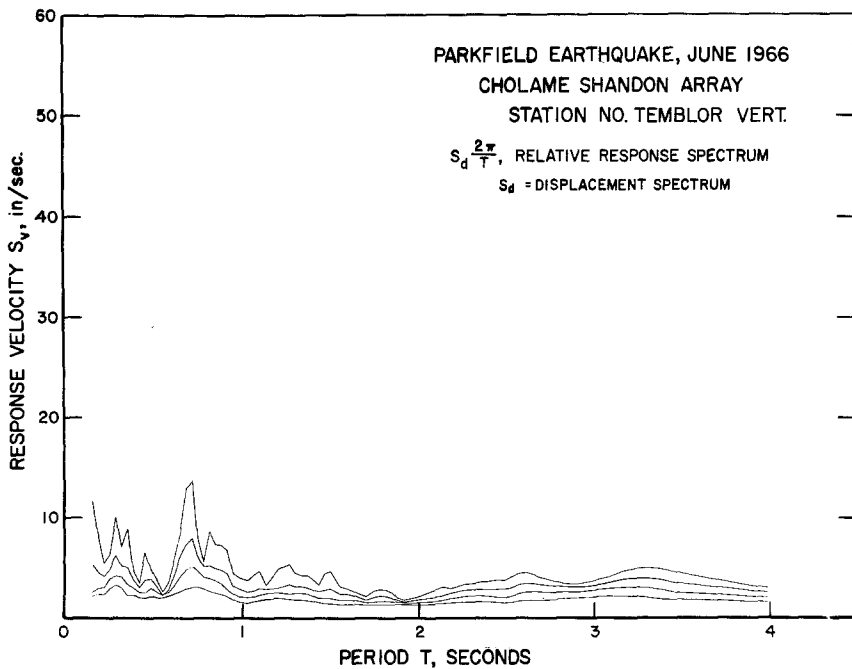


FIG. 16. Response Spectra, Temblor-Vertical. The curves are for 0, 2, 5 and 10% damping.

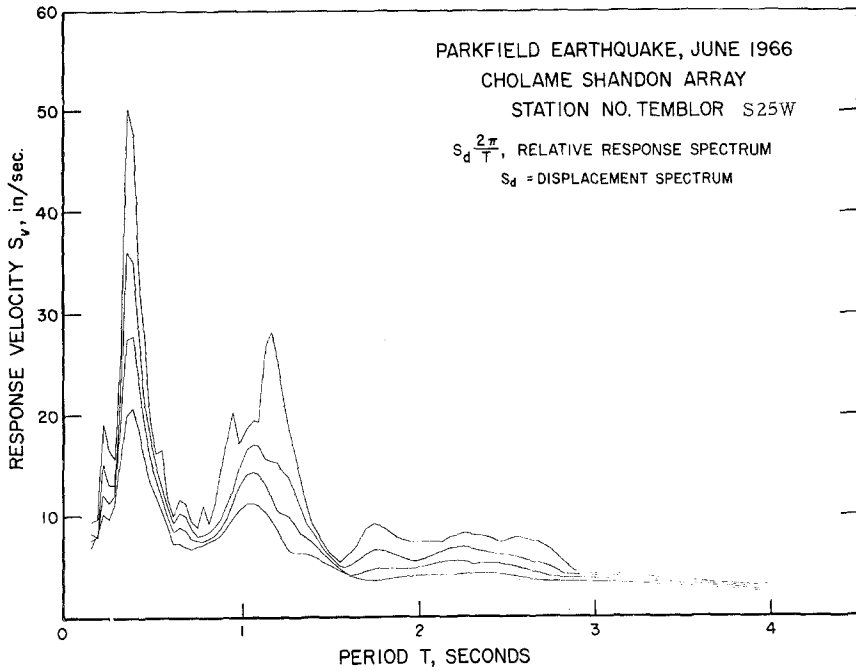


FIG. 17. Response Spectra, Temblor-S25W. The curves are for 0, 2, 5 and 10% damping.

