SHEAR-WAVE VELOCITIES AND DESIGN RESPONSE SPECTRA - AN EXAMINATION USING STRONG-MOTION DATA FROM THE GILROY ARRAY: PRELIMINARY RESULTS

Robert B. Darragh
EERI/FEMA Professional Fellow at the
Department of Civil and Environmental Engineering
University of California at Davis

and

I. M. Idriss
Department of Civil and Environmental Engineering
University of California at Davis

ABSTRACT

Borcherdt (1994) proposed that the short- and mid-period amplification factors used to scale the estimate of site-dependent response spectra could be calculated as a continuous function of shear-wave velocity averaged in the upper 30 m for various input ground-motion levels. This proposal appears to be an improvement for estimating design response spectra over site classifications defined by soil descriptions (e.g., SEAOC, 1988) or by ranges of average shear-wave velocity (e.g., NEHRP, 1991).

However, it is not clear that the accuracy available in current measurements of shear-wave velocity is sufficient to support their use directly in design calculations of motion. For example, at Gilroy #2 there are differences of about 300 m/sec in the shear-wave velocity measurements in the upper 30 m (EPRI, 1993). In this paper, we analyze the effect of variations of shear-wave velocity in the upper 30 m for design applications including the effects of nonlinear soil response using an equivalent-linear site response formulation (Schnabel et al., 1972). The analysis uses the extensive geotechnical site characterization and shear-wave velocity measurements at Gilroy #2, a stiff soil site that has been characterized to a depth of 240 m (EPRI, 1993). Response spectral accelerations from the recorded strong motions are compared to calculated values from the equivalent-linear analyses with several shear-wave velocity profiles in the top 30 m.

The preliminary analyses suggest that the Borcherdt (1994) methodology works well at this stiff-soil site for design levels of motion near 0.4 g, appropriate for many parts of California, even though there is a difference of 60% in the measured average of the shear-wave velocities in the upper 30 m.

INTRODUCTION

The use of the average of the measured shear-wave velocities to a depth of 30 m (100') below the surface was incorporated by Boore et al. (1993, 1994) as a site effect term in the estimation of peak accelerations and response spectral ordinates from earthquake ground motion attenuation relations. Borcherdt (1994) proposed this average in a methodology to directly estimate the site specific response spectra for design purposes. Thirty meters is selected since in many applications this is the typical depth of geotechnical site investigations that include borings, detailed sample testing and occasionally shear-wave velocity measurements. An ideal parameter may be the average of the shear-wave velocity to a depth of one-quarter wavelength for the period of interest as proposed by Joyner et al. (1981) and used by Joyner and Fumal (1984). However, only soils with an average shear-wave velocity of 120 m/sec or less would be properly characterized with a 30 m boring for a period of 1.0 second. Unfortunately, the necessary velocity measurements to a depth of one-quarter wavelength are not common.

Studies by Day (1996) and Anderson et al. (1996) have found that the response of the upper 30 m of material has a greater influence on surface strong ground motions than might be expected based on total thickness alone. The upper 30 m represents only 0.3% of the seismic wave travel path for an earthquake located directly underneath a site with a typical focal depth of 10 km. The peak acceleration and velocity recorded at the surface were found to be relatively independent of the properties below 30 m in these studies.

In this paper, we analyze the effect of variations of shear-wave velocity in the upper 30 m for design applications including the effects of nonlinear soil response. This variability may limit the use of velocity in design calculations of spectra and time histories. The recorded earthquake response data at Gilroy #2 are compared to those calculated by an equivalent-linear response analysis using the computer program SHAKE91 (Idriss and Sun, 1992) which is a recently modified edition of the original SHAKE program (Schnabel et al., 1972). The motion recorded at Gilroy #1 was used as the input rock outcrop motion in these analyses. The extensive geotechnical site characterization at Gilroy #2 (Fumal et al., 1982; Fumal, 1991; EPRI, 1993) includes shear-wave velocity measurements from several methods to a depth of 240 m. These velocity measurements show considerable variation in the upper 30 m and at greater depths.

The intent of this study is to evaluate the usefulness of the average of the measured shear-wave velocities in the upper 30 m. It is planned to conduct a series of ground response analyses at the Gilroy #2 site for earthquake ground motions recorded during several events to make this evaluation. The best estimate of the measured shear-wave velocities at this site will first be used to compare the calculated with the recorded motions. Such evaluations were done for many sites following the Loma Prieta earthquake and have indicated that this method of analyses provides a reasonable estimate of the recorded motions (e.g., Idriss, 1993; Dickenson and Seed, 1991; Chin and Aki, 1991; Schneider et al., 1991; EPRI, 1993). This study will include calculations for the Gilroy #2 site during the Loma Prieta earthquake and two of its aftershocks in addition to the 1979 Coyote Lake and the 1984 Morgan Hill earthquakes.

These studies are underway and the final results are expected in the summer of 1997. This paper provides preliminary results from the initial parts of the study and should be considered a progress report.

GILROY STRONG-MOTION ARRAY

The Gilroy array is an alignment of six strong motion stations that extends across the alluvial Santa Clara Valley in northern California. This array is a cooperative effort of the

California Strong Motion Instrumentation Program (SMIP) and the U. S. Geological Survey (USGS). The array is currently instrumented and maintained by SMIP. For this analysis, only the earthquake records from Gilroy #1 and Gilroy #2 are used because they are the closest rock and stiff-soil station pair (Fig. 1). Gilroy #1 is located just west of the western edge of the Santa Clara Valley and Gilroy #2 is located 2 km to the east. The soil depth varies from 0 m at Gilroy #1 to about 170 m at Gilroy #2 and deepens considerably to the east across the valley.

GEOTECHNICAL CHARACTERIZATION OF THE GILROY #2 SITE

The Gilroy #2 site has been well characterized to a depth of 240 m (790') during an Electric Power and Research Institute study (EPRI, 1993). In summary, Gilroy #2 is underlain by stiff soil to a depth of 168 m (550'). Loams, sands and clays of Holocene and Pleistocene age are present in the upper 46 m. Extensive deposits of Pleistocene gravels with sands and some clays are found beneath this depth. Bedrock is at a depth of 168 m and is a deeply weathered siltstone of the Monterey Shale Formation. The bottom of the hole is in serpentinite that has been deeply weathered to sandy clay.

EPRI (1993) performed an extensive series of geophysical surveys in the borehole to measure low-strain in-situ P- and S-wave velocities (Fig. 2) to a depth of 240 m. The seven measurements made in the top 122 m (400') show the variability in estimates of shear-wave velocity at this site. For example, in the top 30 m velocity measurements may differ by up to 300 m/sec (1000 ft/sec). In contrast, in the Pleistocene lake deposits all measurements cluster tightly around 305 m/sec. At greater depths, differences in shear-wave velocity of nearly 600 m/sec (2000 ft/sec) are shown.

