RECENT DATA RECORDED FROM DOWNHOLE GEOTECHNICAL ARRAYS

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ABSTRACT

Data recorded by downhole arrays with sensors installed at different depths and geologic layers provide critical information for studies of local site amplification effects.

The soft-soil/rock array at Treasure Island near San Francisco was installed by the California Strong Motion Instrumentation Program in cooperation with other agencies. Analysis of the recorded low amplitude data shows that the average amplification factor from the bedrock to the surface of the soft soil reaches factor of 10 at periods of 1.2-1.3 seconds.

Geotechnical arrays at La Cienega in Los Angeles, Meloland in El Centro, in Eureka and the newly instrumented arrays near the Vincent Thomas Bridge in Long Beach represent deep soft alluvium sites. A comparison was made of the average site amplifications calculated for a number of $M<5$ events with the site amplification for the 7.1 M_w Hector Mine earthquake. The site amplification curves are similar at short periods, but at longer periods the amplification factor is significantly lower for the distant large-event records.

The Tarzana downhole is located on the top of a small hill, and represents a soft-rock site. The downhole data from small events recorded so far demonstrate a significantly higher amplification effect for the component perpendicular to the hill than for the component parallel to the hill.

Large (up to 10 cm) long-period (up to 8 seconds) displacements were recorded at the La Cienega, El Centro, Tarzana and Long Beach arrays during the Hector Mine earthquake at the distances of more than 200 km from the epicenter. In contrast to the small events, the data recorded during the Hector Mine earthquake show that for the displacements and velocity curves there is practically no near-surface site amplification.

Introduction

In an effort to study site amplification effects the California Strong Motion Instrumentation Program (CSMIP) began instrumenting boreholes with strong-motion accelerometers in 1989. As of August 2000 eleven geotechnical arrays are operational (listed in Table 1), and installation of eight new arrays is planned for 2000-2001. Most of the arrays were installed with the support and cooperation of the California Department of Transportation (Caltrans), but others were installed with the National Science Foundation (NSF), Electric Power Research Institute (EPRI) and the U. S. Geological Survey.

Table 1. CSMIP Instrumented Geotechnical Arrays

	Station No.	**Station Name**	**Lat.**	**Long.**	**No. of Depths**	**No. of Sen-sors**	**Sensor Depths, m**	**Geology**	**Partner**
1	36520	Parkfield - Turkey Flat #2	35.882	120.350	3	9	Surface, 11, 23	Alluvium	SMIP
2	36529	Parkfield - Turkey Flat #1	35.878	120.358	2	6	Surface 24	Rock	SMIP
3	58642	Treasure Island - Geotechnical Array	37.825	122.373	7	21	Surface 7, 16, 31, 44, 104,122	Fill, Alluvium, Rock	NSF
4	24703	Los Angeles - La Cienega Geotech Array	34.036	118.378	4	12	Surface 18, 100 252	Deep Soft Alluvium	Caltrans
5	58700	San Francisco - Golden Gate Bridge	37.818	122.477	1	3	152	Rock	Golden Gate Bridge District
6	89734	Eureka - Geotechnical Array	40.819	124.164	5	15	Surface 19, 33, 56, 136	Deep Soft Alluvium	Caltrans
7	24764	Tarzana - Cedar Hill B	34.160	118.534	2	6	Surface 60	Soft Rock	ROSRINE
8	14785	Los Angeles - Vincent Thomas Geotech Array East	33.750	118.270	4	12	Surface 18, 46 91	Deep Soft Alluvium	Caltrans
9	14786	Los Angeles - Vincent Thomas Geotech Array West (two close sites combined)	33.750	118.280	6	21	Surface 15, 30, 30, 91, 189	Deep Soft Alluvium	Caltrans
10	1794	El Centro - Meloland Geotechnical Array	32.773	115.447	4	12	Surface 30, 100, 195	Deep Alluvium	Caltrans
11	58798	Hayward - San Mateo Br Geotech Array	37.617	122.153	5	15	Surface 10, 23, 46, 91	Deep Alluvium	Caltrans

Treasure Island Geotechnical Array

The Treasure Island Array near San Francisco represents a soft-soil/rock geological profile. One of the goals of the array is to explain the amplification of rock motion by soil deposits observed during the M_L 7.0 Loma Prieta earthquake.

Treasure Island is a 400-acre manmade island created in the 1930's by hydraulic filling. The island was constructed over a natural sand spit and Bay Mud, and is located in the San Francisco Bay north of the Franciscan outcrops on Yerba Buena Island. Figure 1 shows the depth profile of the instrumentation. The P and S-wave velocity (after Gibbs and others, 1992) are also shown. At the array site there is approximately 12 m of hydraulic fill and sand overlying about 15 m of medium-stiff Holocene Bay Mud (soft silt and clay sediments) over dense sand and stiff Pleistocene Bay Mud (Old Bay Clay). Generally, the clay stiffness increases with depth. Franciscan sandstone and shale are encountered at 91 m beneath the site. The hydraulic fill consists of silty fine sands with clayey zones. The fill is in a relatively loose condition due to the construction method. After the Loma Prieta earthquake sand boils on Treasure Island indicated liquefaction within 100 m of the array site (Shakal and others, 1989; Darragh and Shakal, 1991). Array site characterization studies are described in greater detail in Darragh and others (1993), and de Alba and others (1994).

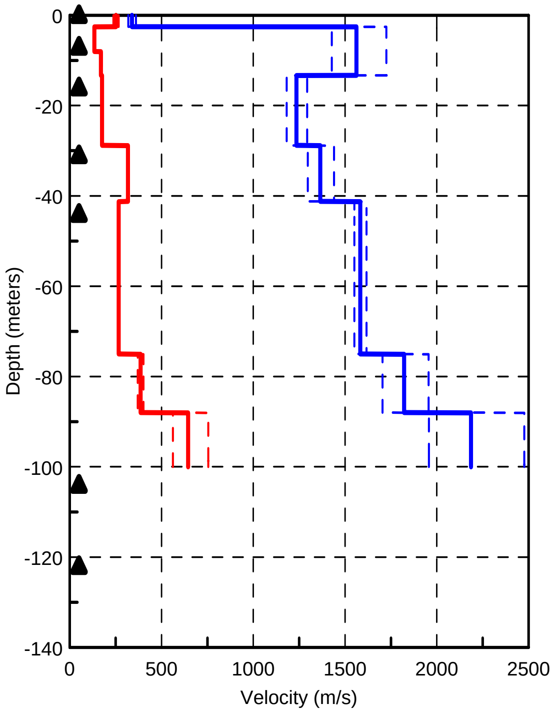

Figure 1. P- and S-wave velocities, and sensor location depths (triangles) at Treasure Island.

