THE SITE RESPONSE OF TWO ROCK AND SOIL STATION PAIRS TO STRONG AND WEAK GROUND MOTION

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ABSTRACT

The site response to strong and weak ground motion depends largely on the subsurface conditions at the soil site for the two rock-soil station pairs studied. The first station pair consists of a soft-soil site and a sandstone/shale site (Treasure Island and Yerba Buena Island). For strong motion, the soft-soil site is amplified by a factor of about 3 over the rock site from 0.5 to 2.0 Hz. The amplification is much higher for weak motion and suggests a dependence on signal amplitude.

A second station pair near Gilroy consisting of a stiff-soil site and a sandstone site was studied with contrasting results. Unlike the results for the soft-soil study above, the estimated stiff-soil site response is not significantly different for strong and weak motion from 0.5 to 2.0 Hz.

INTRODUCTION

A dependence of ground motion on site conditions is clearly seen in the Loma Prieta damage pattern (e.g., EERI, 1990) and the strong motion records (Shakal et al., 1989; Maley et al., 1989). In general, the effect of site conditions is shown in the strong motion accelerograms by smaller amplitudes recorded at rock sites than at soil sites located at comparable distances and azimuths from the mainshock. For example, rock and soil sites in the San Francisco - Oakland area have peak ground accelerations of approximately 0.08 and 0.20 g, respectively (Shakal et al., 1989: Maley et al., 1989)

In this study, two rock and soil station pairs are chosen for analysis because of their proximity, the availability and quality of strong and weak ground motion recordings, and the differing subsurface conditions at the soil sites. The soil site for the first pair is a soft-soil site, while it is a stiff-soil site for the second pair. An analysis using Fourier spectral ratios allows the isolation of the soil site response from the effects of the source and the path. Also, a comparison of the site response estimated from weak and strong ground motions further defines the range of subsurface conditions and levels of ground motion for which techniques that estimate the ground motions of large earthquakes from the recordings of more frequent smaller earthquakes are applicable (e.g., Tucker and King, 1984).

THE STATION PAIRS

Soft-soil. Yerba Buena Island and Treasure Island form a rock and soil station pair located in San Francisco Bay, approximately 100 km from the Loma Prieta epicenter and 2.5 km from each other. The station at Yerba Buena Island is located on an outcrop of Franciscan sandstone and shale. Treasure Island is a manmade island created in the 1930s. According to Gibbs et al. (1992), the station is located on 14 m of hydraulic fill over sand and bay mud (soft clay sediments). The depth to basement, consisting of shale and sandstone, is 88 m at this site. The site geology and the P- and S-wave velocities are given in Gibbs et al. (1992). After the Loma Prieta earthquake sand boils provided evidence of liquefaction near the station on Treasure Island (Shakal et al., 1989; EERI, 1990).

This pair of stations was installed over 15 years ago by California's Strong Motion Instrumentation Program (CSMIP) specifically to record strong ground motion on these very different site conditions. This station pair triggered for the first time during the Loma Prieta earthquake. Because of the important characteristics of the mainshock accelerograms (Shakal et al., 1989) CSMIP recommended these sites to Lawrence Livermore National Laboratory (LLNL) as good candidate sites at which to locate high-gain instruments LLNL planned to deploy. As described in Jarpe et al. (1989) high-gain seismometers were co-located by LLNL at these sites for several weeks to record the weak ground motion from aftershocks. The instrumentation at each site consisted of a 16-bit fixed-gain recorder and a three component seismometer with a 1 Hz free period and a recording bandwidth (flat in velocity) from 0.2 to 100 Hz. A total of nine Loma Prieta aftershocks were recorded on both horizontal components at the two stations (Jarpe et al., 1989). From these nine aftershocks recordings, four were selected for this study that had the broadest useable bandwidth based on a signal-to-noise ratio analysis (see Darragh and Shakal, 1991). Table I summarizes various parameters of the set of five Loma Prieta events studied at this pair of stations.