Table 1 is an interpretation of the velocity structure at Gilroy #2 modified from EPRI (1993). Surface shear-wave velocities of about 230 m/sec more than double to 475 m/sec near 14 m. Beneath this depth the profile contains two low-velocity-zones. The upper zone, with shear-wave velocities ranging from 305 to 375 m/sec, extends from 22 to 42 m and consists of mainly Pleistocene lake deposits and the top of the Pleistocene alluvium. Between these two zones is a thick (40 m) soil with a velocity of 640 m/sec composed of primarily gravels and gravelly sands. The lower zone extends from 82 to 98 m. Shear-wave velocities range from 475 to 525 m/sec and reflect the increased proportion of clay in the soil at these depths. The velocity in the soil from 98 m to bedrock is 700 m/sec again reflecting the presence of gravels at these depths. The bedrock velocity is 1190 m/sec. Profiles of the site geology and the P- and S-wave velocities at Gilroy #2 and #1 are also given in Fumal et al. (1982) and Fumal (1991).

The average shear-wave velocities in the top 30 m and in the entire soil profile at Gilroy #2 are 302 and 578 m/sec, respectively. Using the site classification of Borcherdt (1994), the top 30 m is SC-III (stiff clays and sandy soils), while the entire profile is SC-II (gravelly soils) reflecting the presence of gravels at depths greater than 46 m. The bedrock is also appropriately classified as SC-Ib (firm rock). For comparison, Gilroy #1 is underlain by moderately weathered sandstone at the surface, with thin beds of shale at depth as determined in a 20 m borehole (Fumal et al., 1982; Fumal, 1991). The average shear-wave velocity in the top 20 m is 1230 m/sec and would be classified as SC-Ib (firm rock) by Borcherdt (1994).

In addition, nine undisturbed soil samples were collected for laboratory testing to determine modulus-reduction and damping curves. From the testing sets of curves were developed for the depth range 0 to 12 m (40'), 12 to 24 m (80'), 24 to 40 m (130') and for deeper than 40 m (Table 2). The effect of gravels in the profile below 40 m produces increased damping and lower modulus-reduction at greater depths. This effect is counter to the effects of increasing confining pressure. Low-strain damping values of 3% (Q=17) were measured in the EPRI (1993) study (Table 2). An extensive discussion of the measurements and testing results are given in EPRI (1993).

EARTHQUAKE RECORDS

The Gilroy array has recorded a large range of earthquake response (Table 3). The recorded earthquakes range in local magnitude (M_L) from 4.3 to 7.0. Peak horizontal accelerations are from 0.04 to 0.37 g at Gilroy #2 with corresponding accelerations of 0.08 to 0.49 g at Gilroy #1. Peak velocities range from 2.2 to 39.2 cm/sec at the soil site with corresponding velocities ranging from 2.7 to 33.8 cm/sec at the rock site (Table 3).

In this preliminary study only the records from the north-south component from the Loma Prieta mainshock are used in the equivalent-linear analyses. The north-south base-line corrected and band-pass filtered acceleration, velocity and displacement time histories for Gilroy #1 and Gilroy #2 are shown in Figure 3. The peak accelerations are 0.43 and 0.37 g on the north-south component of Gilroy #1 and Gilroy #2, respectively. The 5% damped response spectral accelerations for the north-south component at Gilroy #1 and #2 are shown in Figure 4. This component was selected to facilitate comparison with an input level of acceleration of 0.4 g in Borcherdt (1994).

SITE RESPONSE ESTIMATION METHOD

The north-south component of the Loma Prieta mainshock ground motion and spectrum recorded at Gilroy #2 (Figs. 3 and 4) are modeled using the equivalent-linear method to calculate the seismic response of horizontally layered soil deposits that was implemented in the computer program SHAKE (Schnabel et al., 1972; Idriss and Sun, 1992). The program computes the response of a semi-infinite horizontally layered soil deposit over a uniform half-space subjected to vertically propagating shear waves. The analysis is done in the frequency domain, and therefore, for any set of properties is a linear analysis. An equivalent-linear procedure (Idriss and Seed, 1968; Seed and Idriss, 1970) is used to account for the nonlinearity of the soil using an iterative procedure to obtain values for modulus and damping that are compatible with the equivalent uniform strain induced in each sublayer. The recorded north-south accelerations at Gilroy #1 from the Loma Prieta earthquake (Fig. 3) are assumed to be the input motions in the equivalent-linear analysis.

The initial values for shear-wave velocity, modulus-reduction and damping used in the equivalent-linear analysis are from a geotechnical model given in EPRI (1993). Tables 1 and 2 are the low-strain shear-wave velocity, modulus-reduction and damping curves used for the best-fit model, respectively. The shear-wave velocity profile from EPRI (1993) has been slightly modified to obtain a response spectrum from the equivalent-linear analysis that reasonably matches the recorded response spectrum from the Loma Prieta mainshock (Fig. 4).

Figure 4 compares the recorded spectrum at Gilroy #2 with the best-fit spectrum from the equivalent-linear site response analysis. Also shown on the figure is the spectrum of the north-south acceleration recorded at Gilroy #1 during the Loma Prieta earthquake. The high-frequency energy content in the Gilroy #1 spectrum has been reduced in the equivalent-linear analysis. Over the usable data bandwidth from 0.04 to 7.35 seconds the fit is generally quite good. The predicted peak acceleration value is 0.47 g within 30% of the observed value of 0.37 g.

The low-strain and strain-compatible shear-wave velocities are compared in Figure 5. The low-strain in-situ shear-wave velocity has been reduced significantly in the equivalent-linear analysis. The average velocity in the upper 30 m is reduced 21% from 302 to 249 m/sec. The average low-strain shear-wave velocity in the 170 m profile is reduced 25% from 578 to 465 m/sec. The fundamental period of the soil profile has correspondingly increased from 1.18 to 1.47 seconds.

VARIATION OF SHEAR-WAVE VELOCITY IN THE TOP 30 M

The shear-wave velocity above 30 m at Gilroy #2 is varied in the equivalent-linear model using the measured velocities (Fig. 2). The low-strain shear-wave velocities are not varied from the best-fit model for depths greater than 30 m (Table 1 and Fig. 5). The low-strain modulus-reduction and damping curves are also not varied (Table 2) in the equivalent-linear analysis.

Five velocity profiles for the top 30 m (100') and the low-strain velocity profile used in the best-fit equivalent-linear analysis are shown in Figure 6. The lower and upper shear-wave velocity profiles are from the bounds on the measured velocities (Fig. 2). The average shear-wave velocity in these profiles is 220 (720 ft/sec) and 355 (1165 ft/sec) m/sec, respectively. Three profiles with constant velocities of 200 (660 ft/sec), 300 (990 ft/sec) and 375 m/sec (1230 ft/sec) in the upper 30 m are also shown. One of the constant velocity profiles is the average velocity (300 m/sec) from the low-strain shear-wave velocity used in the best-fit equivalent-linear model. The other two constant velocity profiles are the minimum (200 m/sec) and the maximum (375 m/sec) mean shear-wave velocity from Borcherdt (1994) for site classification, SC-III (stiff clays and sandy soils). These two profiles increase the range of mean shear-wave velocity beyond the measured range at Gilroy #2 (Fig. 2). They are included in the analysis to bracket the range of response for this site classification.