The array includes seven triaxial accelerometers that have been installed at the surface and in six boreholes (Fig. 1). Borehole accelerometers are located in the artificial fill at 7 m; near the top of the Young Bay Mud at 16 m; near the top of a dense gray sand at 33 m; near the top of the Old Bay Mud at 44 m; and below the bedrock surface at 104 m and

122 m (instruments added at this depth in 1996). The accelerometers are secured in the borehole using the CSMIP orientation and locking system (Shakal and Petersen, 1992).

Low amplitude data from 7 earthquakes with magnitudes up to 5.4 (Table 2) have been recorded by the Treasure Island Array (Graizer and others, 1999). Maximum ground acceleration recorded at the site was 2% g.

Table 2. Earthquakes recorded by the Treasure Island Geotechnical Array

No.	Date yr/mo/dy	Time (UTC) Hour:min:sec	M_L	Lat	Long	Depth (km)	Epic dist. (km)	Azim	PGA (g)
1	93/01/16	06:29:35.0	4.8	37.018	121.463	7.9	120.4	318	.015
2	94/06/26	08:42:50.3	4.0	37.916	122.286	6.6	12.6	217	.020
3	96/05/21	20:50:20.2	4.5	37.359	121.723	8.1	77.3	312	.009
4	98/08/12	14:10:25.1	5.4	36.753	121.462	9.2	143.8	326	.005
5	98/12/04	12:16:07.8	4.1	37.920	122.287	6.9	13.0	169	.014
6	99/08/18	01:06:18.9	5.0	37.907	122.687	6.7	29.0	108	.017
7	00/09/03	08:36:30.0	5.2	38.377	122.414	9.4	61.4	183	.009

Comparison of strong-motion data recorded in the deepest holes demonstrates that records obtained in the bedrock at the depths of 104 m and 122 m are very similar to each other in amplitude and shape, as shown in the sample record set in Figure 2. The motion is significantly amplified by the relatively soft surface layers.

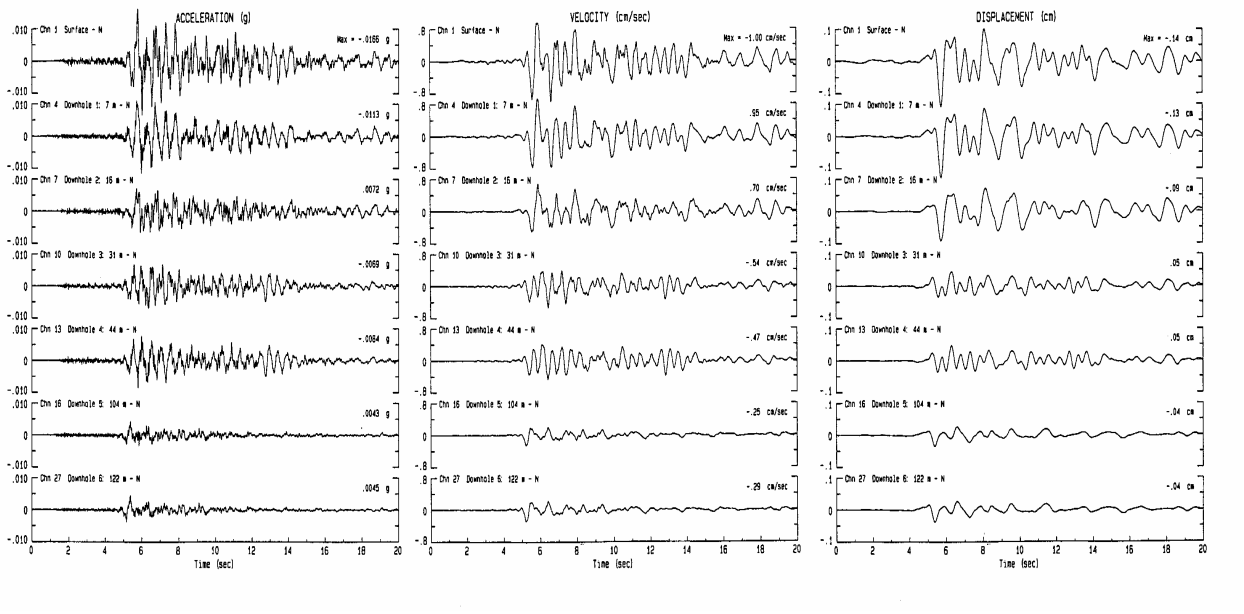

Figure 2. Acceleration, velocity and displacement recorded during the M5.0 earthquake of Aug.18, 1999 at Treasure Island, at the surface and depths of 7, 16, 31, 44, 104 and 122m.

Comparison of the response spectra (with 5% damping) for the surface and downhole records was made. Spectral ratios show that the average amplification from the bedrock to the surface of the soft soil reaches a factor of 6 at a period of 0.55 seconds, and a factor of 10 at periods of 1.2-1.3 seconds (Fig. 3).

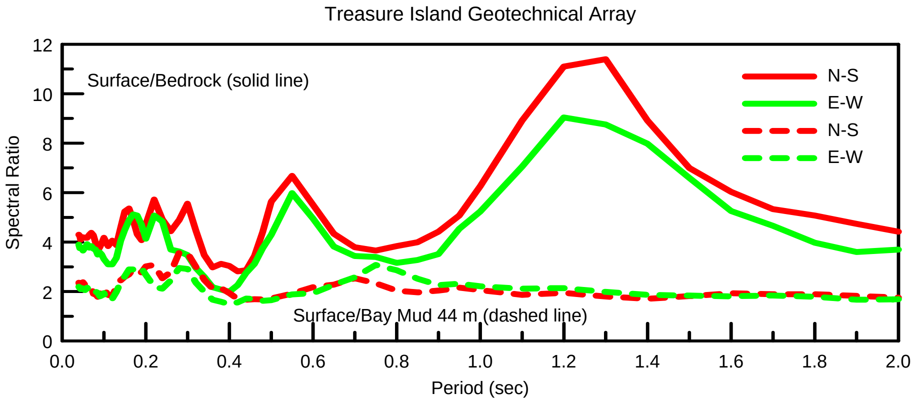

Figure 3. Average spectral site amplification calculated for 5 earthquakes with 4.0≤M≤5.4.

These data demonstrate strong site amplification effect (up to 10 times) from the bedrock to the surface of the soft soil at Treasure Island for low-amplitude motion.

La Cienega Downhole Array

To study the site response effect of a deep soil geologic structure an array was installed with support of Caltrans near the Santa Monica freeway (I-10) at La Cienega, which collapsed during the Northridge earthquake. Topographic maps from 1902 and 1926 (R. Sydnor, personal communication) show small lakes and marshy ground on the surface near the site of the collapsed Santa Monica freeway (La Cienega means "the swamp" in Spanish).