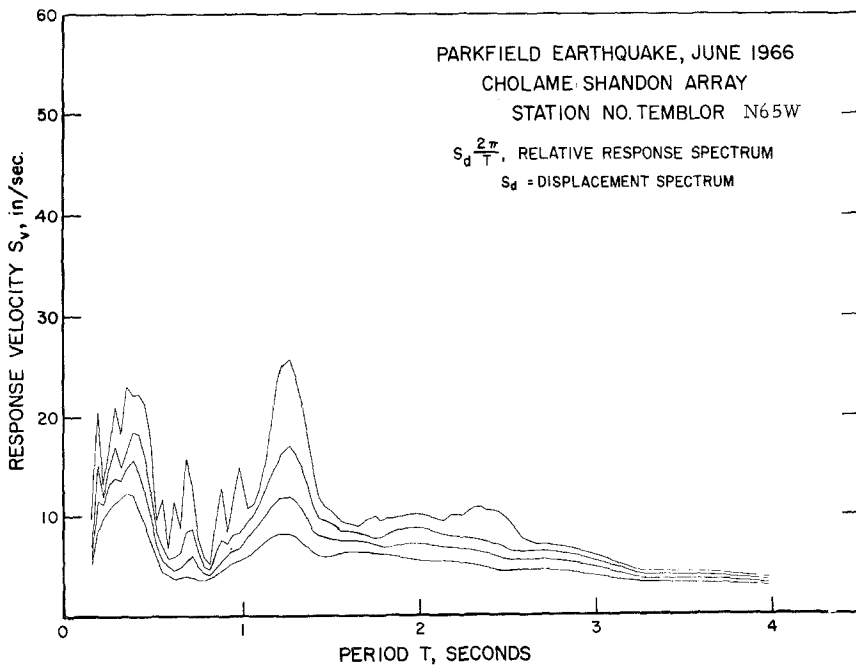


FIG. 18. Response Spectra, Temblor-N65W. The curves are for 0, 2, 5 and 10% damping.

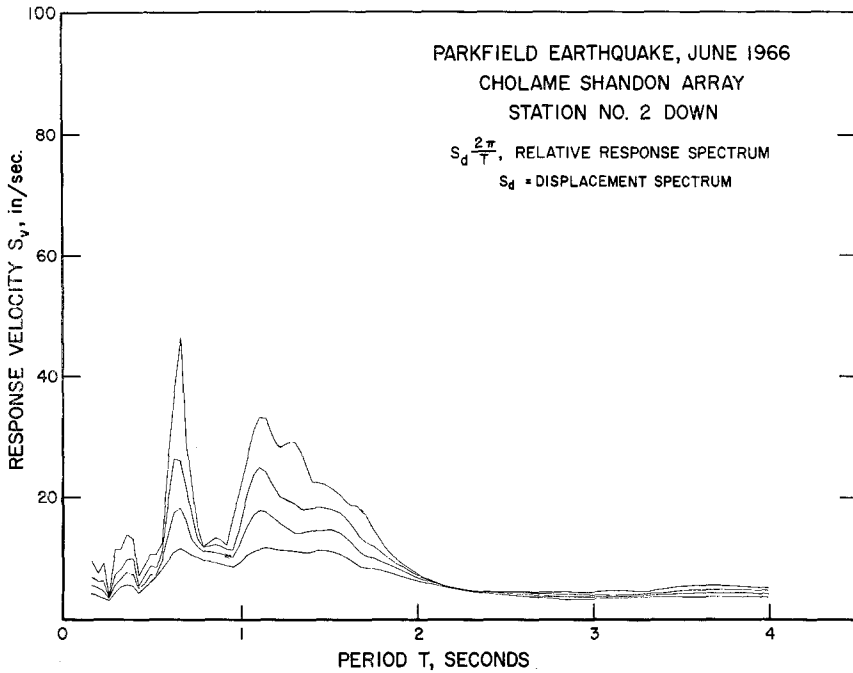


FIG. 19. Response Spectra, Station 2-Vertical. The curves are for 0, 2, 5 and 10% damping.

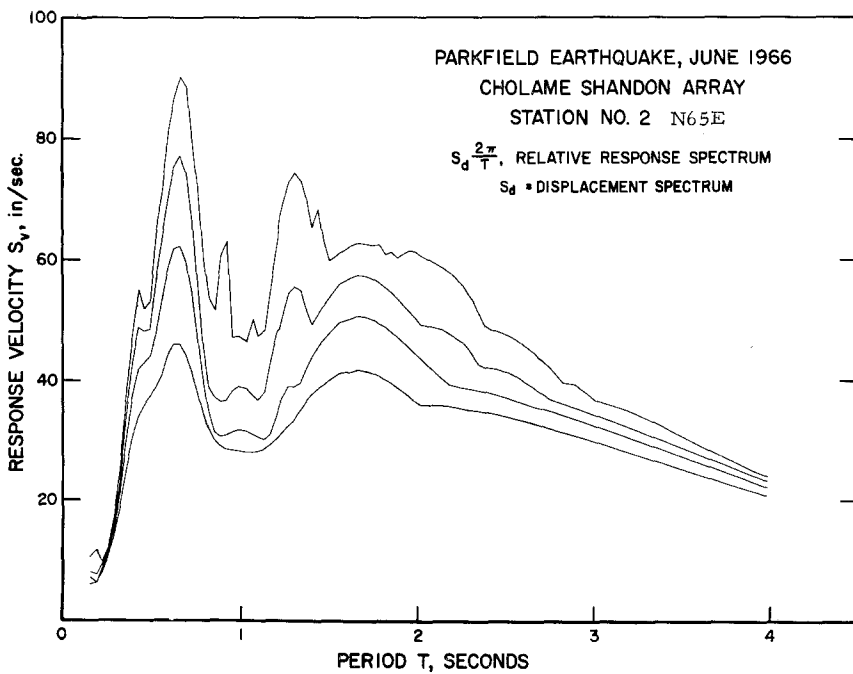


FIG. 20. Response Spectra, Station 2-N65E. The curves are for 0, 2, 5 and 10% damping.