The calculated response spectra from these five velocity profiles (Fig. 6) are compared to the spectrum from the best-fit model and the recorded data (Fig. 7). The recorded peak acceleration at Gilroy #2 was 0.37 g. The peak acceleration from the best-fit equivalent-linear model was 0.47 g. Peak accelerations from the five additional velocity profiles range from 0.36 to 0.56 g. The profile with the lower bound shear-wave velocity (Fig. 6) produced the largest peak acceleration of 0.56 g and the largest spectral response at most periods. The calculated response spectral acceleration is similar at periods greater than 2 seconds for the six soil profile models.

SUMMARY AND DISCUSSION

Borcherdt (1994) proposed that the short- and mid-period amplification factors used to scale design spectrum could be calculated as a continuous function of mean shear-wave velocity in the top 30 m (100'). However, there are large differences in the measured shear-wave velocity at Gilroy #2, a stiff-soil site. In the top 30 m shear-wave velocity differences of 300 m/sec are observed (Fig. 2). The measured mean shear-wave velocity in the top 30 m varies from 220 to 355 m/sec, an increase of 60%.

An equivalent-linear site response analysis was performed using the site characterization at Gilroy #2 (EPRI, 1993) to determine the significance of these measured velocity variations in calculations of design spectrum in the Borcherdt (1994) methodology. The variation in spectral acceleration, over a broad range of periods from 0.04 to 7.35 seconds, are compared to the spectrum computed for soil models with variation of nearly a factor of 2 in the mean shear-wave velocity in the upper 30 m. For input levels near 0.45 g the spectrum calculated in the several equivalent-linear analyses match the recorded spectrum at Gilroy #2 reasonably well in this period range. At high frequencies, the peak acceleration computed in the analysis is from 0.36 to 0.56 g, on average about 14% larger than the observed peak acceleration of 0.37 g at the stiff-soil site.

A preliminary observation is that the proposed methodology to compute design spectrum from the average of the shear-wave velocity in the upper 30 m works well for input levels of motion near 0.4 g. These levels are appropriate for many parts of California. This preliminary analysis will be updated with the results from an equivalent-linear analysis of the other four earthquakes with input motions near 0.1 g (Table 3).

ACKNOWLEDGEMENTS

The first author is grateful for support from the Earthquake Engineering Research Institute and the Federal Emergency Management Agency that funded the 1997 EERI/FEMA NEHRP Professional Fellowship. The use of facilities and resources in the College of Engineering, Department of Civil and Environmental Engineering at University of California at Davis are gratefully acknowledged. The first author is on a leave-of-absence from the California Strong Motion Instrumentation Program.

The processed strong-motion records analyzed in this report were made possible through the efforts of SMIP and USGS technicians who installed and maintained these stations, and the SMIP and USGS seismologists who digitized and processed the analog film records. SMIP extends its appreciation to the site owners for their long-term cooperation with strong-motion instrumentation.

REFERENCES

Anderson, J. G., Y. Lee, Y. Lee and S. Day (1996). Control of strong motion by the upper 30 meters, Bull. Seism. Soc. Am., 86, 1749-1759.

Boore, D. B., W. B. Joyner, and T. E. Fumal (1993). Estimation of response spectra and peak accelerations from western North American earthquakes: An interim report, U. S. Geological Survey Open File Report 93-509, 72 pp.

Boore, D. B., W. B. Joyner, and T. E. Fumal (1994). Estimation of response spectra and peak accelerations from western North American earthquakes: An interim report, Part 2, U. S. Geological Survey Open File Report 94-127, 40 pp.

Borcherdt, R. D. (1994). Estimates of site-dependent response spectra for design (methodology and justification), Earthquake Spectra, 10, 617-653.

Brady, A. G., P. N. Mork, V. Perez, and L. D. Porter (1981). Processed data from the Gilroy array and Coyote Creek records from the Coyote Lake earthquake of 6 August 1979, California Division of Mines and Geology, Preliminary Report 24, 171 pp.

Chin, B-H., and K. Aki (1991). Simultaneous study of the source, path and site effects on strong ground motion during the 1989 Loma Prieta earthquake: A preliminary result of pervasive nonlinear site effects, Bull. Seism. Soc. Am., 81, 1859-1884.

Darragh, R. B., and A. F. Shakal (1991). The site response of two rock and soil station pairs to strong and weak ground motion, Bull. Seism. Soc. Am., 81, 1885-1899.

Day, S. D. (1996). RMS response of a one-dimensional half-space to SH, Bull. Seism. Soc. Am., 86, 363-370.

Dickenson, S. E. and R. B. Seed (1991). Correlations of shear wave velocity and engineering properties for soft soil deposits in the San Francisco Bay region, Earthquake Engineering Research Center, University of California at Berkeley, UCB/EERC 91-, 110 pp.

EPRI (1993). Guidelines for determining design basis ground motions, Electric Power Research Institute Report TR-102293s.

Fumal, T. E., J. F. Gibbs, and E. F. Roth (1982). In-situ measurements of seismic velocity at 10 strong motion accelerograph stations in Central California, U. S. Geological Survey Open File Report 82-407, 76 pp.

Fumal, T. E. (1991). Shear-wave velocity estimates and site geology for strong-motion recording sites of the Loma Prieta earthquake of October 17, 1989, U. S. Geological Survey Open File Report 91-311, 163 pp.

Idriss, I. M., and H. B. Seed (1968). Seismic response of horizontal soil layers, Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers, 94, No. SM4, 1003-1031.

Idriss, I. M., and J. I. Sun (1992). User's manual for SHAKE91: A computer program for conducting equivalent-linear seismic response analyses of horizontally layered soil deposits, Center for Geotechnical Modeling, University of California at Davis, 71 pp.

Idriss, I. M. (1993). Assessment of site response analysis procedures – A report to the National Institute of Standards and Technology, Department of Civil and Environmental Engineering, University of California, Davis.

Joyner, W. B., R. E. Warrick, and T. E. Fumal (1981). The effect of Quaternary alluvium on strong ground motion in the Coyote Lake, California of 1979, Bull. Seism. Soc. Am., 71, 1333-1349.

Joyner, W. B. and T. E. Fumal (1984). Use of measured shear-wave velocity for predicting geologic site effects on strong ground motion, Proceedings of the Eighth World Conference on Earthquake Engineering, 2, 777-783.

NEHRP (1991). Recommended provisions for the development of seismic regulations for new buildings, prepared by the Building Seismic Safety Council for the Federal Emergency Management Agency, 1, 199 pp.

Schnabel, P. B., J. Lysmer, and H. B. Seed (1972). SHAKE: A computer program for earthquake response analysis of horizontally layered sites, Earthquake Engineering Research Center, University of California at Berkeley, UCB/EERC 72-12, 102 pp.

Schneider, J. F., W. J. Silva, and C. L. Stark (1993). Ground motion model for the 1989 M 6.9 Loma Prieta earthquake including effects of source, path and site, Earthquake Spectra, 9, 251-287.