The geology of the two shallow holes was logged during drilling by Robert Sydnor. The profile consists of recent fluvial deposits of about 30 m in thickness over marine deposits (sands, silts, clays and gravels). P-wave and S-wave velocity surveys performed by Caltrans (suspension logging method) and the U. S. Geological Survey (averaging along the geologic layers) are shown in Figure 4. S-wave velocities are about 140 m/sec near the surface and increase to about 600 m/sec at the depth of 100 m. Using the site classification proposed by Boore et al. (1993) the La Cienega Geotechnical Array is a deep soft soil site (site class D).

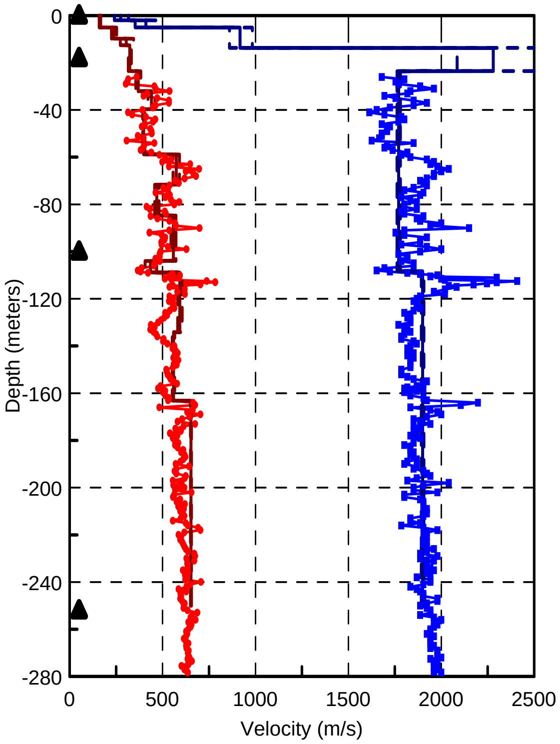

Figure 4. P- and S-wave velocities, and sensor location depths (triangles) at La Cienega array.

Table 3. Earthquakes recorded at La Cienega Geotechnical Array

No.	Date yr/mo/dy	Time (UTC) Hour:min:sec	M_L	Lat	Long	Depth (km)	Epic dist. (km)	Azim	PGA (g)
1	95/06/95	08:40:28.9	5.0	34.390	118.670	13.3	47.6	145	.011
2	97/03/18	15:24:47.7	5.1	34.970	116.820	1.8	176.7	235	.004
3	97/04/04	09:26:24.5	3.3	33.980	118.350	4.2	6.7	337	.078
4	97/04/04	09:35:09.5	2.4	33.990	118.360	4.5	6.4	342	.010
5	97/04/05	14:33:25.3	2.5	33.990	118.360	4.1	6.4	342	.022
6	97/04/26	10:37:30.7	5.1	34.370	118.670	16.5	45.8	144	.015
7	97/04/27	11:09:28.4	4.9	34.380	118.650	15.2	45.7	147	.007
8	98/01/12	06:36:24.9	3.4	34.190	118.470	11.3	19.1	154	.009
9	98/04/15	20:13:21.6	3.2	34.100	118.260	9.2	13.0	237	.014
10	98/05/05	18:14:08.6	1.9	34.050	118.390	9.2	1.9	144	.012
11	99/06/17	01:11:50.1	3.0	34.010	118.220	8.5	15.2	275	.012
12	99/06/29	12:55:00.8	3.8	34.010	118.220	8.0	15.2	275	.042
13	99/10/16	09:46:44.1	7.1	34.594	116.271	6.0	203.6	253	.035
14	99/10/16	09:59:35.1	5.8	34.682	116.285	5.8	205.0	250	.007
15	99/11/30	18:27:02.1	3.3	34.121	118.417	2.8	10.1	159	.017
16	99/11/30	18:46:27.1	3.1	34.125	118.416	2.8	10.5	160	.011

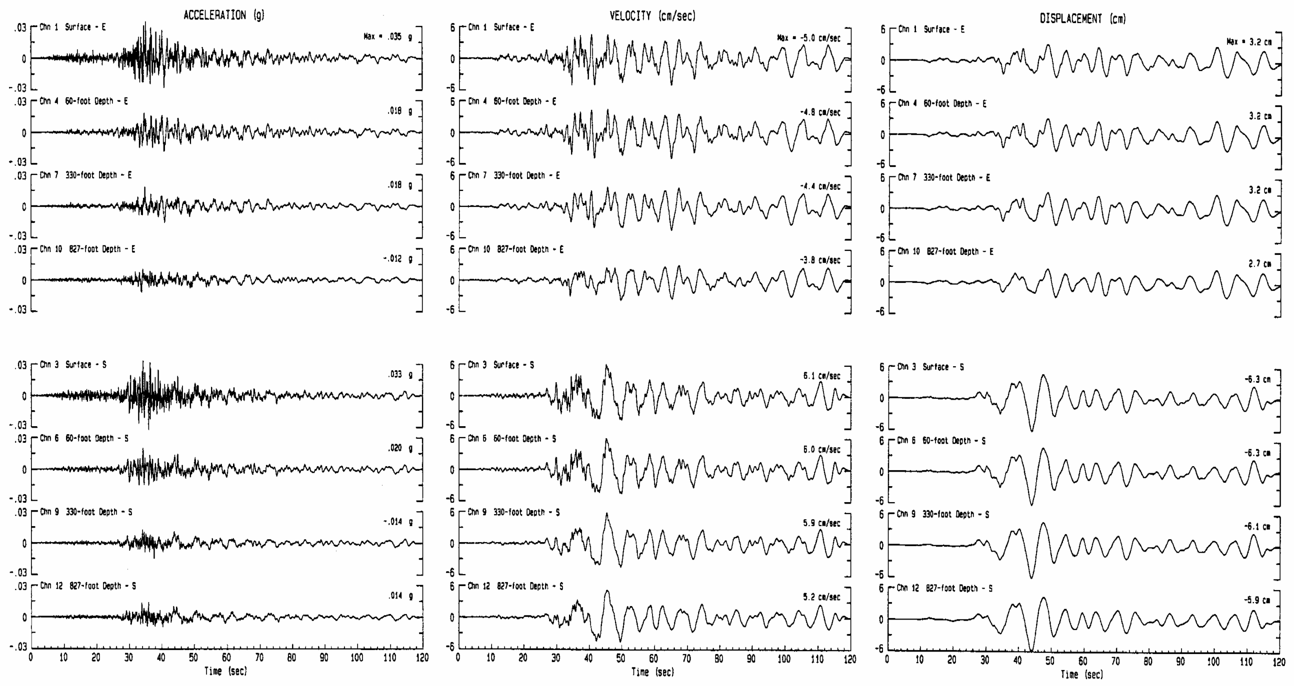

Figure 5. Acceleration, velocity and displacement recorded at the La Cienega array during the M7.1 Hector Mine earthquake, at the surface and depths of 18, 100, and 252 m. The maximum displacement is about 6 cm, at all depths.

