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DATA FROM DOWNHOLE ARRAYS INSTRUMENTED BY THE CALTRANS/CDMG PROJECT

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INTRODUCTION

Data recorded by downhole arrays with sensors installed at different depths and geologic layers provide critical information for studies of local site amplification effects. 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 May 2001 eleven downhole arrays are operational, and installation of eight new arrays is planned for 2001-2002. The arrays instrumented with the support and cooperation of the California Department of Transportation are listed in Table 1, and several more arrays have been installed with support of the National Science Foundation, Electric Power Research Institute and the U.S. Geological Survey (Graizer et al., 2000). At each site there is triaxial accelerometer package installed at each of the listed depths.

TABLE 1. Downhole Arrays Instrumented by the Caltrans/CDMG Project

	Station No.	Station Name	Lat.	Long.	No. of Depths	No. of Sen-sors	Sensor Depths, m	Geology
1	24703	Los Angeles - La Cienega Geotech Array	34.036	118.378	4	12	Surface, 18, 100, 252	Deep Soft Alluvium
2	89734	Eureka - Geotechnical Array	40.819	124.164	5	15	Surface, 19, 33, 56, 136	Deep Soft Alluvium
3	14785	Los Angeles - Vincent Thomas Geotech Array East	33.750	118.270	4	12	Surface, 18, 46, 91	Deep Soft Alluvium
4	14786	Los Angeles - Vincent Thomas Geotech Array West (Anchorage)	33.750	118.280	3	12	Surface, 30, 91, 189	Deep Soft Alluvium
5	14786	Los Angeles - Vincent Thomas Geotech Array West (Approach)	33.750	118.280	3	9	Surface, 15, 30	Deep Soft Alluvium
6	01794	El Centro - Meloland Geotechnical Array	32.773	115.447	4	12	Surface, 30, 100, 195	Deep Alluvium
7	58798	Hayward - San Mateo Br Geotech Array	37.617	122.153	5	15	Surface, 10, 23, 46, 91	Deep Alluvium

LA CIENEGA DOWNHOLE ARRAY

To study the site response effect of a deep soil geologic structure an array was installed near the Santa Monica freeway (I-10) at La Cienega, where the freeway 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 geologic 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 1 (Darragh et al., 1997). S-wave velocities are about 140 m/sec near the surface and increase to about 600 m/sec at 100 m depth. The La Cienega Geotechnical Array site is classified as a deep soft soil site (site class D, Boore et al., 1993).

Nineteen 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 2). 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.

TABLE 2. 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	1995/06/26	08:40:28.9	5.0	34.390	118.670	13.3	47.6	145	.011
2	1997/03/18	15:24:47.7	5.1	34.970	116.820	1.8	176.7	235	.004
3	1997/04/04	09:26:24.5	3.3	33.980	118.350	4.2	6.7	337	.078
4	1997/04/04	09:35:09.5	2.4	33.990	118.360	4.5	6.4	342	.010
5	1997/04/05	14:33:25.3	2.5	33.990	118.360	4.1	6.4	342	.022
6	1997/04/26	10:37:30.7	5.1	34.370	118.670	16.5	45.8	144	.015
7	1997/04/27	11:09:28.4	4.9	34.380	118.650	15.2	45.7	147	.007
8	1998/01/12	06:36:24.9	3.4	34.190	118.470	11.3	19.1	154	.009
9	1998/04/15	20:13:21.6	3.2	34.100	118.260	9.2	13.0	237	.014
10	1998/05/05	18:14:08.6	1.9	34.050	118.390	9.2	1.9	144	.012
11	1999/06/17	01:11:50.1	3.0	34.010	118.220	8.5	15.2	275	.012
12	1999/06/29	12:55:00.8	3.8	34.010	118.220	8.0	15.2	275	.042
13	1999/10/16	09:46:44.1	7.1	34.594	116.271	6.0	203.6	253	.035
14	1999/10/16	09:59:35.1	5.8	34.682	116.285	5.8	205.0	250	.007
15	1999/11/30	18:27:02.1	3.3	34.121	118.417	2.8	10.1	159	.017
16	1999/11/30	18:46:27.1	3.1	34.125	118.416	2.8	10.5	160	.011
17	2000/08/01	19:53:18.2	3.0	33.927	118.359	15.9	12.2	352	.038
18	2000/09/16	13:24:41.3	3.3	33.976	118.424	12.2	7.9	33	.064
19	2001/01/14	02:26:13.0	4.3	34.923	118.403	6.1	28.6	175	.021

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 2. Acceleration (short period motion) at the surface is amplified 2.5-3 times relative to the motion at depth, but the displacements at all depths was almost same (the difference between displacements recorded at all four depths during this earthquake is less than 10%). Long-period (up to 8 sec) displacements with amplitudes more than 6 cm were recorded at this array at a distance of more than 200 km from the epicenter of the Hector Mine earthquake. Both the velocity and displacement show practically no amplification from the depth to the surface for the distant large earthquake.