SEAOC (1988). Recommended lateral force requirements and tentative commentary. Seismology Committee of the Structural Engineers Association of California, San Francisco.

Seed, H. B., and I. M. Idriss (1970). Soil moduli and damping factors for dynamic response analysis, Report NO. UCB/EERC 70-10, Earthquake Engineering Research Center, University of California, Berkeley, 48 pp.

Shakal, A. F., M. J. Huang, D. L. Parke and R. W. Sherburne (1986). Processed data from the strong-motion records of the Morgan Hill earthquake of 24 April 1984, California Division of Mines and Geology, Office of Strong Motion Studies, Report No. OSMS 85-04, 249 pp.

SMIP (1991). Plots to accompany tapes: Loma Prieta 1989 ground-response stations, California Division of Mines and Geology, Office of Strong Motion Studies, Report No. OSMS 91-06.

TABLE 1
Shear-Wave Velocity and Lithology for Gilroy #2 (modified from EPRI, 1993)

Thickness (ft)	Vs (ft/sec)	Thickness (m)	Vs (m/sec)	Lithology
35	750	10.7	229	Holocene Alluvium
10	1000	3.1	305	Late Pleistocene Alluvium
30	1560	9.1	476	Pleistocene Lake Deposits
31	1000	9.5	305	
20	1140	6.1	348	Pleistocene Alluvium
12	1230	3.7	375	
132	2100	40.2	640	
23	1550	7.0	473	
29	1730	8.8	527	
238	2300	72.6	701	
	3900		1189	Monterey Shale

TABLE 2
Modulus-Reduction, Damping and Q (attenuation) Values for Gilroy #2
(modified from EPRI, 1993)

Strain (%)	G/Gmax (0-12 m) (0-40')	G/Gmax (12-24 m) (40-80')	G/Gmax (24-40 m) (80-130')	G/Gmax (>40 m) (>130')
1.0E-4.0	1.00	1.00	1.00	1.00
1.0E-3.5	1.00	1.00	1.00	1.00
1.0E-3.0	1.00	1.00	1.00	1.00
1.0E-2.5	0.99	0.99	1.00	0.95
1.0E-2.0	0.91	0.93	0.95	0.81
1.0E-1.5	0.72	0.76	0.80	0.57
1.0E-1.0	0.47	0.51	0.56	0.32
1.0E-0.5	0.24	0.27	0.31	0.14
1.0E-0.0	0.09	0.11	0.14	0.05

Strain (%)	Damping % (0-12 m)	Damping % (12-24 m)	Damping % (24-40 m)	Damping % (>40 m)
1.0E-4.0	3.0	3.0	3.0	3.0
1.0E-3.5	3.0	3.0	3.0	3.0
1.0E-3.0	3.0	3.0	3.0	3.0
1.0E-2.5	3.0	3.3	3.2	3.3
1.0E-2.0	3.5	4.4	4.1	4.1
1.0E-1.5	4.7	6.9	6.3	10.0
1.0E-1.0	7.5	11.2	10.1	15.9
1.0E-0.5	12.1	17.3	16.0	22.2
1.0E-0.0	24.4	23.5	22.3	27.5

Strain (%)	Q (0-12 m)	Q (12-24 m)	Q (24-40 m)	Q (>40 m)
1.0E-4.0	16.7	16.7	16.7	16.7
1.0E-3.5	16.7	16.7	16.7	16.7
1.0E-3.0	16.7	16.7	16.7	15.2
1.0E-2.5	14.3	15.2	15.6	12.2
1.0E-2.0	10.6	11.4	12.2	8.2
1.0E-1.5	6.7	7.2	7.9	5.0
1.0E-1.0	4.1	4.5	5.0	3.1
1.0E-0.5	2.7	2.9	3.1	2.3
1.0E-0.0	2.1	2.1	2.2	1.8

TABLE 3

Strong-Motion Data at Gilroy #1 and Gilroy #2 (Notes 1 and 2)

		Peak Parameters									
		Gilroy #2 (stiff soil)					Gilroy #1 (rock)				
Earthquake Name	M_L (UCB)	Comp (deg)	Acc (g)	Vel (cm/sec)	Disp (cm)	Dist* (km)	Comp (deg)	Acc (g)	Vel (cm/sec)	Disp (cm)	Dist* (km)
Coyote Lake	5.9	050	0.20	10.2	2.2	14	320	0.12	10.3	1.7	16
		140	0.26	31.9	5.3	(7)	230	0.10	4.0	0.7	(8)
Morgan Hill	6.1	360	0.16	5.0	1.1	38	320	0.10	2.7	0.5	39
		090	0.21	12.5	2.0	(17)	230	0.07	2.5	0.3	(18)
Loma Prieta	7. 0	360	0.37	33.3	6.7	30	360	0.43	31.9	6.5	29
		090	0.33	39.2	10.9	(16)	090	0.49	33.8	6.3	(15)
Loma Prieta	(Note 3)	360	0.04	2.2	0.2		360	0.08	2.7	0.1	
Aftershock #1		090	0.03	1.6	0.1		090	0.06	1.4	0.1	
Loma Prieta	4.3	360	0.17	4.0	0.2	23	360	0.11	2.1	0.1	22
Aftershock #2		090	0.10	3.0	0.2		090	0.07	1.3	0.1	

* The distances given are epicentral (top) and when appropriate the distance to the nearest point on the surface projection of the fault inferred from the aftershock distribution (bottom, in parenthesis).

Notes:

1) The processed data are from Brady et al. (1981), Shakal et al. (1986) and SMIP (1991) for the Coyote Lake, Morgan Hill and Loma Prieta mainshocks, respectively. The Loma Prieta aftershock data are discussed in Darragh and Shakal (1991). These processed records are distributed by SMIP.

2) The filter corner frequencies and the Usable Data Bandwidth vary for each of these earthquakes. The corner frequencies used for the processed data are:
   Coyote Lake: 0.05-0.25 Hz, 23-25 Hz
   Morgan Hill: 0.20-0.40 Hz, 23-25 Hz (Gilroy #1); 0.08-0.16 Hz, 23-25 Hz (Gilroy #2)
   Loma Prieta: 0.14 to 23.6 Hz (0.04 to 7.35 sec)
   Loma Prieta (aftershock #1): 0.40-0.80 Hz, 23-25 Hz
   Loma Prieta (aftershock #2): 0.40-0.80 Hz, 23-25 Hz.
   The Usable Data Bandwidth for the Loma Prieta earthquake is from 0.14 to 23.6 Hz (0.04 to 7.35 sec).

3) The U.C. Berkeley Seismographic Stations did not estimate the epicenter and magnitude for the first Loma Prieta aftershock because the motions occurred during the coda of the mainshock that occurred 86 seconds earlier.