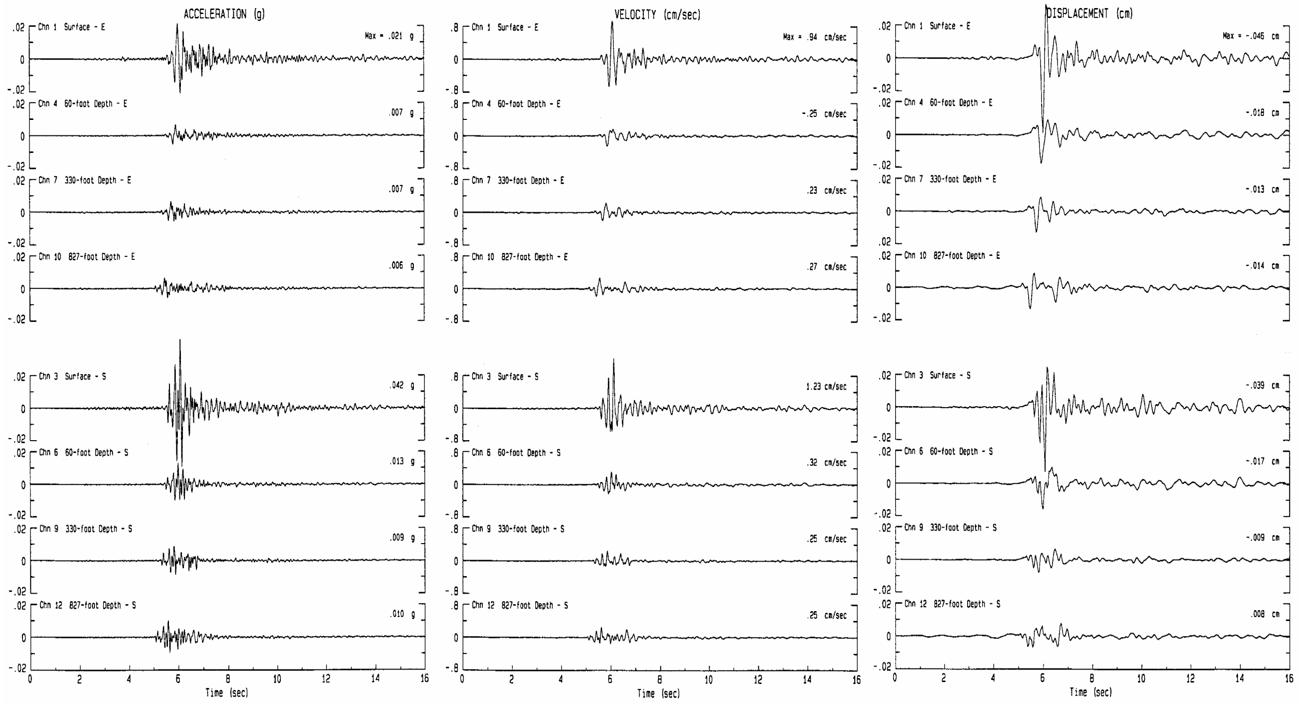

Figure 6. Contrasting example of acceleration, velocity and displacement recorded at the La Cienega array during the local M3.8 June 29, 1999 earthquake, at the surface and depths of 18, 100, and 252 m.

Sixteen earthquakes with magnitudes 1.9<M<7.1 have been already recorded at this site, at the surface and at depths of 18 and 100 m (Table 3). The last four events, including the M7.1 Hector Mine and its M5.8 aftershock, were also recorded at the recently instrumented deepest hole (252 m). Maximum ground acceleration recorded at the site was 8% g.

Acceleration, velocity and displacement recorded at the La Cienega array at the surface and 3 depths during the M7.1 Hector Mine earthquake are shown in Figure 5. Acceleration (short period motion) at the surface is amplified 2.5-3 times relative to the motion at depth. Long-period (up to 8 seconds) displacements with amplitudes more than 6 cm were recorded at this array during the Hector Mine earthquake, at a distance of more than 200 km. The difference between displacements recorded at all four depths during this earthquake is less than 10%. Both the velocity and displacement show practically no amplification from the depth to the surface for the distant large earthquake.

In contrast, ground motion during a M3.8 earthquake at the La Cienega array is shown in Figure 6. This is typical of small local events - acceleration, velocity and displacement are all amplified 3-4 times at the surface relative to the motion at depth.

The average site amplification (spectral ratio) at La Cienega calculated from thirteen events with 1.9<M<5.1 was compared with the site amplification from the 7.1 M_w Hector Mine earthquake (Fig.7). The site amplification curves are similar at short periods. But at longer periods (1.2<T<2.0 sec), the site amplification factor is significantly lower for the distant, larger event (Graizer and others, 2000). Periods are limited to 2 seconds because of the filter's bandwidth used to process low magnitude earthquake data, for which noise is dominant at longer periods.

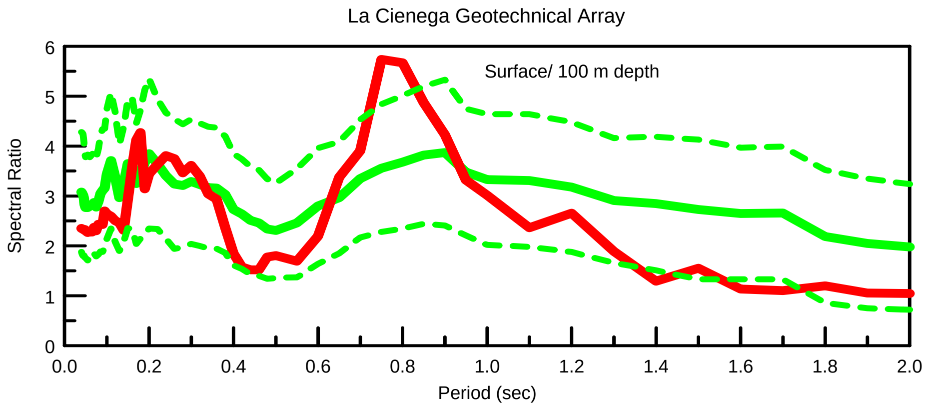

Figure 7. Comparison of site amplification (surface/100 m depth) during the Hector Mine event (dark solid line) and the average amplification for thirteen M<5.1 events (light solid line) ±one standard deviation (dashed lines).