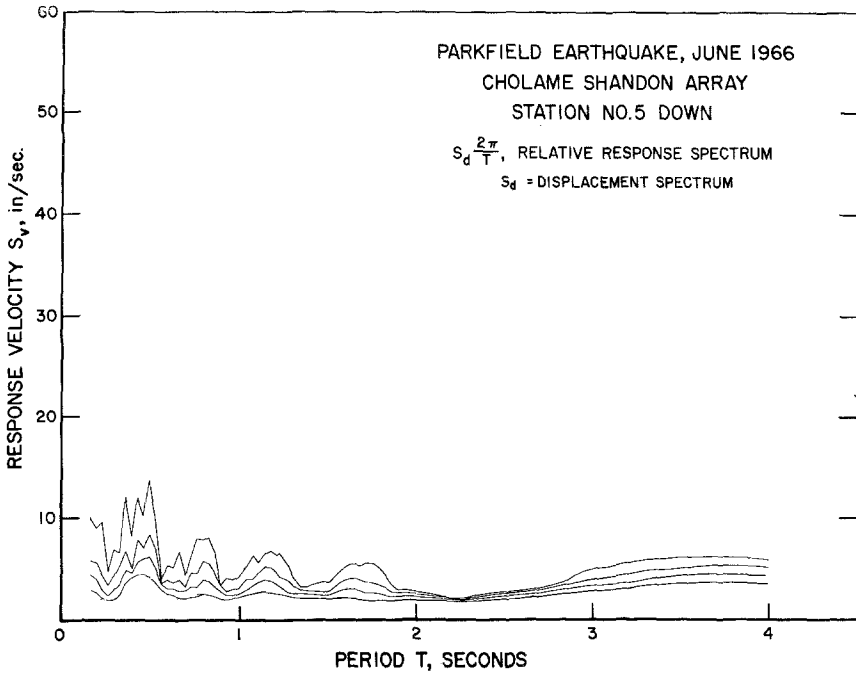


FIG. 21. Response Spectra, Station 5-Vertical. The curves are for 0, 2, 5 and 10% damping.

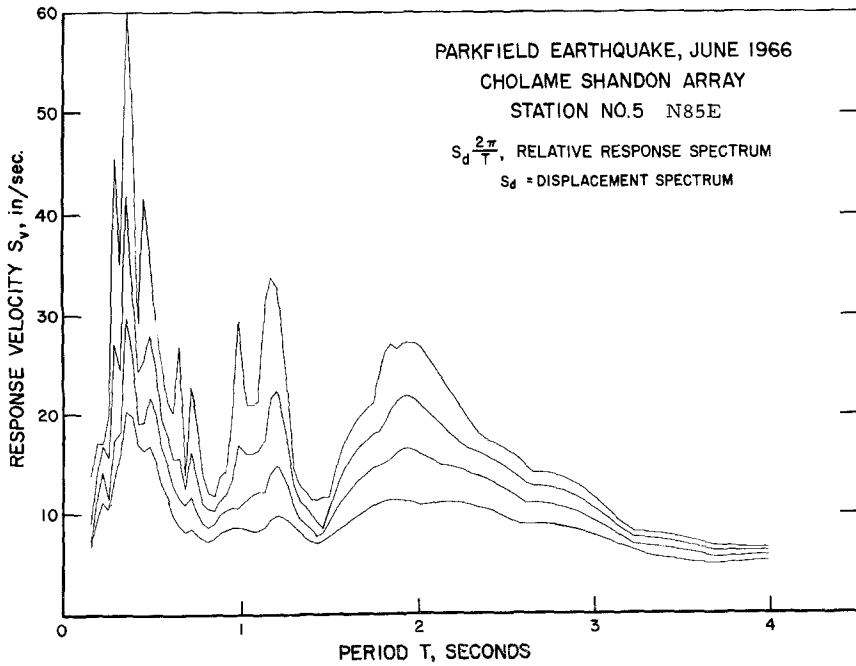


FIG. 22. Response Spectra, Station 5-N85E. The curves are for 0, 2, 5 and 10% damping.