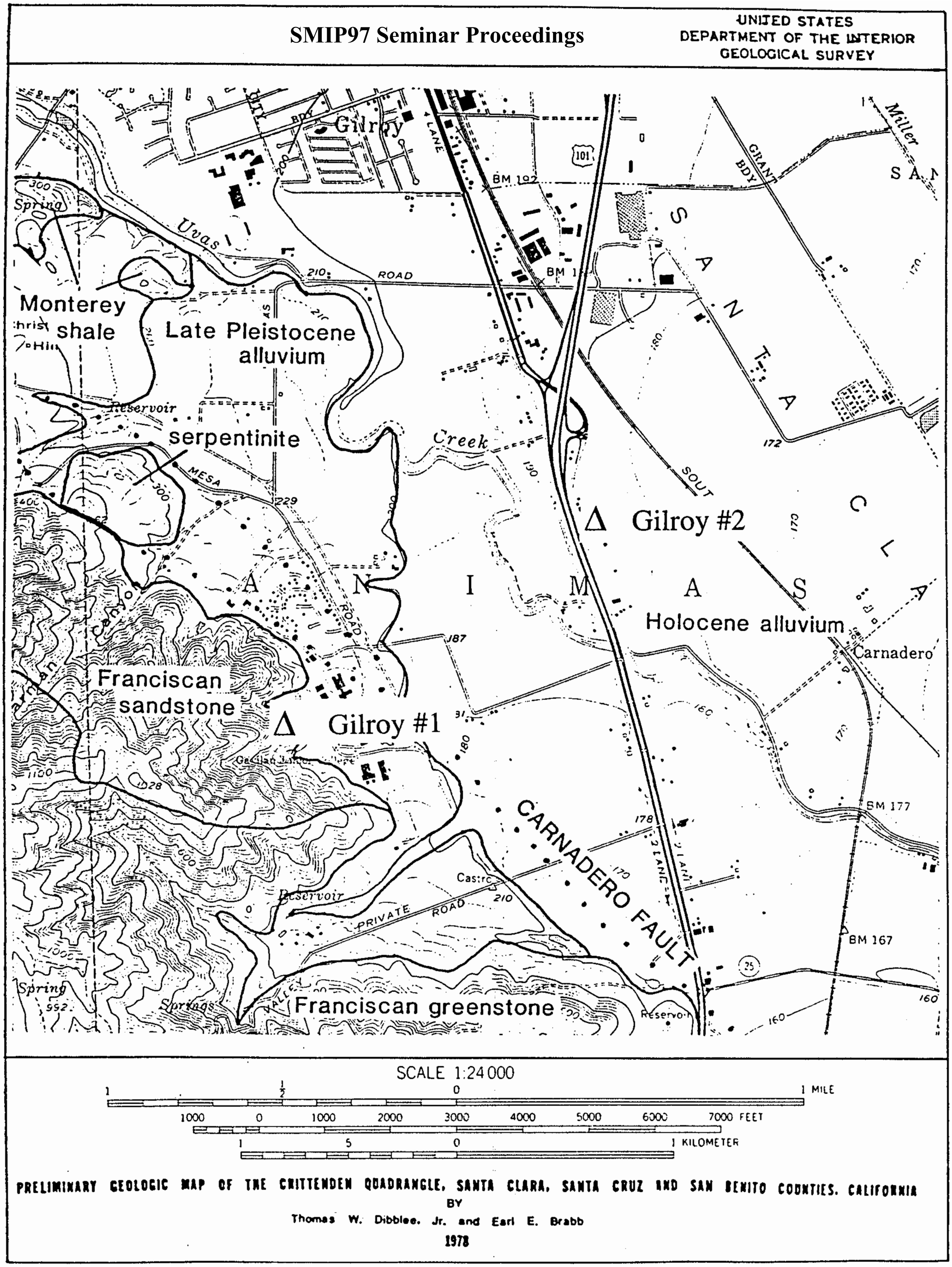

Fig. 1. Site location map for Gilroy #1 and Gilroy #2. The geology of the southern Santa Clara Valley region in California is also shown (modified from Fumal, 1991).

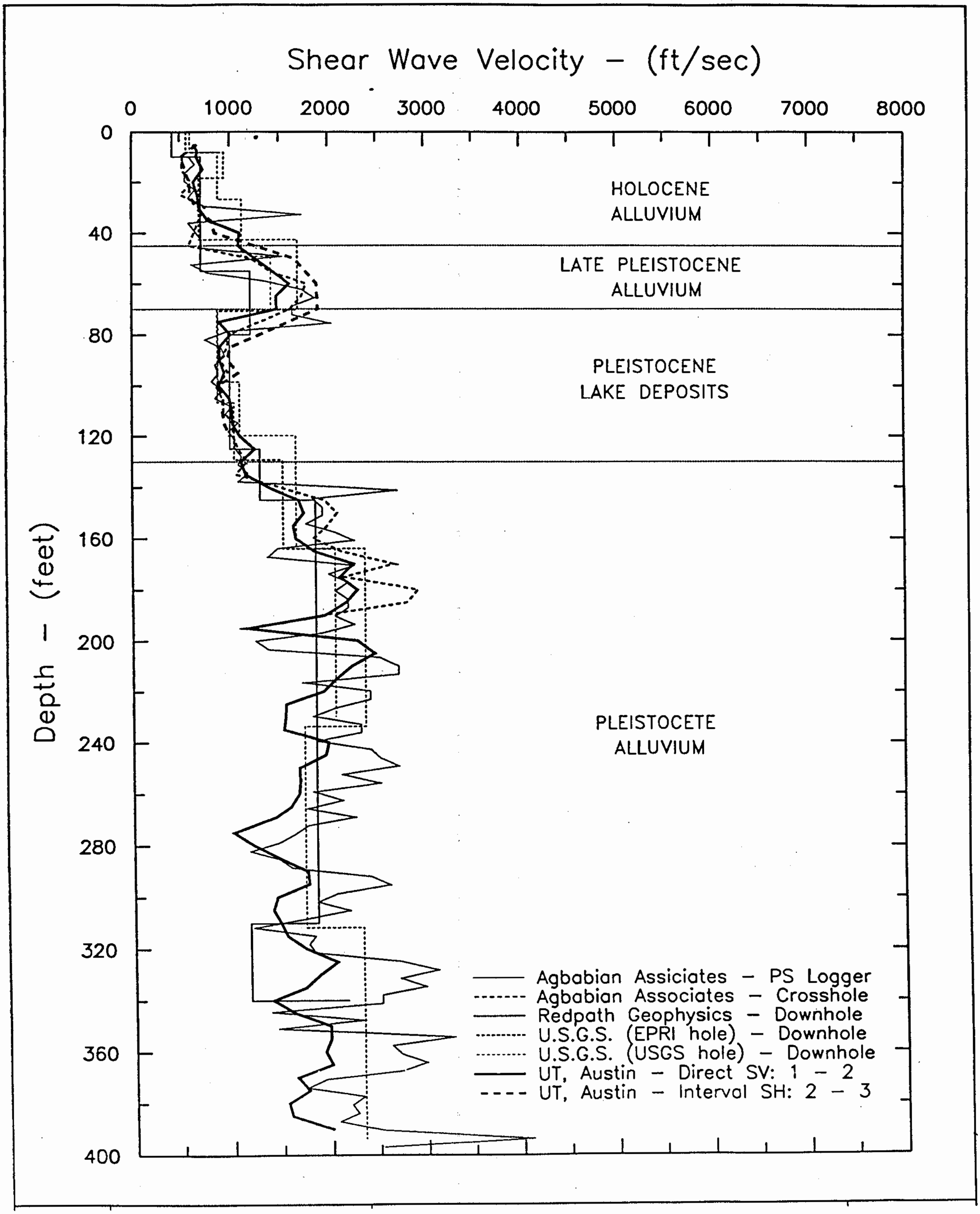

Fig. 2. Shear-wave velocity measurements at Gilroy #2 (modified from EPRI, 1993).