El Centro Downhole Array

A downhole array was instrumented recently at Meloland Overpass near El Centro (surface and 2 depths). Similarly to La Cienega, it also represents a deep soft alluvium profile, with shear wave velocities increasing from approximately 150 m/sec near the surface to 450 m/sec at the depth of 100 m (silt, sand, clay) (Norris, 1988). P-wave and S-wave velocity surveys of the recently drilled downhole were performed by Caltrans.

Five earthquakes recorded by the array are listed in Table 4. Maximum ground acceleration recorded at the site was 4% g.

Table 4. Earthquakes recorded at El Centro Geotechnical Array

No.	Date yr/mo/dy	Time (UTC) Hour:min:sec	M_L	Lat	Long	Depth (km)	Epic dist. (km)	Azim	PGA (g)
1	99/07/24	02:01:26.0	3.9	32.770	115.560	15.4	10.6	88	.015
2	99/10/16	09:46:44.1	7.1	34.594	116.271	6.0	216.0	159	.016
3	00/04/09	10:48:09.7	4.3	32.692	115.392	10.0	10.4	330	.043
4	00/06/14	19:00:20.0	4.2	32.896	115.502	5.1	14.6	159	.015
5	00/06/14	21:49:18.0	4.5	32.884	115.505	4.9	13.5	156	.009

Acceleration, velocity and displacement recorded at the El Centro array at the surface and 2 depths during the M7.1 Hector Mine earthquake are shown in Figure 8. Acceleration (short period motion) at the surface is amplified approximately 2 times relatively to the motion at the depth. Long-period (up to 8 seconds) displacements with amplitudes up to 7 cm were recorded at this array during the Hector Mine earthquake at the distances of 216 km from the epicenter. The difference between displacements recorded during this earthquake at all four depths is less than 10%. There is almost no near-surface amplification for the displacement and velocity (Fig. 8).

Ground motion at the El Centro array during a M4.2 earthquake is shown in Figure 9. Typical of the small local earthquakes recorded, accelerations, velocities and displacements are all amplified approximately 3-4 times at the surface relative to the 100 m depth.

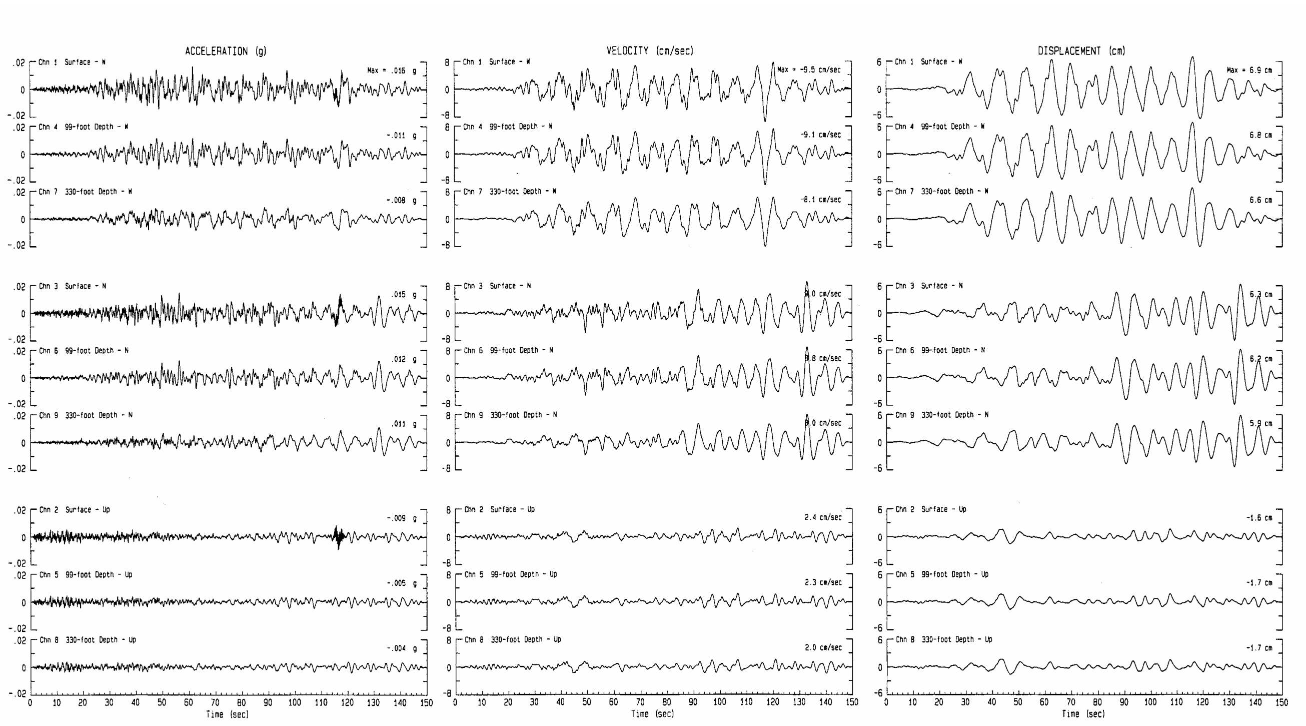

Figure 8. Acceleration, velocity and displacement recorded at El Centro array during the M7.1 Hector Mine earthquake, at the surface and depths of 30, and 100 m. The maximum displacement is about 7 cm, at all depths.