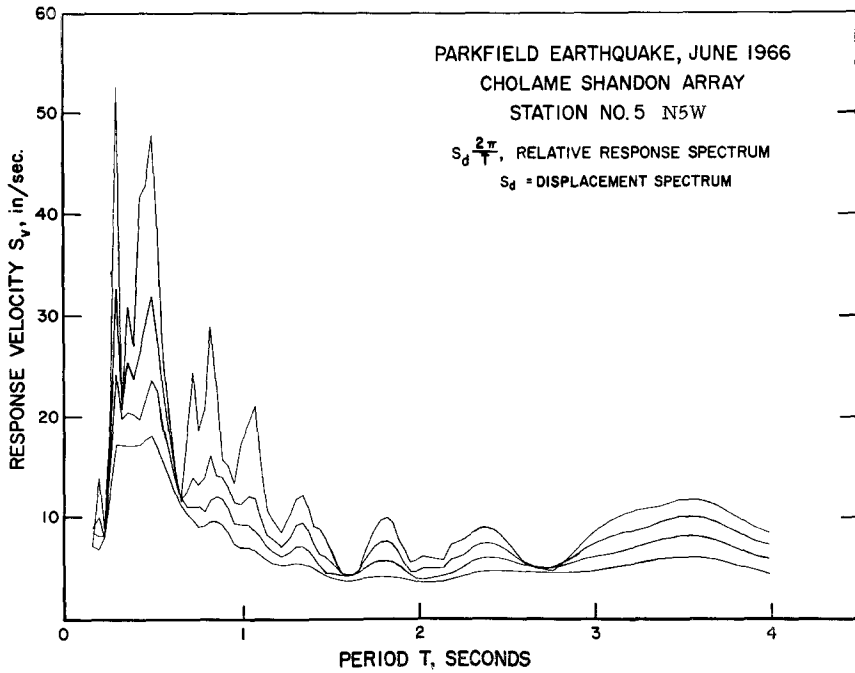


FIG. 23. Response Spectra, Station 5-N5W. The curves are for 0, 2, 5 and 10% damping.

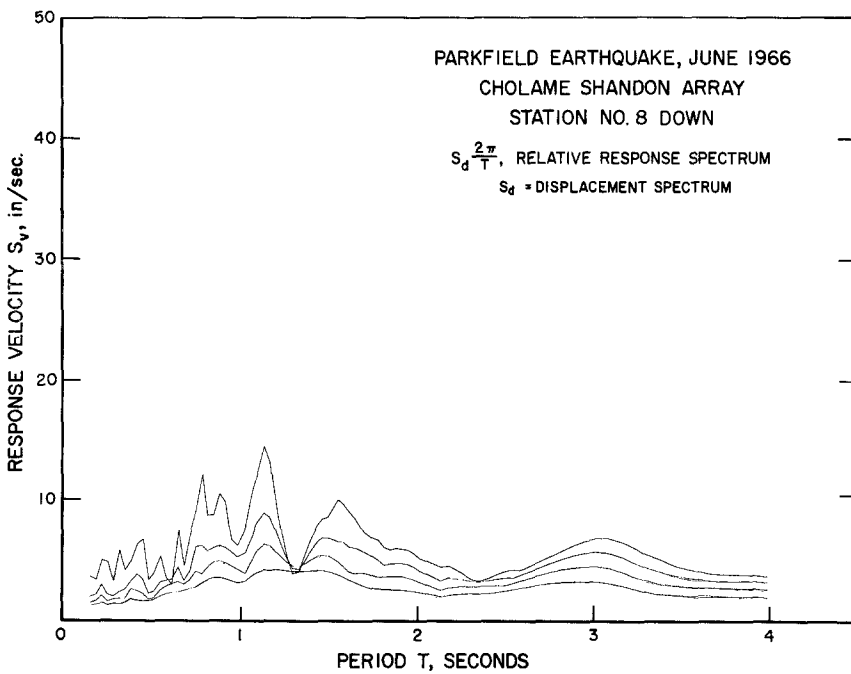


FIG. 24. Response Spectra, Station 8-Vertical. The curves are for 0, 2, 5 and 10% damping.

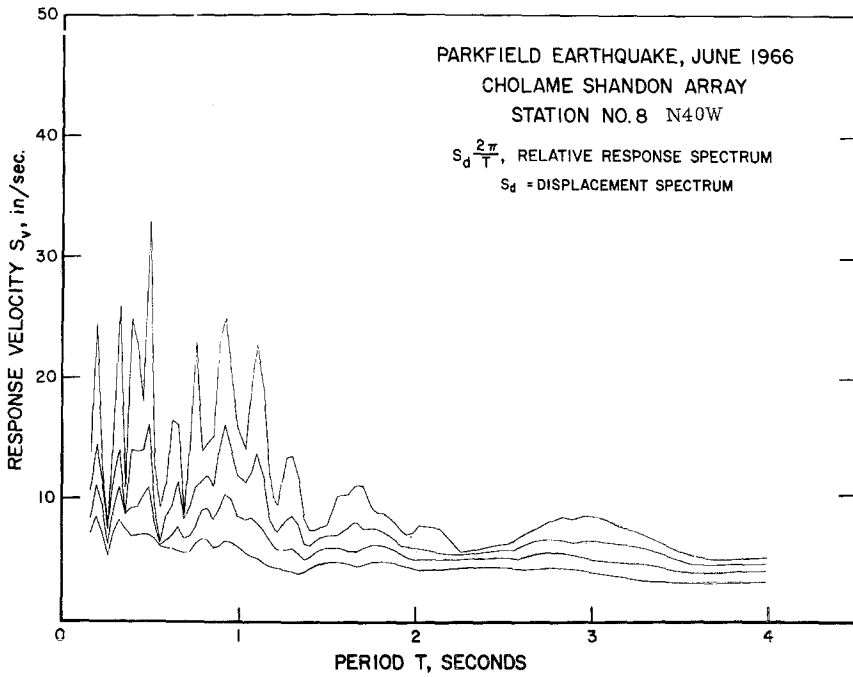


FIG. 25. Response Spectra, Station 8-N40W. The curves are for 0, 2, 5 and 10% damping.