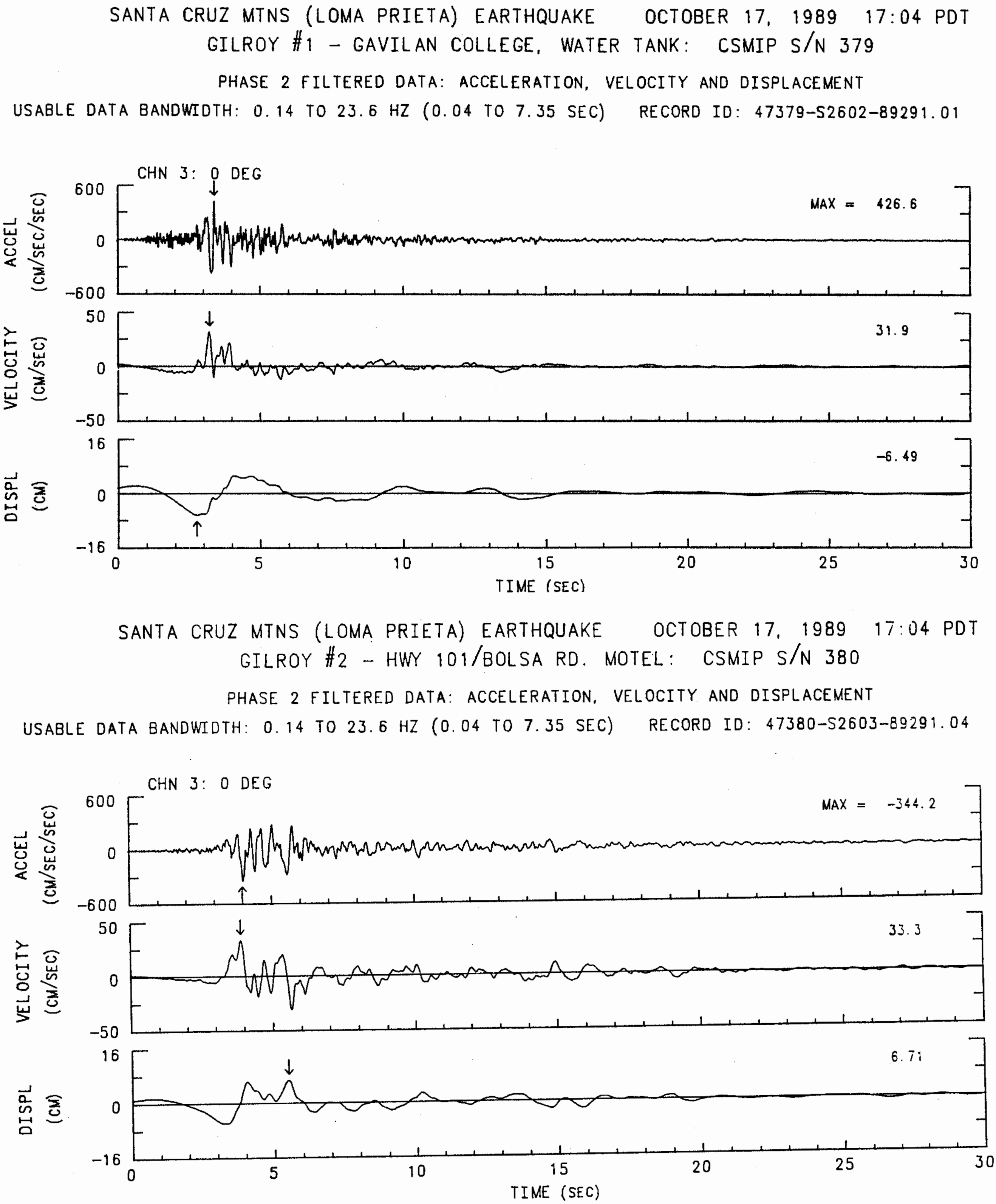

Fig. 3. The base-line corrected and band-pass filtered acceleration, velocity and displacement for the north-south component of Gilroy #1 (top) and Gilroy #2 (bottom) from the Loma Prieta mainshock. The Usable Data Bandwidth of the processed data is from 0.14 to 23.6 Hz (0.04 to 7.35 sec) (modified from SMIP, 1991).