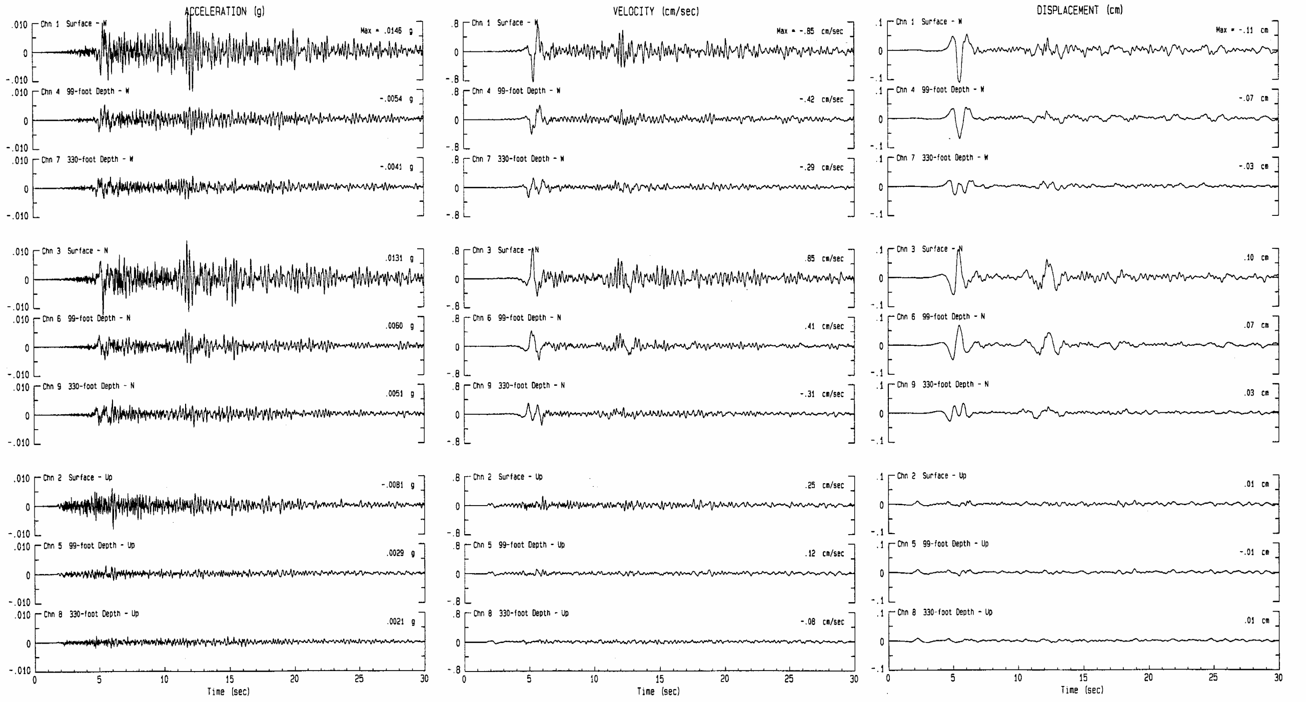

Figure 9. Contrasting example of acceleration, velocity and displacement recorded at El Centro array during the local M4.2 June 14, 2000 earthquake, at the surface and depths of 30, and 100 m.

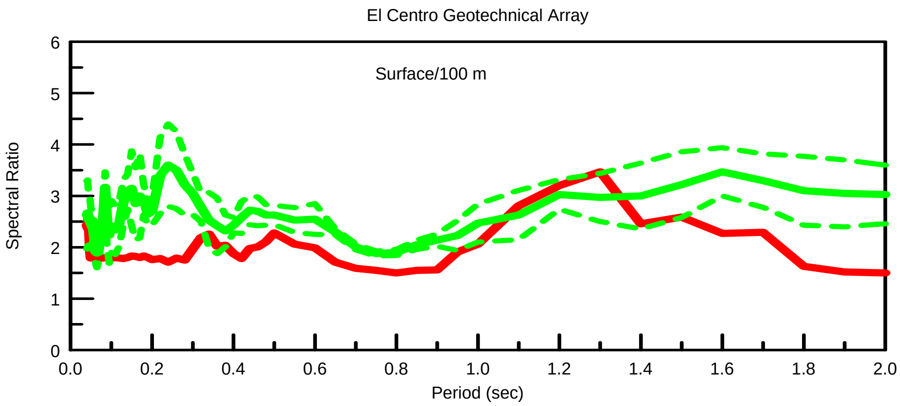

Figure 10. Comparison of site amplification during the Hector Mine event (dark solid line) and the average amplification for four M<5.0 events (light solid line) ±one standard deviation (dashed lines).

The average site amplifications (spectral ratios) at El Centro calculated from four events with M<5 were compared with the site amplification from the 7.1 M_w Hector Mine earthquake (Fig.10). Similar to the La Cienega data, site amplification curves at longer periods (1.4<T<2.0 sec), are lower for the distant, larger events.

The Hector Mine earthquake was also recorded at another deep soft alluvium site near the Vincent Thomas Bridge near Long Beach at a distance of 200 km from the epicenter. Long-period (up to 8 seconds) displacements with amplitudes up to 10 cm were recorded at this site. Similarly to the La Cienega and El Centro arrays, there is almost no difference among displacements recorded at all depths.

Tarzana Downhole

Ground motion amplification has been observed at Tarzana in many earthquakes and for both strong and weak motions. Both the Whittier Narrows and Northridge mainshocks produced larger than expected motions at Tarzana (Shakal et al., 1988). In contrast with the Northridge amplification, some events (Landers, Big Bear and Sierra Madre mainshocks, Whittier Narrows aftershock and some Northridge aftershocks) did not produce significant site amplifications.

The Tarzana site is located on a gentle 20 m high hill, about 500 m in length by 130 m in width with a strike near N78^{0}E. The Tarzana site has been drilled and logged to a depth of 100 m by Agbabian Associates under contract with CSMIP. Low shear-wave velocities (about 200 m/sec) were found in the top 4 m in colluvial soil (soft, silty diatomaceous clay). Decomposed shale is found from 4 to 12 m. Highly to slightly weathered shale of the Modelo formation was found from the 12 to 100 m. Gypsum crystals were observed in the drill cuttings near 6 m. Velocities generally increased gradually to near 750 m/sec near 80 m depth, except in several zones of hard shale and at the water table (Darragh and others, 1997). The hill was found to be well drained with a water table at a depth of 17 m. The results of P-wave and S-wave velocity surveys performed by the U. S. Geological Survey and Agbabian Associates are shown in Fig. 11.

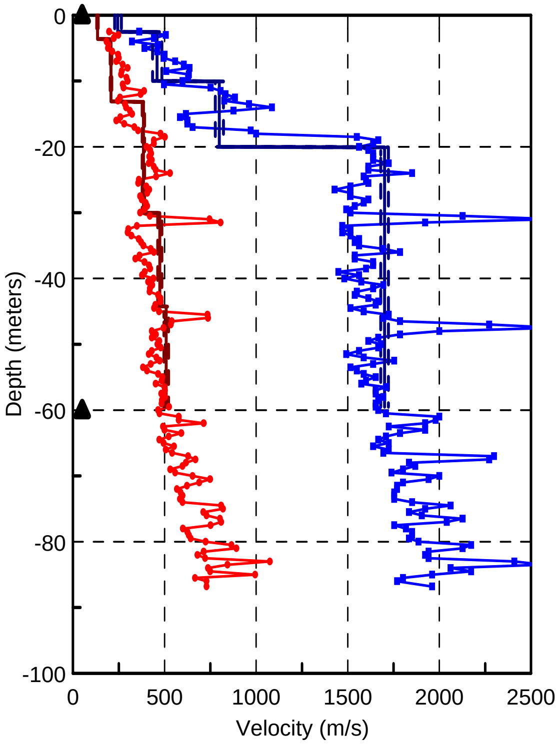

Figure 11. P- and S-wave velocities, and sensor location depths (triangles) at Tarzana downhole.

The Tarzana site was instrumented with support of the ROSRINE project. Eleven earthquakes recorded by the array are listed in Table 5. Maximum ground acceleration recorded by the array was 6% g.