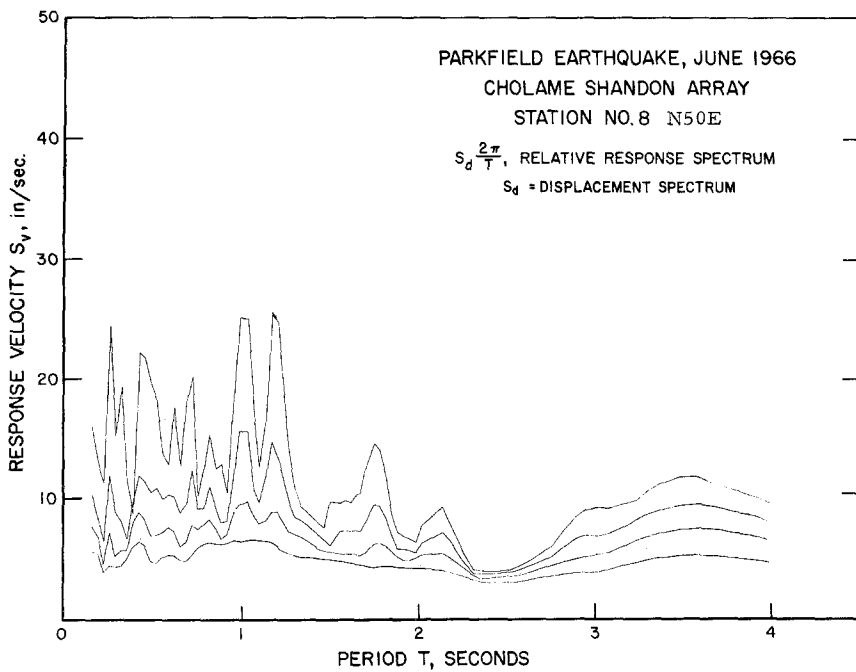


FIG. 26. Response Spectra, Station 8-N50E. The curves are for 0, 2, 5 and 10% damping.

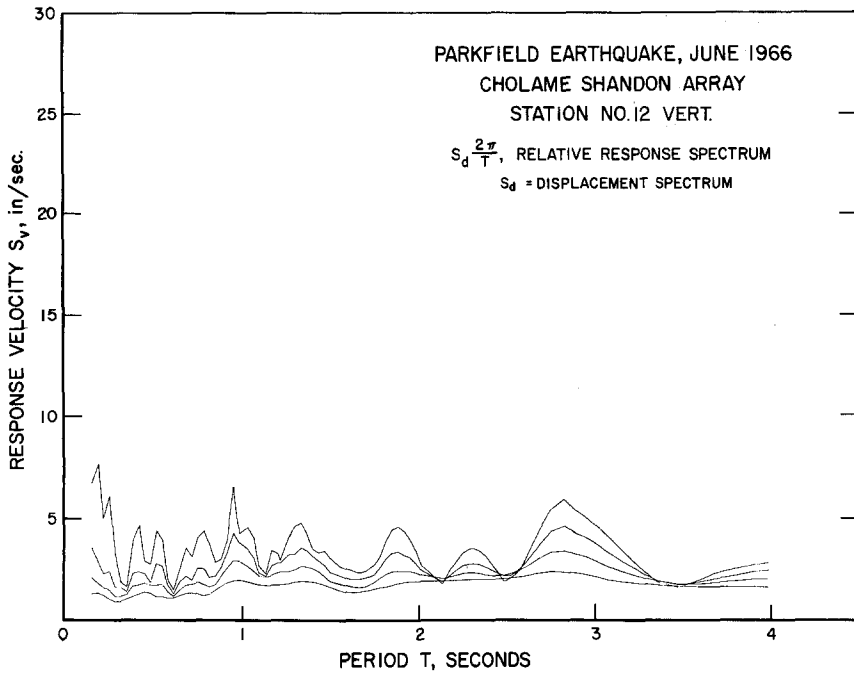


FIG. 27. Response Spectra, Station 12-Vertical. The curves are for 0, 2, 5 and 10% damping.