Previous investigators using the data recorded at this station pair have analyzed the effect of soft-soils on strong and weak ground shaking from the Loma Prieta earthquake sequence (Jarpe et al., 1989; Shakal et al., 1990). These studies showed amplification of ground motion at the soft-soil site relative to the rock site for frequencies from approximately 0.5 to 5 Hz, and the level of amplification was greater for weak ground motion than for strong ground motion. This research extends these earlier studies by including a signal-to-noise analysis for the aftershocks (see Darragh and Shakal, 1991), a consideration of the dependence of amplification on signal amplitude, and a discussion of a similar analysis at a stiff-soil and rock station pair.

Stiff-soil. The second pair of stations is part of the Gilroy array, approximately 30 km east of the Loma Prieta epicenter. The Gilroy array is an alignment of six stations extending from sandstone on the east, across the alluvial Santa Clara Valley, to sandstone on the west. This array is a cooperative effort of CSMIP and the U.S. Geological Survey and is currently instrumented and maintained by CSMIP.

The array provides an opportunity to study the response of rock and deep soil sites to strong and weak ground motion. For this analysis, only the records from Gilroy #1 and #2, the closest rock and soil pair, are used. These stations are located 2 km from each other. The site geology and the P- and S-wave velocities at these stations are given in Fumal et al. (1982), Joyner et al. (1981) and Gibbs et al. (1992). Gilroy #1 is underlain by moderately weathered sandstone at the surface, with thin beds of shale at depth, while Gilroy #2 is underlain by alluvium (stiff-soil) to a depth of 167 m. Sandstone, siltstone and shale are encountered below this depth.

Previous investigators using data recorded at the Gilroy array have analyzed the effect of the stiff-soils on strong ground shaking recorded from the 1979 Coyote Lake earthquake (Joyner et al., 1981; Silva et al., 1986) and the 1984 Morgan Hill earthquake (Silva et al., 1986). Joyner et al. (1981), using a linear plane-layered model, showed that there is no clear evidence of nonlinear response at the stiff-soil site. Silva et al. (1986) concluded that the stiff-soil site response estimated from strong (direct S-wave window) and weak ground motions (S-wave coda window) were not significantly different for peak accelerations and velocities less than 0.25 g and 32 cm/sec, respectively.

This study extends these previous analyses by incorporating the ground-motion data from the Loma Prieta mainshock and thirteen aftershocks that CSMIP recorded on analog and high-gain digital accelerographs. The record from the mainshock increases the largest peak acceleration and velocity recorded at the stiff-soil site to 0.35 g and 39 cm/sec, respectively (Table II). The records from the aftershocks, ranging in local magnitude from 4.1 to 5.4, provide many records of weak ground motion at the sites (Table II).

METHOD

In this study, an estimate of the response of a soil site is obtained by calculating the ratio of the smoothed Fourier amplitude spectra at the soil site and a nearby rock site. This method is similar to that described in Tucker and King (1984), Silva et al. (1986) and Jarpe et al. (1988). For soil and rock sites located at similar distances and azimuths from the earthquake, the spectral-ratio method isolates the site response from the effects of the source and the path.

The method used in this study consists of the following principal steps. First, for each horizontal accelerogram, a time window of approximately 10 seconds duration containing the direct S-wave arrival is selected and the mean removed. Next, the start and the end of the record are tapered with a five percent Hanning window. The Fourier spectrum is then estimated from the time history using a standard fast Fourier transform algorithm. The average horizontal spectrum is computed by adding the squared moduli of the horizontal spectra together, dividing by two, and taking the square root. The resulting spectrum is then smoothed with a running-mean filter with a bandwidth of approximately 1 Hz. The ratio obtained by dividing the smoothed average horizontal spectrum at the soil site by the corresponding rock site spectrum is an estimate of the soil-site response. These ratios are discussed in the following sections.

SOFT-SOIL SITE RESPONSE

The soft-soil site response estimated from the smoothed Fourier spectral ratios for Treasure and Yerba Buena islands are shown in Figure 1 for earthquakes with local magnitudes of 7.0, 4.3, 4.1, 3.5, and 3.3. In this figure, amplification of ground motion at the soft-soil site relative to the rock site is observed for both strong and weak ground motions in the frequency range from approximately 0.5 to 7 Hz.