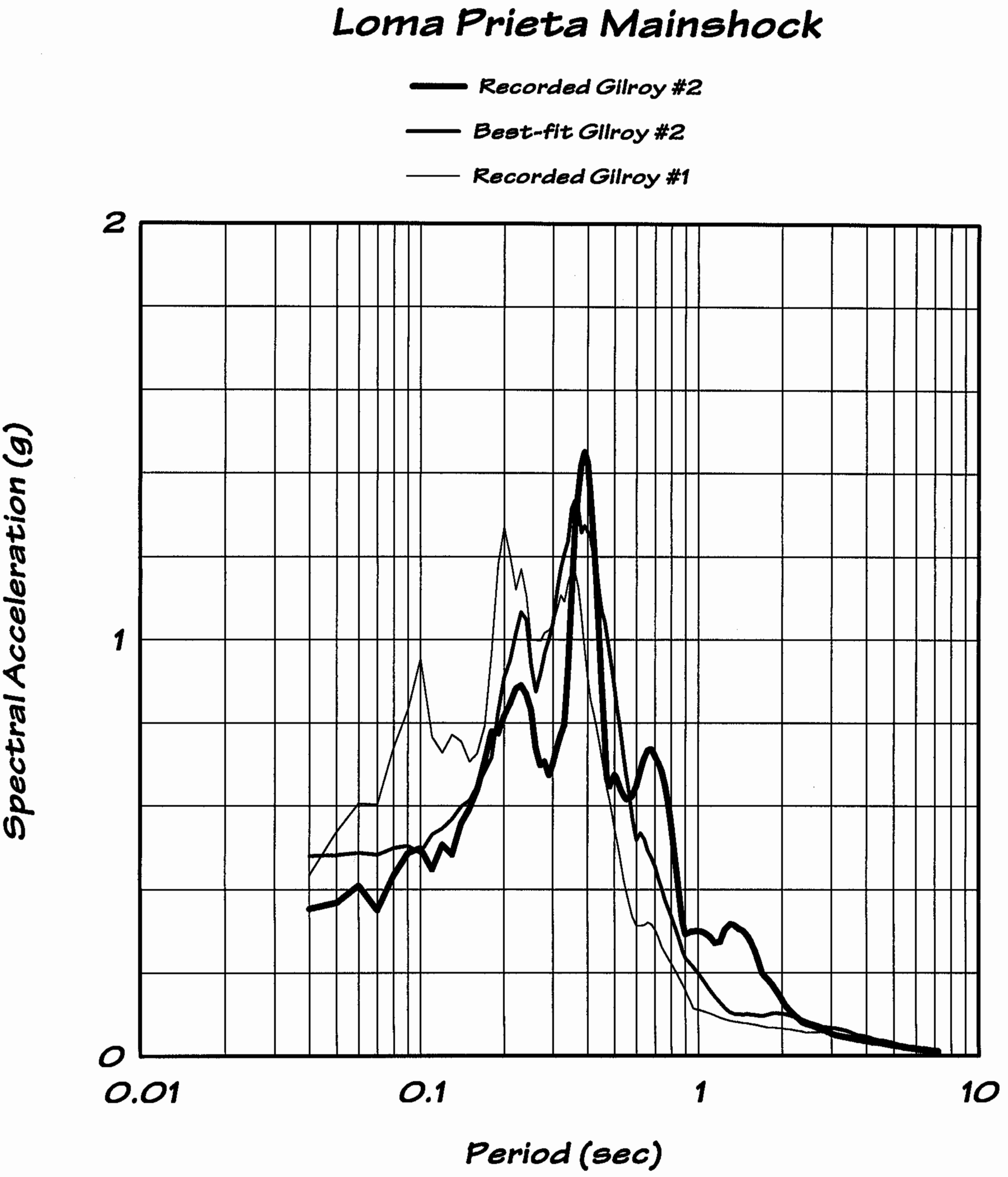

Fig. 4. Response spectra (5% damped) for the north-south component of the Loma Prieta mainshock at Gilroy #1 and #2. Also, the best-fit spectrum at Gilroy #2 from the SHAKE analysis.

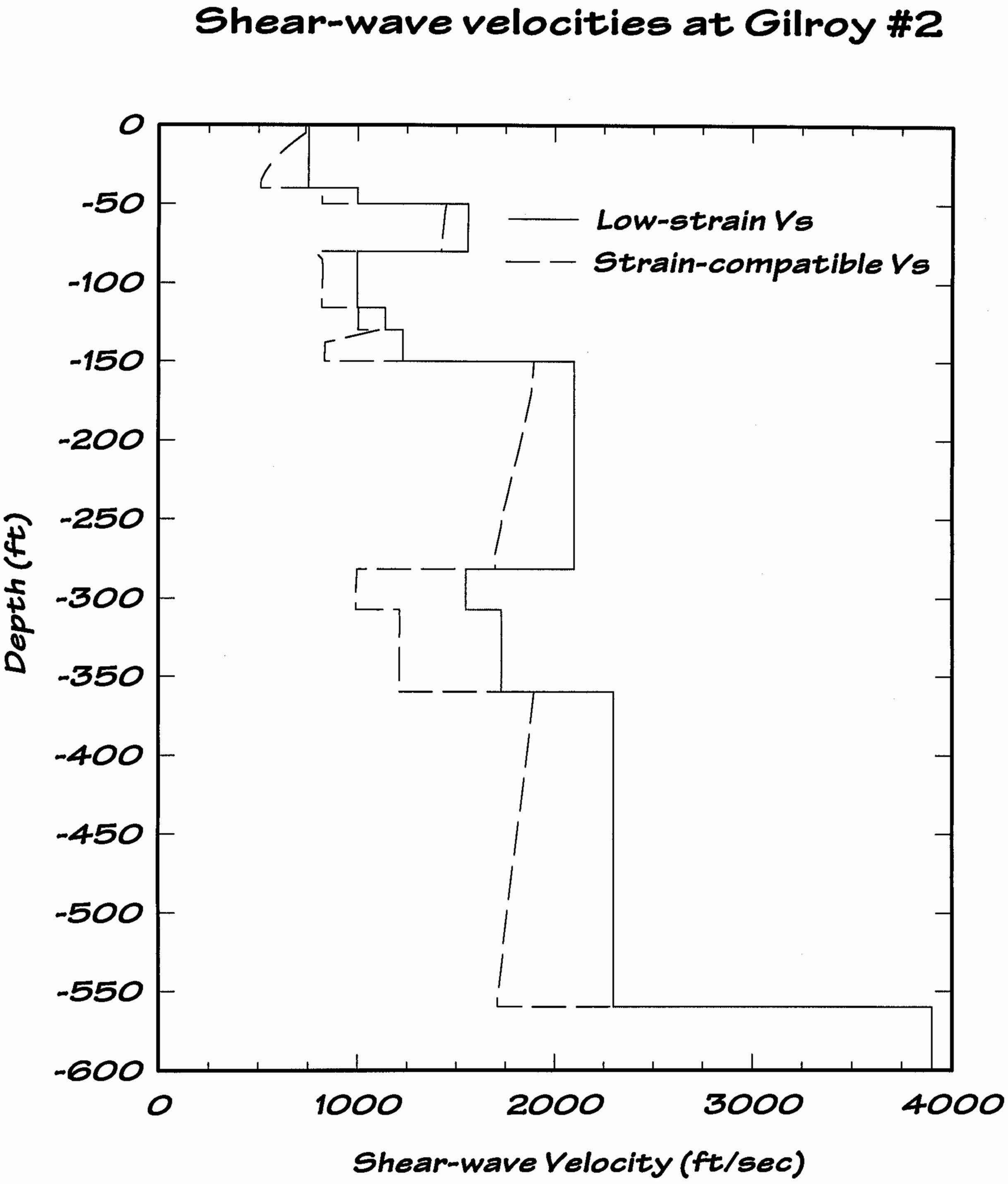

Fig. 5. Low-strain and strain-compatible shear-wave velocities at Gilroy #2. The low-strain and strain-compatible velocities are from EPRI (1993) and the best-fit SHAKE analysis, respectively.