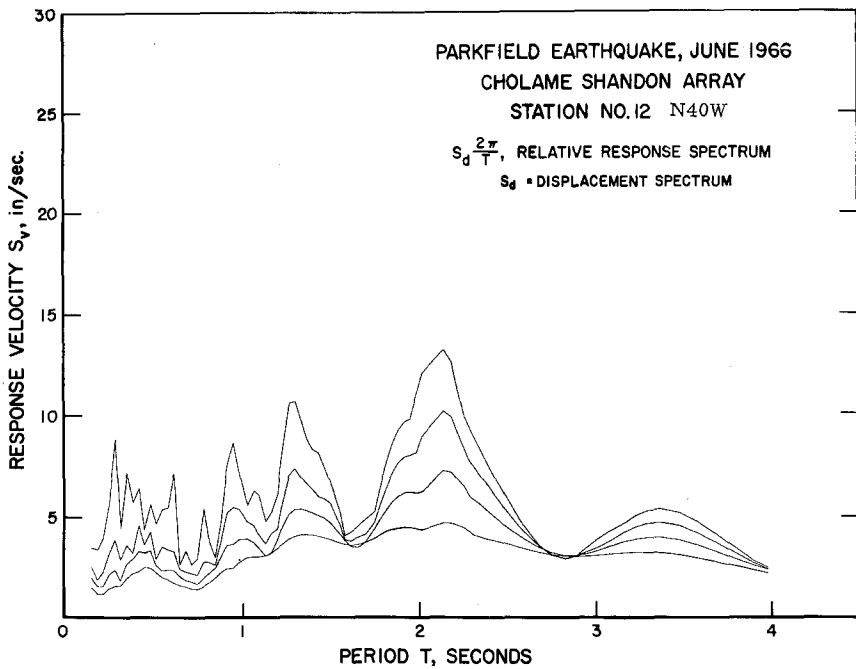


FIG. 28. Response Spectra, Station 12-N40W. The curves are for 0, 2, 5 and 10% damping.

motion at Station 3 was much reduced; that is, the 10 per cent damped spectrum curve in the neighborhood of 0.75 seconds period was much reduced over the value at 0.78 seconds at Station 2. The response spectrum displacement values at Station 3 were 0.9 inches single amplitude transverse and 0.65 inches longitudinal, whereas

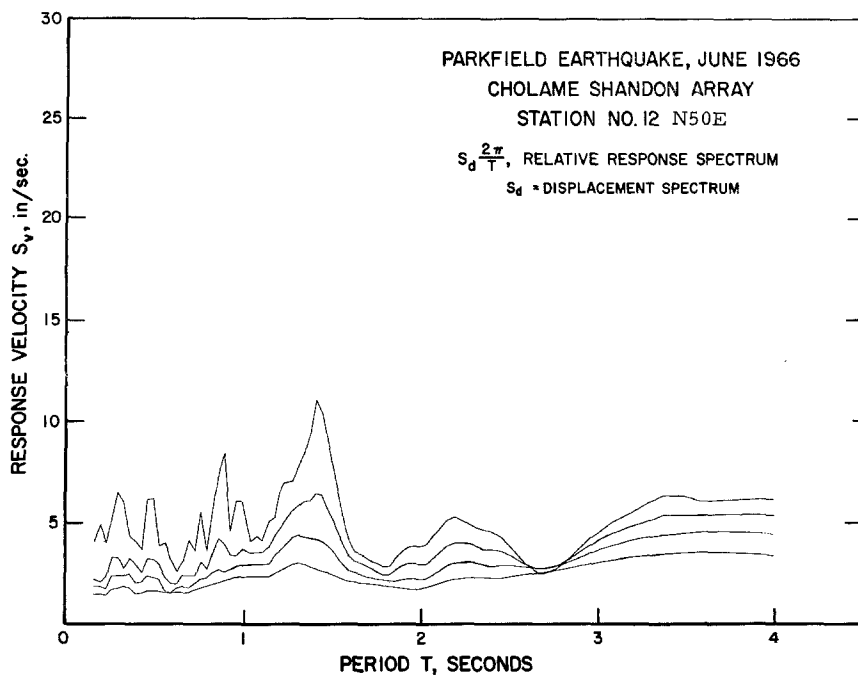


FIG. 29. Response Spectra, Station 12-N50E. The curves are for 0, 2, 5 and 10% damping.

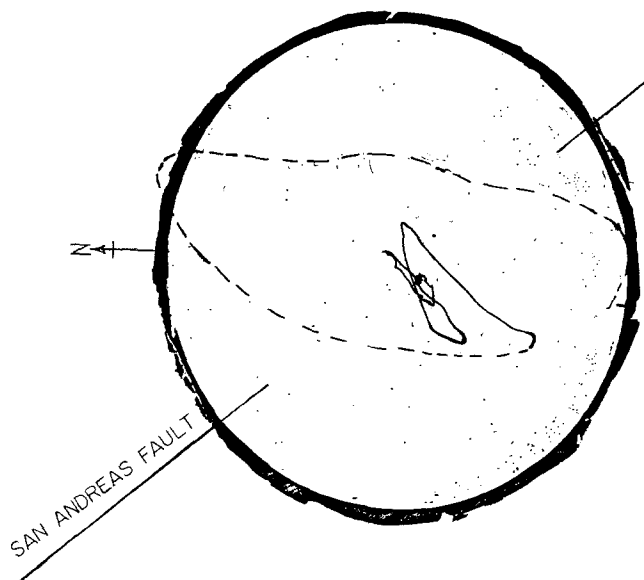


FIG. 30. Seismoscope Record Station 2.