For the Loma Prieta mainshock, Figure 1 shows that the motion at the soft-soil site is amplified over the rock site by a factor of about 4 over a broad frequency range. In contrast, for weak ground motion from Loma Prieta aftershocks, the motion at the soil site is amplified over the rock site by a factor of 12 to 25 near 1 Hz. For these five earthquakes, the level of amplification near 1 Hz appears to vary with the earthquake magnitude, dependent on the level of input motion (peak ground velocity) at the rock site. The maximum amplification is approximately 25, 19, 17, 12, and 4 for earthquakes with local magnitude 3.3, 3.5, 4.1, 4.3, and 7.0, respectively. Correspondingly, as the peak rock velocity increases from 0.005 to 0.007, 0.015, 0.099, and 14.7 cm/sec, the maximum amplification decreases from 25 to 19, 17, 12, and 4, respectively. However, note that the factor-of-two difference in weak motion amplification from 12 to 25 is within the normal range of scatter (Tucker and King, 1984). Also, the local magnitude 3.3 and 3.5 earthquakes have quite similar peak rock velocities of 0.005 and 0.007 cm/sec, respectively, but they have different maximum amplifications of 25 and 19, respectively. Thus, it will be important to record future earthquakes at these sites to understand this provocative, albeit preliminary, trend in the soft-soil site response.

The shape, or frequency dependence, of the spectral ratios also varies with local magnitude. Figure 1 shows that the soft-soil site response for the aftershocks has strong peaks near 1 and 2 Hz. However, the site response estimated for the mainshock is nearly flat over the same frequency range.

These soft-site soil-response differences, in both amplitude and frequency dependence, demonstrate that caution must be exercised in using weak-motion studies to infer soft-soil site response during strong shaking for seismic hazard estimation and zonation. Weak ground motion may be amplified to a greater extent than strong ground motion, especially at sites similar to Treasure Island where nonlinear effects are observed at peak acceleration and velocity levels as low as 0.16 g and 33 cm/sec, respectively. The corresponding rock motion near this soft-soil site is only 0.07 g and 15 cm/sec.

STIFF-SOIL SITE RESPONSE

The stiff-soil site response, as estimated from smoothed Fourier spectral ratios for Gilroy #1 and Gilroy #2, are shown for three mainshocks and selected Loma Prieta aftershocks in Figures 2 and 3, respectively. The figures show that significant amplification of ground motion occurred at the stiff-soil site relative to the rock site for earthquakes with local magnitudes from 4.1 to 7.0, and for frequencies from approximately 0.5 to 2 Hz. Amplification at the soil site is about 3, similar to the soft-soil site response and previous work (e.g. King and Tucker, 1984; Tucker and King, 1984). However, in contrast to the behavior of the soft-soil site response discussed above, the stiff-soil site response is similar for strong and weak ground motions over the frequency range of 0.5 to 2 Hz, as discussed below.

The motion at the stiff-soil site is amplified over the rock site by a factor of about 2 for the Loma Prieta mainshock from 0.5 to 2 Hz (Figure 2). The amplification factor is approximately 4 over the same frequency range for the Coyote Lake and the Morgan Hill mainshocks, approximately double that estimated for the Loma Prieta mainshock. From 2 to 10 Hz, the amplification factor is generally less than 1 for the Loma Prieta mainshock, and generally greater than 1 for the other two mainshocks. These differences are not large and may be interpreted as the statistical variability in the site response produced by differences in azimuth, angle of incidence or path attenuation or other effects.

Though highly variable, the motion at the stiff-soil site is again amplified over the rock site by a factor of approximately 2 in the same frequency range for the ground motion recorded during the Loma Prieta aftershocks (Figure 3). This is in agreement with the results of Tucker and King (1984) who determined the average site responses for three sediment-filled valleys and found that they were within ±0.25 log units (factor of 1.8).