Table 5. Earthquakes recorded at Tarzana Array

No.	Date yr/mo/dy	Time (UTC) Hour:min:sec	M_L	Lat	Long	Depth (km)	Epic dist. (km)	Azim	PGA (g)
1	98/01/04	09:11:45.1	3.3	34.200	118.640	3.5	10.7	114	.009
2	98/01/05	18:14:06.5	4.3	33.950	117.710	11.5	79.6	287	.004
3	98/01/12	06:36:24.9	3.4	34.190	118.470	11.3	6.8	241	.030
4	98/01/15	22:54:08.1	3.0	34.260	118.430	10.6	14.7	221	.006
5	98/03/11	12:18:51.8	4.5	34.020	117.230	14.9	121.3	278	.006
6	98/05/01	21:02:37.8	3.8	34.350	118.670	14.2	24.5	149	.015
7	98/06/03	05:22:50.6	3.0	34.120	118.480	7.7	6.7	312	.026
8	98/09/24	11:41:42.7	2.6	34.110	118.590	6.0	7.6	43	.007
9	98/11/11	05:40:28.9	2.5	34.160	118.500	11.3	3.1	270	.011
10	99/04/11	09:09:19.0	3.6	34.350	118.580	2.3	21.5	169	.007
11	99/10/16	09:46:44.1	7.1	34.594	116.271	6.0	213.6	258	.055

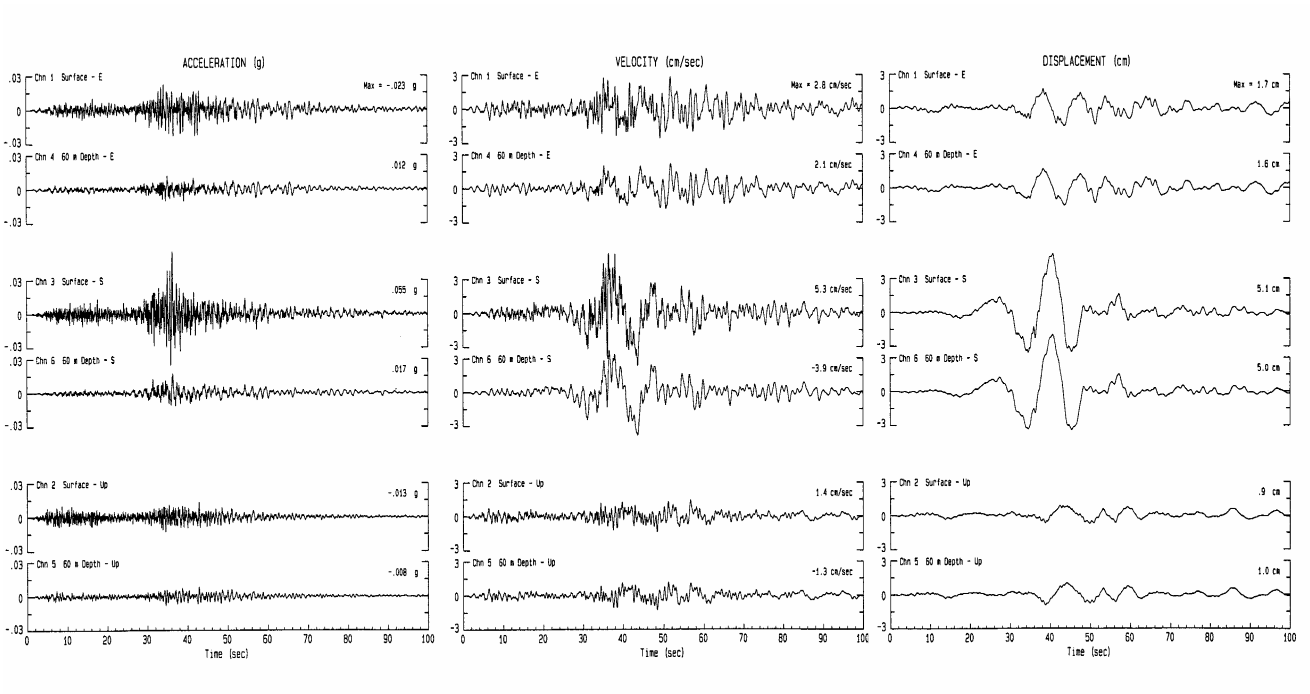

Figure 12. Acceleration, velocity and displacement recorded at Tarzana array during the M7.1 Hector Mine earthquake, at the surface and depth of 60 m. The maximum displacement is about 5 cm.

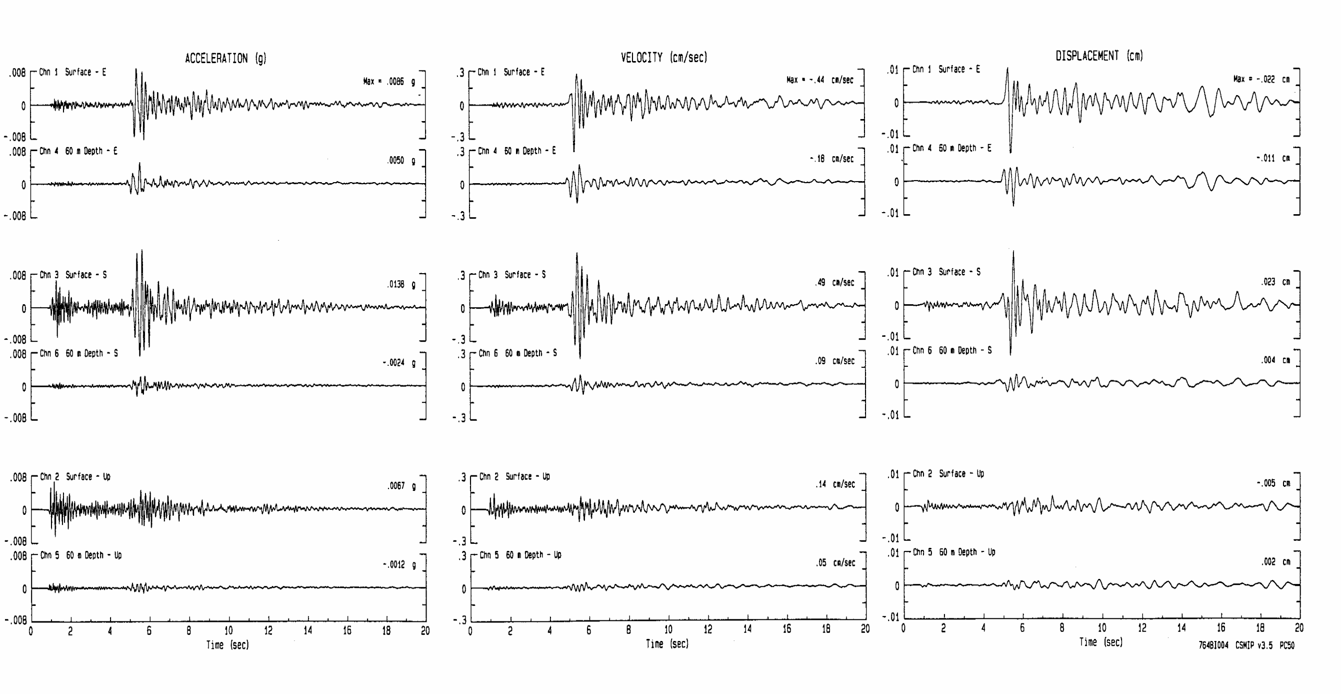

Figure 13. Acceleration, velocity and displacement recorded at Tarzana array during the M3.8 May 1, 1998 earthquake, at the surface and depth of 60 m.