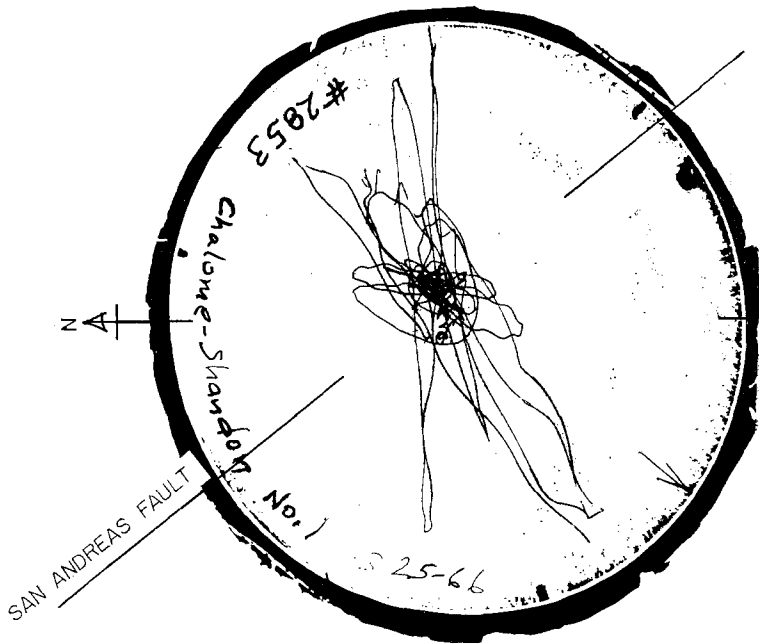


FIG. 31. Seismoscope Record Station 1.

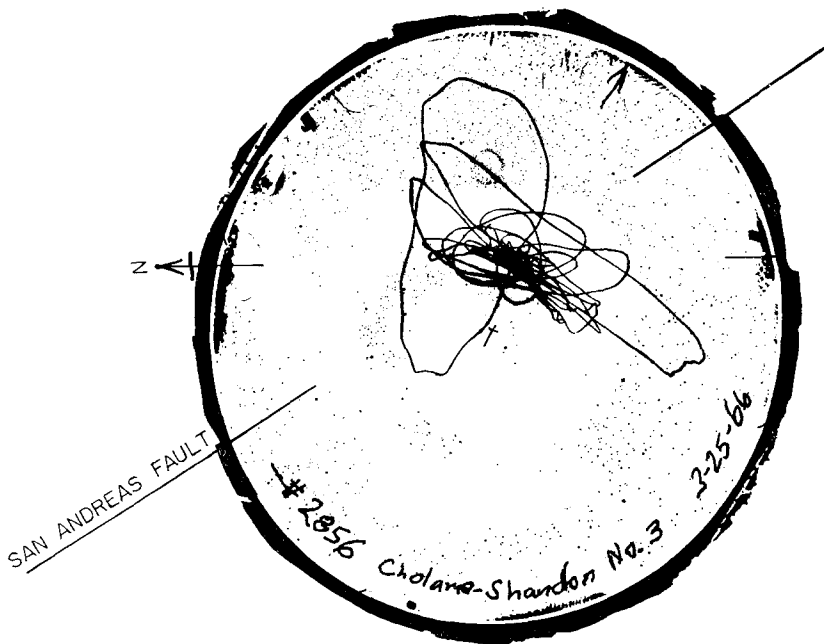


FIG. 32. Seismoscope Record Station 3.

the computed response spectrum displacement at Station 2 is 5.4 inches transverse.

A hodograph of the ground displacement at Station 5 is shown in Figure 33. This shows larger displacements transverse to the fault.

By private communication, Dr. Bruce Bolt reports that at the Berkeley seismographic station, which lies 150 miles northwest of Parkfield near the San Andreas fault, the longitudinal displacement component had approximately one-third the amplitude of the transverse component.