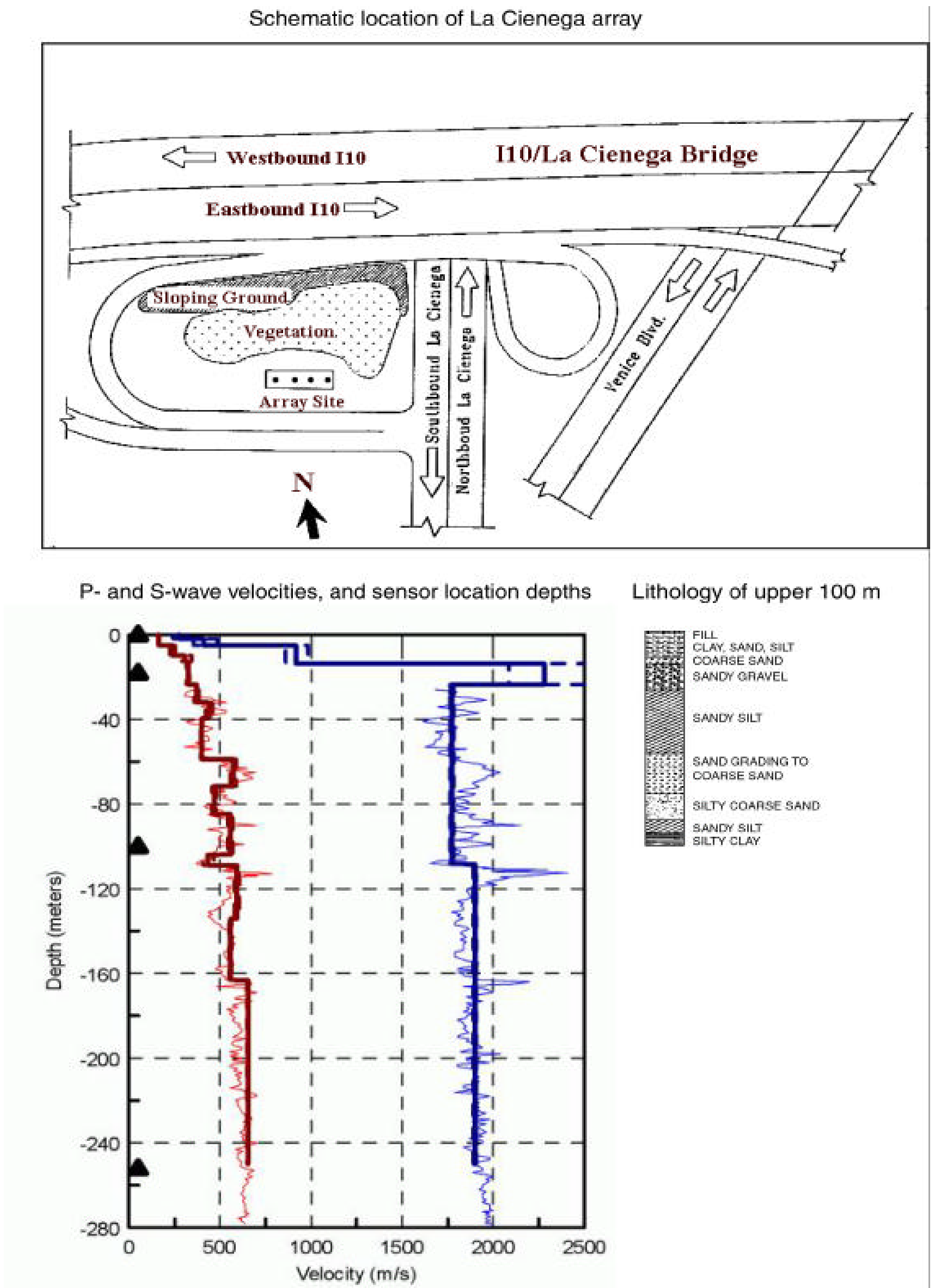

Figure 1. La Cienega downhole array: schematic location of the array, P- and S-waves velocities, sensor location, and lithology.