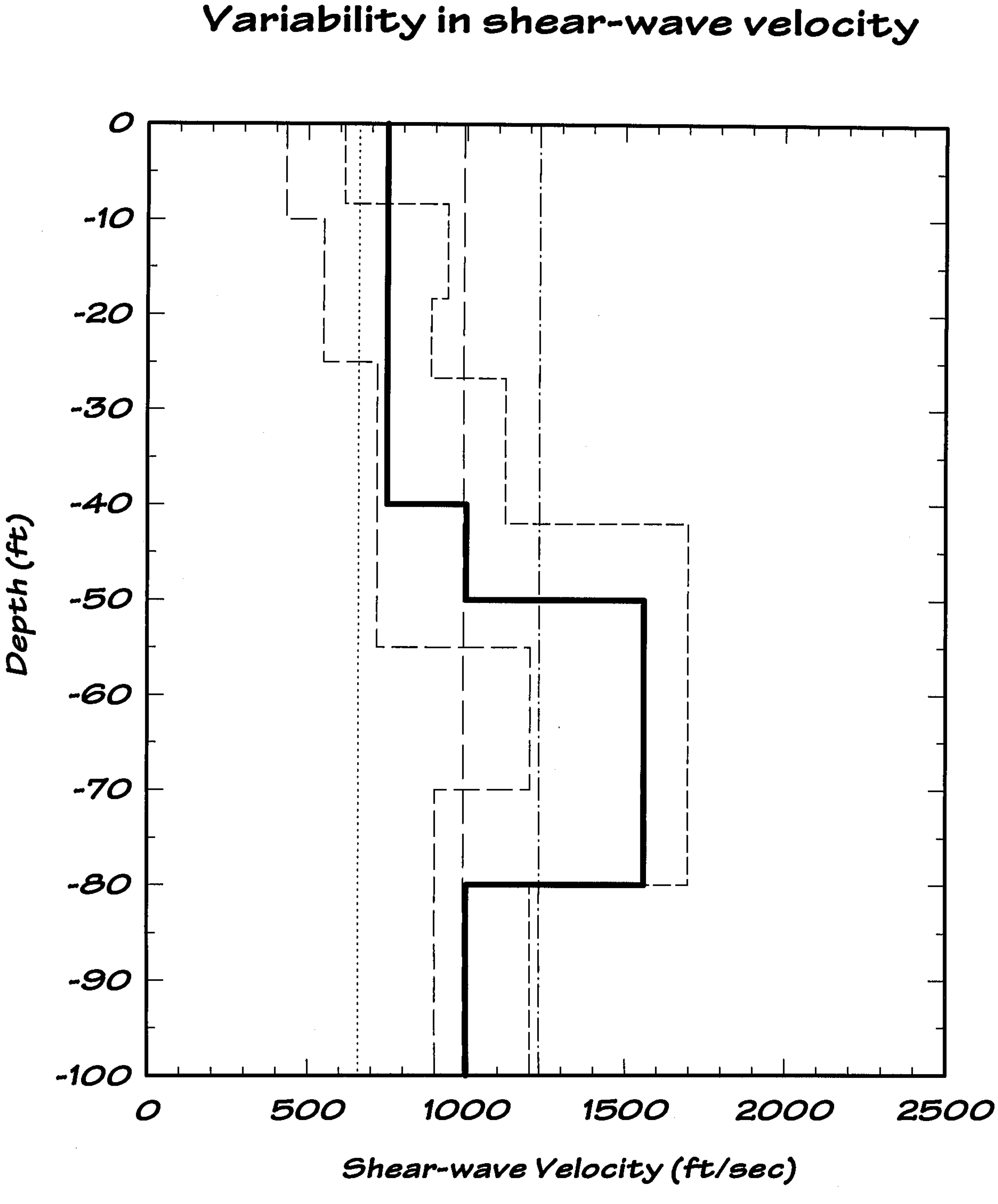

Fig. 6. Variability in the shear-wave velocity in the top 100 ft (30 m) at Gilroy #2. The low-strain velocity is shown with a thick solid line. Other velocity profiles are shown with thinner lines.

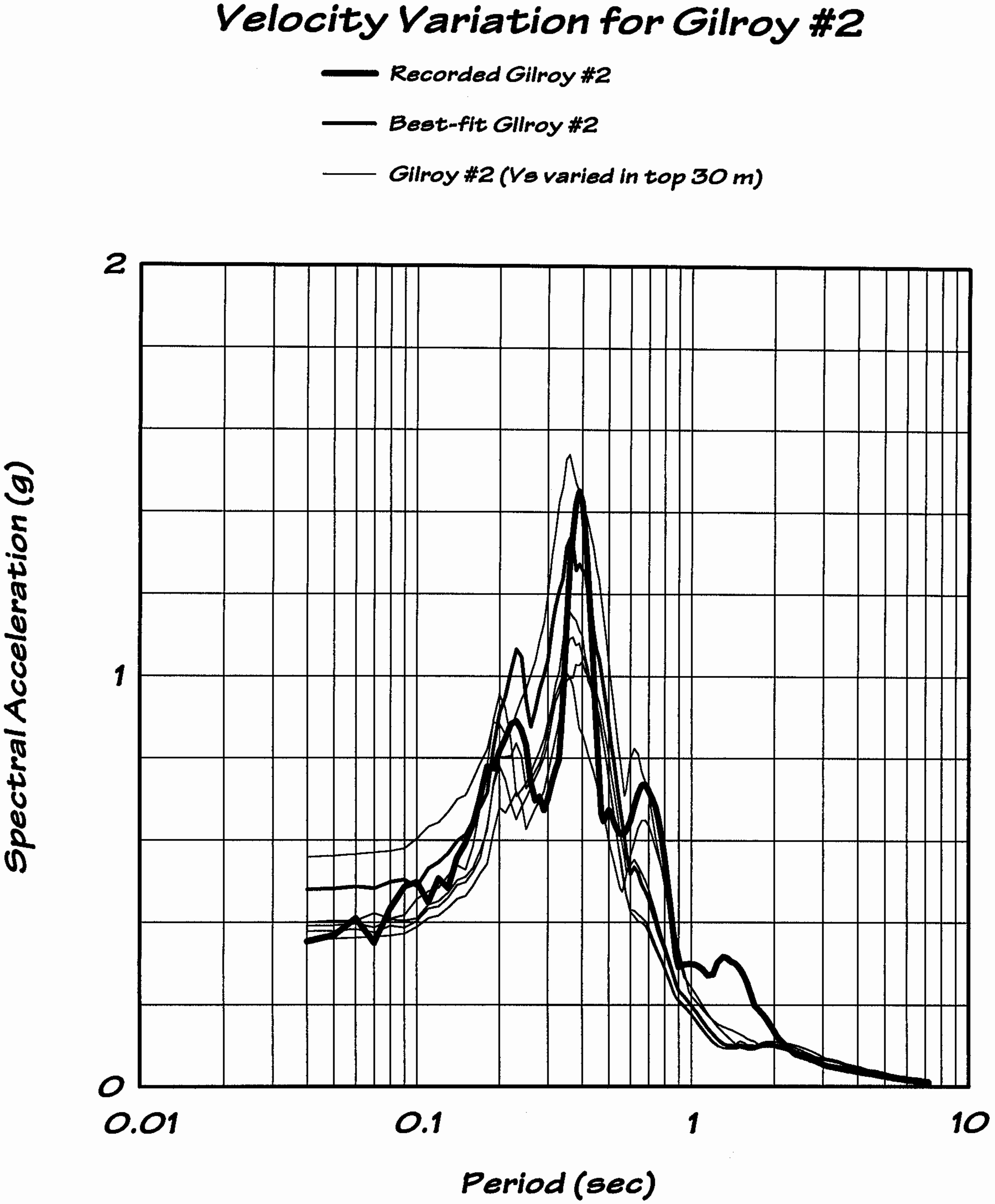

Fig. 7. Response spectral accelerations (5% damped) from the north-south component of the Loma Prieta mainshock at Gilroy #2. The spectrum from the best-fit and other models with variable Vs in the upper 30 m.