Considering higher frequencies, the stiff-soil spectral ratio peaks near 2.5 Hz for weak motion (Figure 3) and for one of the three mainshocks -- Coyote Lake (Figure 2). Near this 2.5 Hz peak the smoothed spectra at both Gilroy #1 and Gilroy #2 have similarly shaped troughs for the Coyote Lake mainshock (see Darragh and Shakal, 1991). For these earthquakes, the amplitude of the spectral ratio ranges from about 2.5 to 6.5, with an average near 3.5. However, the site response estimated from the Loma Prieta mainshock is below unity in this range (Figure 2). In this frequency band, a factor of approximately 6 is observed in the stiff-site soil response between weak and the strongest ground motion. Compared to the soft-soil results, these amplification ratios are smaller and more variable, and suggest that any signal-dependence, if present, is comparable to the intrinsic variability.

SUMMARY AND CONCLUSIONS

The analysis of spectral ratios for two rock-soil station pairs clearly shows the amplification of the ground motion recorded at the soil site relative to the rock site in both strong and weak shaking. At the soil sites, Treasure Island and Gilroy #2, the ground motion is amplified by a factor near 3 for frequencies between 0.5 and 2 Hz during the Loma Prieta mainshock.

At the soft-soil site (Treasure Island), the amplification factor ranges from 12 to 25 near 1 Hz for four Loma Prieta aftershocks. This is approximately 3 to 8 times greater than the amplification of 4 estimated for the mainshock recordings. This difference may be explained by nonlinear response of the soils at Treasure Island during the mainshock for peak acceleration and velocity levels as low as 0.16 g and 33 cm/sec, respectively. This explanation is supported by observations of liquefaction within 100m of the Treasure Island station after the Loma Prieta mainshock (Shakal et al., 1989; EERI, 1990). Also, the effects of liquefaction are observable in the Treasure Island accelerogram. Approximately 15 seconds into the record, at the inferred onset of liquefaction, short period ground motions decrease abruptly from above 0.15 g to low amplitude, long period motion comparable to the motion at Yerba Buena Island (CSMIP, 1989; Shakal et al., 1990). The effect of liquefaction on the smoothed spectra calculated from the Treasure Island accelerograms is discussed in Darragh and Shakal (1991).

In contrast, at the stiff-soil site (Gilroy #2 site), the amplification estimated from aftershocks is generally within the scatter observed for the three mainshocks for 0.5 to 2 Hz. Any effects of nonlinear soil response at this stiff-soil site are difficult to detect from the data and the means of analysis used in this study.

These results document the effects of two contrasting soil profiles on strong and weak ground shaking. They emphasize that the nonlinear effects of soils need to be considered when using weak ground motion data to infer the site response under stronger levels of shaking, especially at soft-soil sites.

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TABLE I

Records From the Loma Prieta Sequence at Treasure and Yerba Buena Islands

DATE (UTC) (Mn/Day/Year) (Hr:Min:Sec)	ML (UCB)	PEAK PARAMETERS * Treasure Island Apk (g)	Vpk (cm/sec)	Dpk (cm)	Yerba Buena Island Apk (g)	Vpk (cm/sec)	Dpk (cm)
10/18/89 00:04:15	7.0	0.16	33.4	12.2	0.07	14.7	4.1
10/28/89 21:27:49	3.5	0.0004	0.03	-	0.00009	0.007	-
10/29/89 13:10:57	3.3	0.0005	0.04	-	0.00006	0.005	-
10/30/89 11:17:13	4.1	0.0010	0.08	-	0.00019	0.015	-
11/07/89 23:42:37	4.3	0.0059	0.46	-	0.0013	0.099	-

The peak parameters tabulated, acceleration (Apk), velocity (Vpk) and displacement (Dpk), are from the Volume 2 processed records for the Loma Prieta mainshock (CSMIP, 1989). For the aftershocks the corrected peak ground velocities (Jarpe et al., 1989) are listed. For comparison purposes, the estimated peak ground accelerations estimated using Apk=4(π)Vpk from a sinusoidal approximation for the waveform are also listed.