Acceleration, velocity and displacement recorded at Tarzana array at the surface and 60 m depth during the M7.1 Hector Mine earthquake and a M3.8 earthquake are shown in

Figures 12 and 13. For the Hector Mine earthquake, acceleration (short period motion) at the surface is amplified 2-3 times relative to the motion at depth, and there is almost no near-surface amplification for the displacement and velocity (Fig. 12). In contrast, for small earthquakes, accelerations, velocities and displacements are all amplified up to 6 times at the surface relative to the 60 m depth (Fig. 13).

Comparison of the average site amplification for the ten 2.5<M<4.5 earthquakes with the amplification during the M7.1 Hector Mine earthquake is shown in Fig. 14. Similarly to the La Cienega and El Centro data, site amplification curves at longer periods (1.0<T<2.0 sec), are lower for the distant, larger events.

The site amplification effect is much higher for the component perpendicular to the hill compared to the parallel component with maximums at periods of 0.2 and 0.5 seconds (5 and 2 Hz). Note that N-S component is almost perpendicular, and the E-W component is almost parallel to the hill. The source of the site amplification that produces large motions at Tarzana is still under investigation. The three-dimensional topographic effect (Spudich et al. (1996) and Bouchon and Barker (1996)) only partially explains the site amplification on the top of the hill.

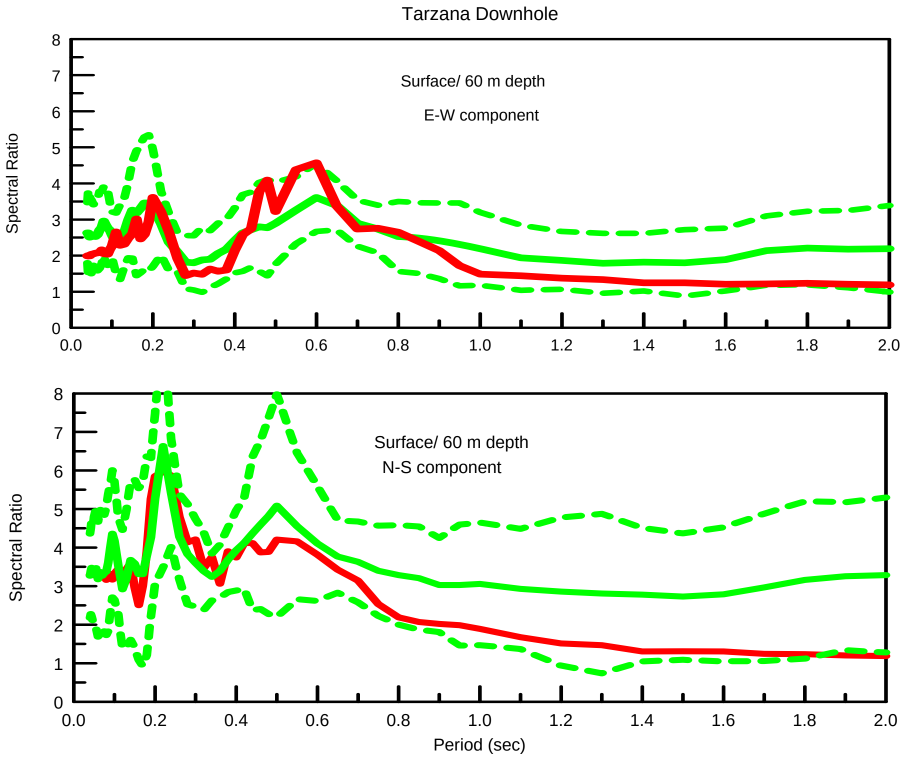

Figure 14. Comparison of site amplification during the Hector Mine event (dark solid line) and the average amplification for M<5.0 events (light solid line) ±one standard deviation (dashed lines).

Conclusions

Data recorded at downhole arrays so far represent low amplitude motions, not exceeding a few percent g (Tables 2-4). This allows relatively representative studies of linear response of the soil profiles.

The 7.1 M_W Hector Mine earthquake of October 16, 1999 and other low amplitude data from a number of events with $M<5.0$ were recorded by the following geotechnical arrays in Southern California instrumented by CSMIP: La Cienega in Los Angeles, Tarzana, Vincent Thomas Bridge (East and West ends) near Long Beach, and Meloland in El Centro. The geotechnical arrays at La Cienega, Meloland, and the newly instrumented arrays near the Vincent Thomas Bridge represent deep soft alluvium sites. Tarzana represents a soft-rock site, and it was instrumented with support of the ROSRINE project.

Long-period (up to 8 seconds) large amplitude (up to 10 cm) displacements were recorded at the La Cienega, El Centro, Tarzana and Long Beach arrays during the Hector Mine earthquake at epicentral distances of 200 - 220 km.

Comparison of site amplification effects during the M7.1 Hector Mine earthquake with that of closer small events with $M<5.0$ was made. Site amplification curves are similar at short periods, but are lower at longer periods for the distant, larger events. In contrast to the small local events, data recorded at the four arrays during the Hector Mine earthquake show that for the displacements and velocity curves there is practically no near-surface site amplification.

A possible explanation of these differences which is being investigated, is that in the case of local earthquakes body waves and waves reflected from upper layer boundaries may be predominant. In the case of distant events like the Hector Mine earthquake, surface and basin waves may be predominant. Those waves are of much longer periods. In contrast to a large earthquake, very few basin waves may be generated in the Los Angeles basin for local events with $M<5.0$.

Further downhole studies are necessary to investigate site amplification effects during different levels of shaking and types of earthquakes. This will allow the generation of empirical site amplification relationship taking into account nonlinear effects, and the effect of different types and periods of waves.

Processed data recorded at the geotechnical arrays are available at the CSMIP website: ftp://ftp.consrv.ca.gov/pub/dmg/csmip/GeotechnicalArrayData

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