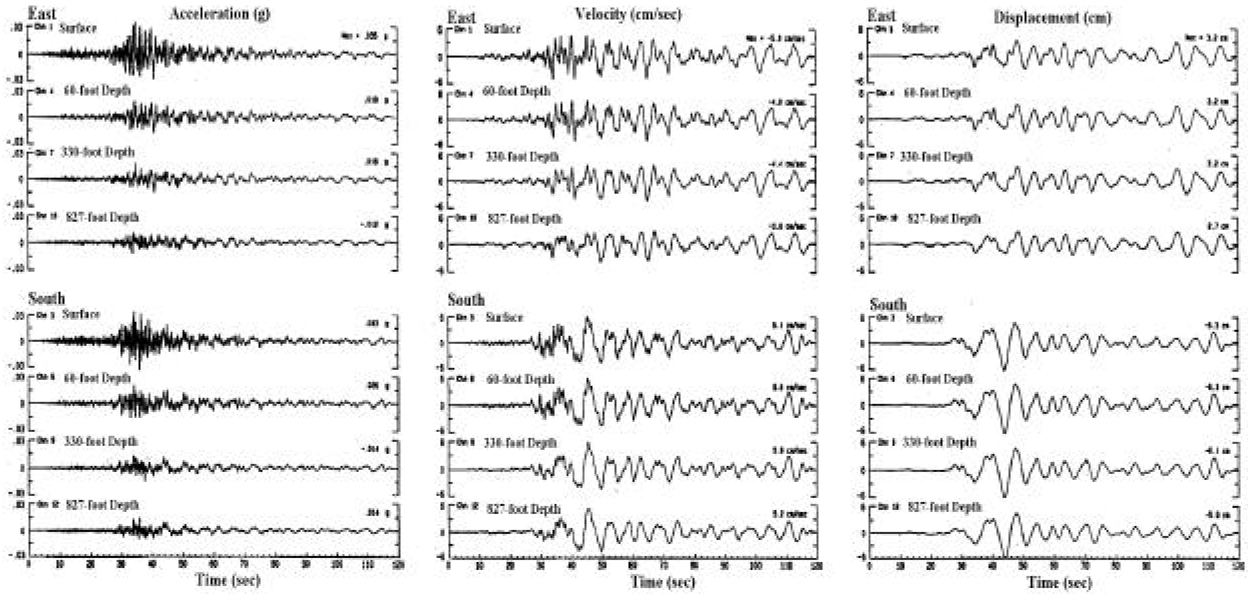

Figure 2. Acceleration, velocity and displacement recorded at the La Cienega array during the M7.1 Hector Mine earthquake, at the surface and depths of 18, 100, and 252 m. The maximum displacement is about 6 cm, at all depths.