TABLE II

Earthquake Records at Gilroy #2 and Gilroy #1

DATE (UTC) (Mn/Day/Year) (Hr:Min:Sec)	ML (UCB)	PEAK PARAMETERS * Gilroy #2			Gilroy #1		
		Apk (g)	Vpk (cm/sec)	Dpk (cm)	Apk (g)	Vpk (cm/sec)	Dpk (cm)
		<u>Mainshocks</u>					
Coyote Lake 08/06/79 17:05:22	5.9	0.25	31.9	5.3	0.11	10.3	1.7
Morgan Hill 04/24/84 21:27:49	6.1	0.21	12.5	2.0	0.10	2.7	0.5
Loma Prieta 10/18/89 00:04:15	7.0	0.35	39.2	10.9	0.44	33.8	6.5
		<u>Loma Prieta Aftershocks</u>					
10/18/89 00:05:41	in coda	0.04	2.2	0.2	0.08	2.7	0.1
10/18/89 06:39:12	4.3	0.16	4.0	0.2	0.10	2.1	0.1
11/02/89 05:50:10	4.9	0.01	-	-	0.02	-	-
11/05/89 01:30:42	4.2	0.002	-	-	0.006	-	-
11/05/89 13:37:33	4.5	0.003	-	-	0.006	-	-
04/07/90 20:08:36	4.2	0.007	-	-	0.02	-	-
04/18/90 13:41:13	5.0	0.02	-	-	0.02	-	-
04/18/90 13:53:44	5.4	0.12	-	-	0.07	-	-
04/18/90 14:45:58	4.3	0.02	-	-	0.04	-	-
04/18/90 15:27:50	4.7	0.02	-	-	0.03	-	-
04/18/90 15:36:26	4.2	0.02	-	-	0.02	-	-
04/18/90 15:45:38	5.2	0.07	-	-	0.12	-	-
04/18/90 16:18:47	4.1	0.02	-	-	0.02	-	-

* The peak parameters tabulated, acceleration (Apk), velocity (Vpk) and displacement (Dpk), are from the Volume 2 records (Huang, et al., 1990) except for eleven later Loma Prieta aftershocks (11/02/89 and later). For these eleven aftershocks only the unprocessed peak ground accelerations are listed.