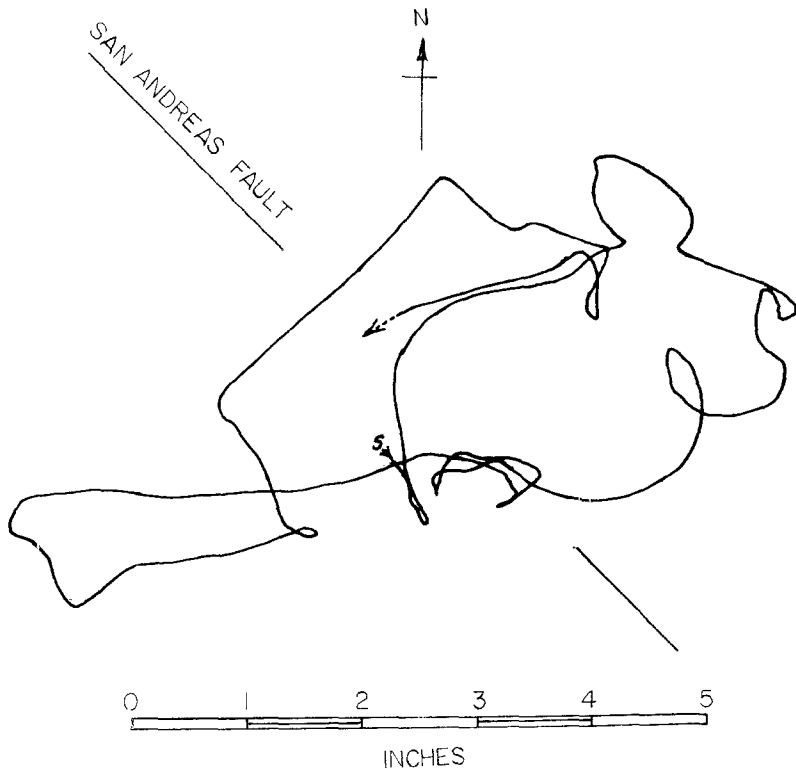


FIG. 33. Hodograph Station 5 First fifteen seconds of horizontal ground motion, 3.3 miles from fault.

An attempt was made to squeeze out information from the seismoscope record at Station 2 together with the known transverse component of acceleration. This analysis indicated a parallel acceleration pulse of approximately 0.5g lagging behind the transverse 0.5g pulse about one-quarter of a wave length.

#### THE PORT HUENEME EARTHQUAKE

The magnitude 4.7 Port Hueneme earthquake of 1957 was recorded close to the epicenter and its motion was also a single displacement pulse similar to that at Station 2 only smaller. The pulse had an amplitude of 1.4 inches, a duration of 0.5 seconds; and its direction was northwesterly, parallel to the San Andreas fault

which was some 30 miles to the east. The maximum acceleration was 16 per cent of  $g$ . In a paper (Housner and Hudson, 1958) analyzing this record it was pointed out that the spectrum curves had ordinates almost three times as great as would normally have been expected for a magnitude 4.7 shock. In that paper it was stated:

“The Port Hueneme accelerogram is the first strong-motion recording of a single-pulse shock. It is thus now known that such exceptional strong ground motions can occur, at least for shocks up to 4.7 magnitude. This raises the question whether it is possible that shocks of larger magnitude could be of this type, for if a shock of magnitude 6 or greater could be of the single-pulse type, it would require a revision of engineering thinking with respect to possible intensities of ground motions. On the basis of past experience, it would appear that the probability of a strong single-pulse shock is relatively small and, hence, engineers should continue to be guided by typical earthquake ground motions. The possibility of strong single-pulse shocks must, however, be kept in mind.”

The Parkfield earthquake thus proves that a pulse-type shock can be generated by a magnitude 5.6 event. This raises the question as to the possibility of a magnitude 6.5 or 7.5 shock generating an even larger pulse. In the Parkfield earthquake the slip apparently extended over a length of fault of some 20 miles and it does not seem likely that a more powerful pulse would have been produced if the slip had extended over a 40-mile length or over twice the depth. It would seem that a greater stress drop on the fault would be required to generate a greater pulse.

#### ENGINEERING SIGNIFICANCE

The fact that a displacement pulse of 10 inches amplitude can occur at a fault is of special engineering significance. Important structures to be located close to a fault along which an earthquake similar to the Parkfield shock may occur should therefore, be designed to withstand a 10-inch displacement pulse without serious consequences.

Also of special engineering significance is the fact that earthquake ground motion of 40 to 50 per cent of  $g$  and spectral velocities of 50 to 80 inches per second do not necessarily constitute a very destructive earthquake. The small damage caused by this earthquake points up the fact that large ground accelerations and large spectral values do not in themselves indicate severe damage to structures, at least of the type in the Cholame-Parkfield area. Such motion, of course, might be highly destructive of unreinforced masonry buildings. It should be noted that except for the bridge there were no structures near Station 2 to receive the unmodified effect of the 10-inch pulse. The nearest structures were at Station 3 in Cholame, and the spectrum here, as indicated by the seismoscope record, was already reduced from that at Station 2.

The different shapes of spectrum curves at locations not widely separated and on similar local geology indicate that in this earthquake the shapes of the spectra were determined largely by such factors as source mechanism and distance from causative fault rather than by local geology.

The unexpected and very significant information revealed by the Cholame array emphasizes the desirability of installing additional such arrays at strategic locations across active faults. It is clear that had the Parkfield earthquake been recorded only at Station 12, ten miles from the fault, there would have been no convincing evidence that this shock was in any way significant, or that there had been large displacements and accelerations associated with the earthquake.

#### ACKNOWLEDGMENTS

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