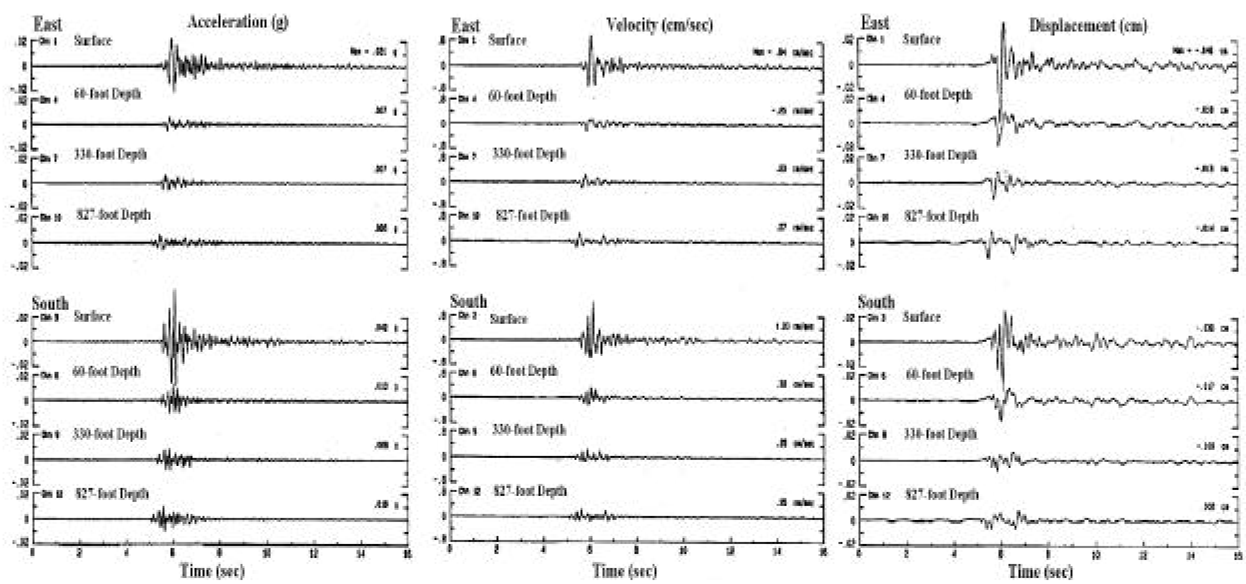

Figure 3. Contrasting example of acceleration, velocity and displacement recorded at the La Cienega array during the local M3.8 June 29, 1999 earthquake, at the surface and depths of 18, 100, and 252 m.

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

EL CENTRO DOWNHOLE ARRAY

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

Five earthquakes recorded by the array are listed in Table 3. The maximum ground acceleration recorded at the site was 4% g.

TABLE 3. 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

The 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 4. Acceleration (short period motion) at the surface is amplified approximately 2 times relatively to the motion at 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 a distance 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 or velocity (Figure 4).

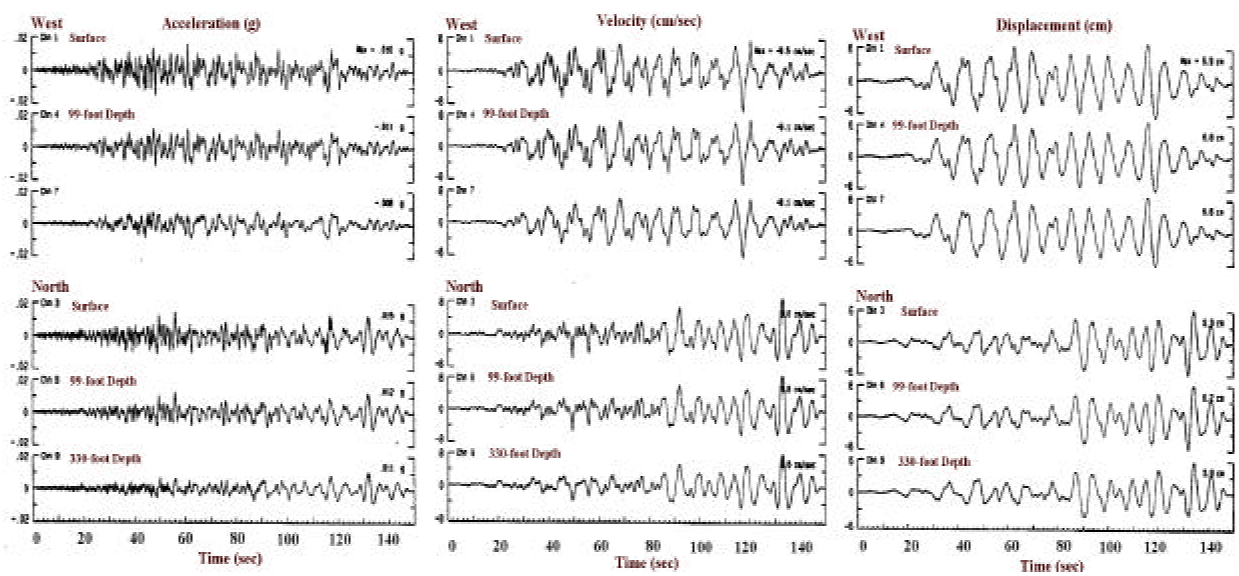

Figure 4. Acceleration, velocity and displacement recorded at the El Centro array during the M7.1 Hector Mine earthquake, at the surface and depths of 30, and 100 m. The maximum displacement is about 7 cm, at all depths.