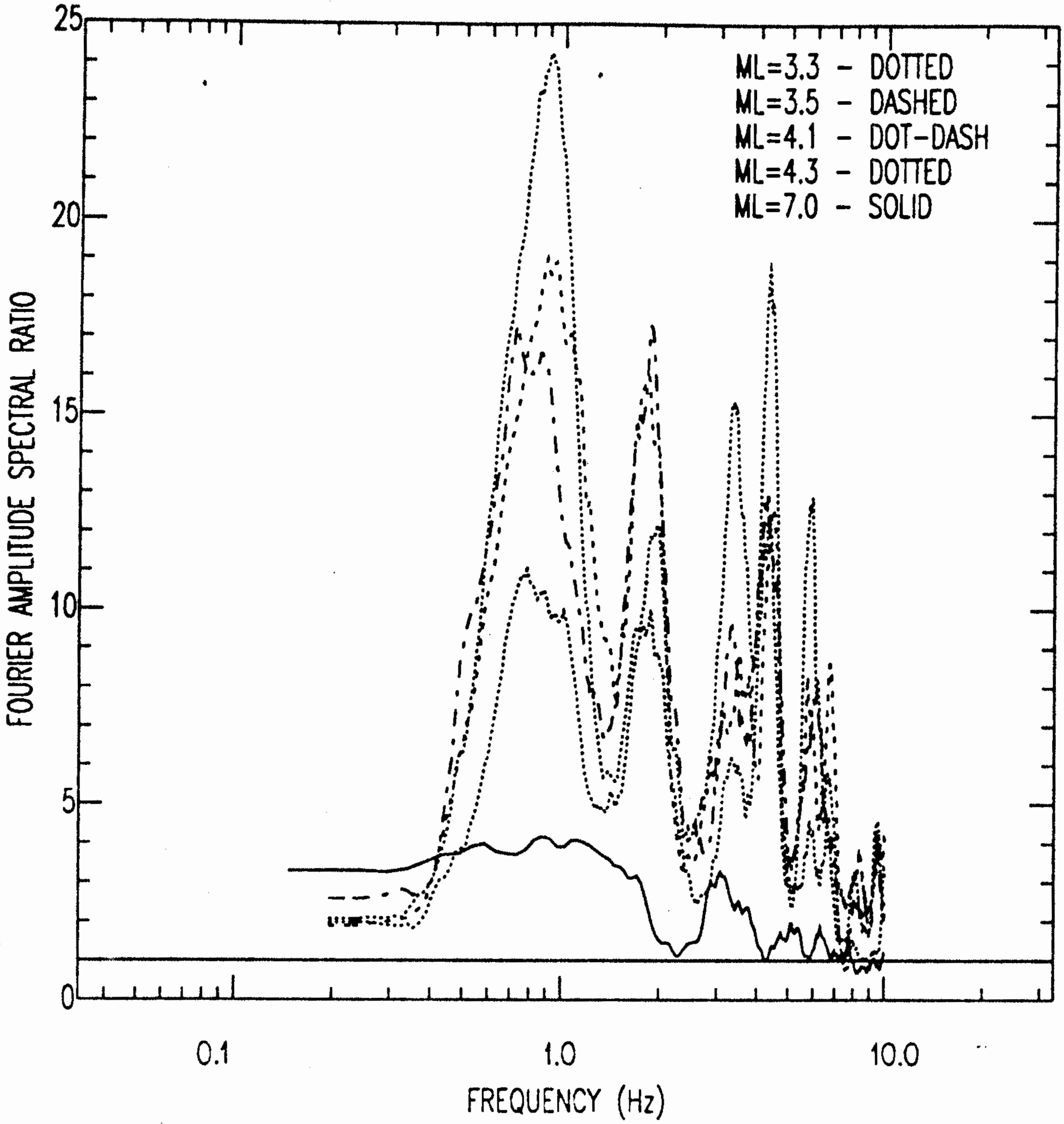

Figure 1: Amplification ratio at the soft-soil Treasure Island site relative to the nearby rock site on Yerba Buena Island for the Loma Prieta mainshock and aftershocks. The smoothed Fourier spectral ratios for the Treasure Island and Yerba Buena Island sites for the local magnitude 7.0, 4.3, 4.1, 3.5, and 3.1 Loma Prieta sequence earthquakes for a 10 second time window containing the direct S-wave arrival. For reference, a line showing no amplification (ratio of 1) is also shown. The bandwidth displayed for the mainshock is from the mid-frequency of the high-pass filter used in the standard CSMIP processing to 10 Hz. For the aftershocks, the bandwidth displayed is from 0.2 to 10 Hz. The upper frequency limit of 10 Hz was chosen to highlight the differences in the spectral ratios below this frequency.

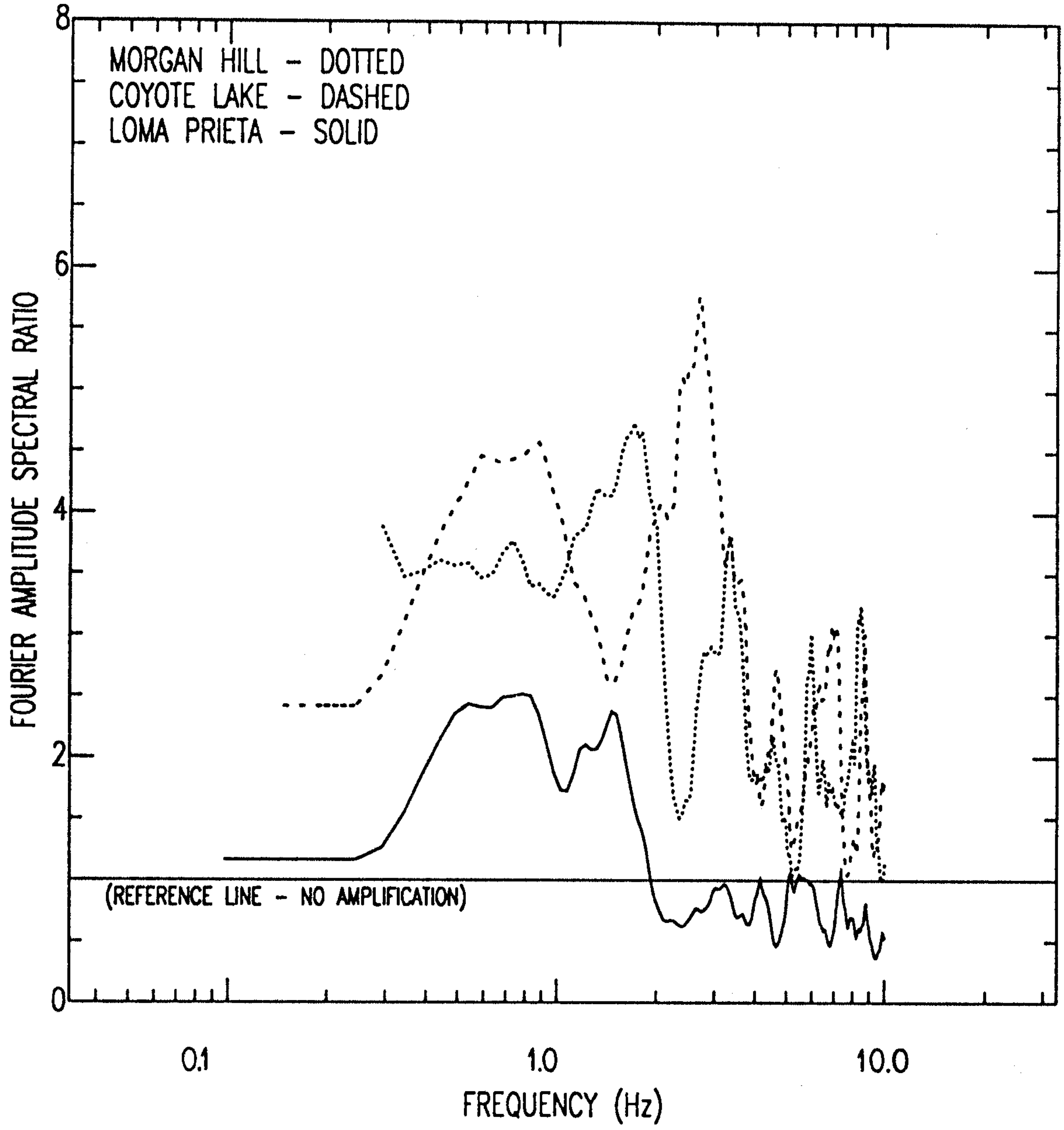

Figure 2: Amplification ratio at the stiff-soil Gilroy #2 site relative to the Gilroy #1 rock site. The amplification ratios are the smoothed Fourier spectral ratio for the Gilroy #2 and Gilroy #1 sites for the local magnitude 7.0 Loma Prieta, 6.1 Morgan Hill and 5.9 Coyote Lake mainshocks for an approximately 10 second time window containing the direct S-wave arrival. A reference line showing no amplification is also shown. The bandwidth displayed is from the mid-frequency of the high-pass filter used in the standard CSMIP processing to 10 Hz.

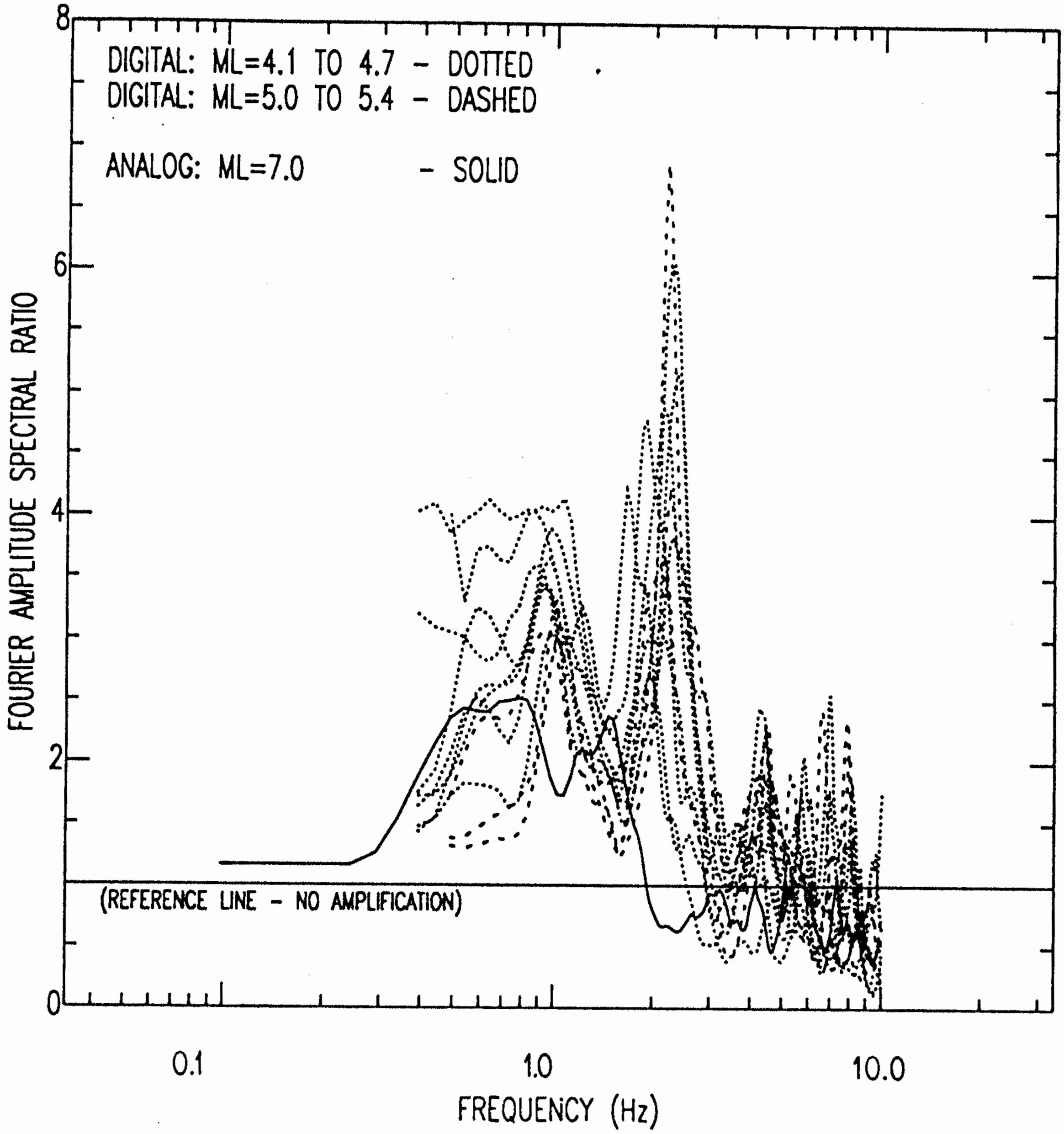

Figure 3: The smoothed Fourier spectral ratio for Gilroy #2 (stiff-soil) and Gilroy #1 (rock) for eleven aftershocks of the Loma Prieta mainshock for a time window containing the direct S-wave arrival. The corresponding spectral ratio for the Loma Prieta mainshock is shown for reference. A reference line showing no amplification is also shown. The mainshock was recorded on analog instruments, and the bandwidth displayed is from the mid-frequency of the high-pass filter used in the standard CSMIP processing to 10 Hz. For the eleven aftershocks, all recorded on digital instruments, the bandwidth displayed is from 0.4 or 0.5 to 10 Hz. The smoothed Fourier spectral ratio for two aftershocks recorded on analog instruments on 10/18/89 (Table II) are similar, and are shown in Darragh and Shakal (1991).