VINCENT THOMAS DOWNHOLE ARRAYS

Downhole arrays were instrumented recently at the east and west ends of the Vincent Thomas suspension bridge near Long Beach. These arrays also represent a deep soft alluvium profile, with shear wave velocities increasing from approximately 150 m/sec near the surface to 500 m/sec at a depth of 100 m. The Hector Mine earthquake record obtained at the east array, at a distance of 200 km from the epicenter, is shown in Figure 5. Long-period (6-7 seconds) displacements with amplitudes up to 10 cm were recorded at this site. Like the La Cienega and El Centro array data, there is almost no difference among displacements recorded at all depths.

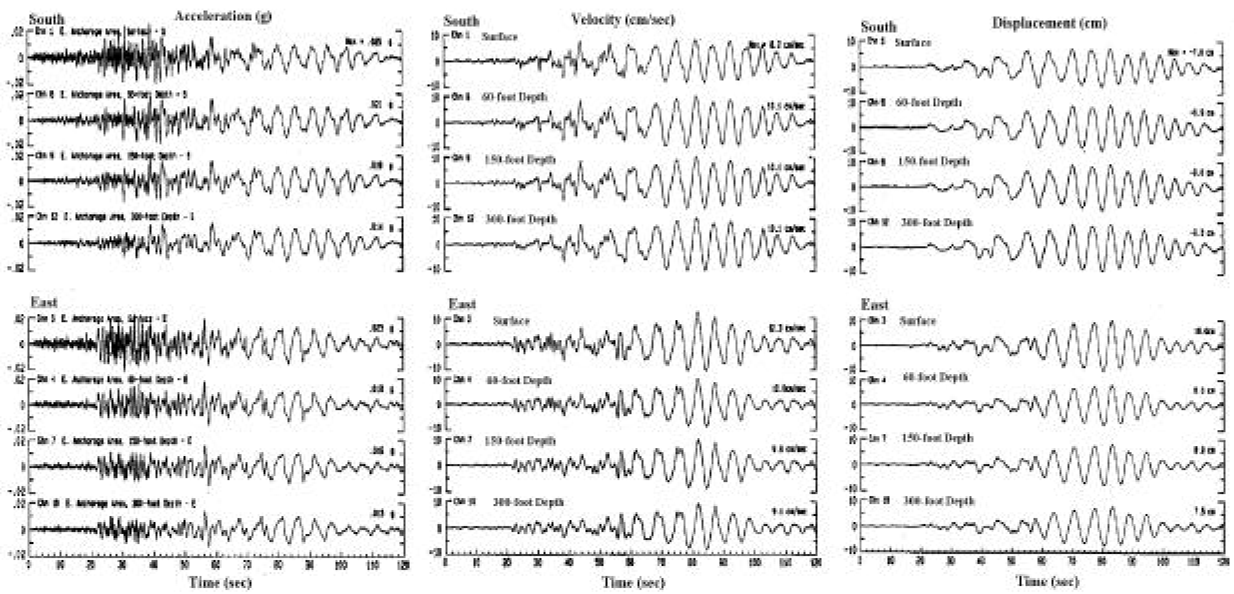

Figure 5. Acceleration, velocity and displacement recorded at Los Angeles –Vincent Thomas Geotechnical array East during the M7.1 Hector Mine earthquake, at the surface and depths of 18, 46 and 91 m. The maximum displacement is 8-10 cm, at all depths.

The Hector Mine records obtained at the deep sedimentary basin sites are characterized by high amplitude of displacements and very long duration of motions: 120-150 seconds. This type of motion appears to be surface waves, primarily Love waves created by multiple reflections of S-waves trapped in deep sedimentary basins. Large amplitude long period (5-8 seconds) surface waves generated by large earthquake sources (M>7) apparently provide enough energy to excite the whole basin structure. In contrast to a large earthquake, local earthquakes with M<5 generate enough energy to excite thin layers locally, but not the whole basin.

Comparison of the horizontal and vertical site amplifications (spectral ratios of response spectra with 5% damping) for the La Cienega, El Centro and Vincent Thomas East arrays is shown in Figure 6. Horizontal site amplifications are higher than vertical ones except for the short periods up to 0.25 seconds. Horizontal spectral ratios for the La Cienega and Vincent Thomas arrays demonstrate two spectral peaks: at approximately 0.25 sec and at 0.8-1.0 sec periods, with spectral amplification values of 3-6. Horizontal site amplification at the El Centro array demonstrates one spectral peak at approximately 1.25 sec with a spectral site amplification value of 3.

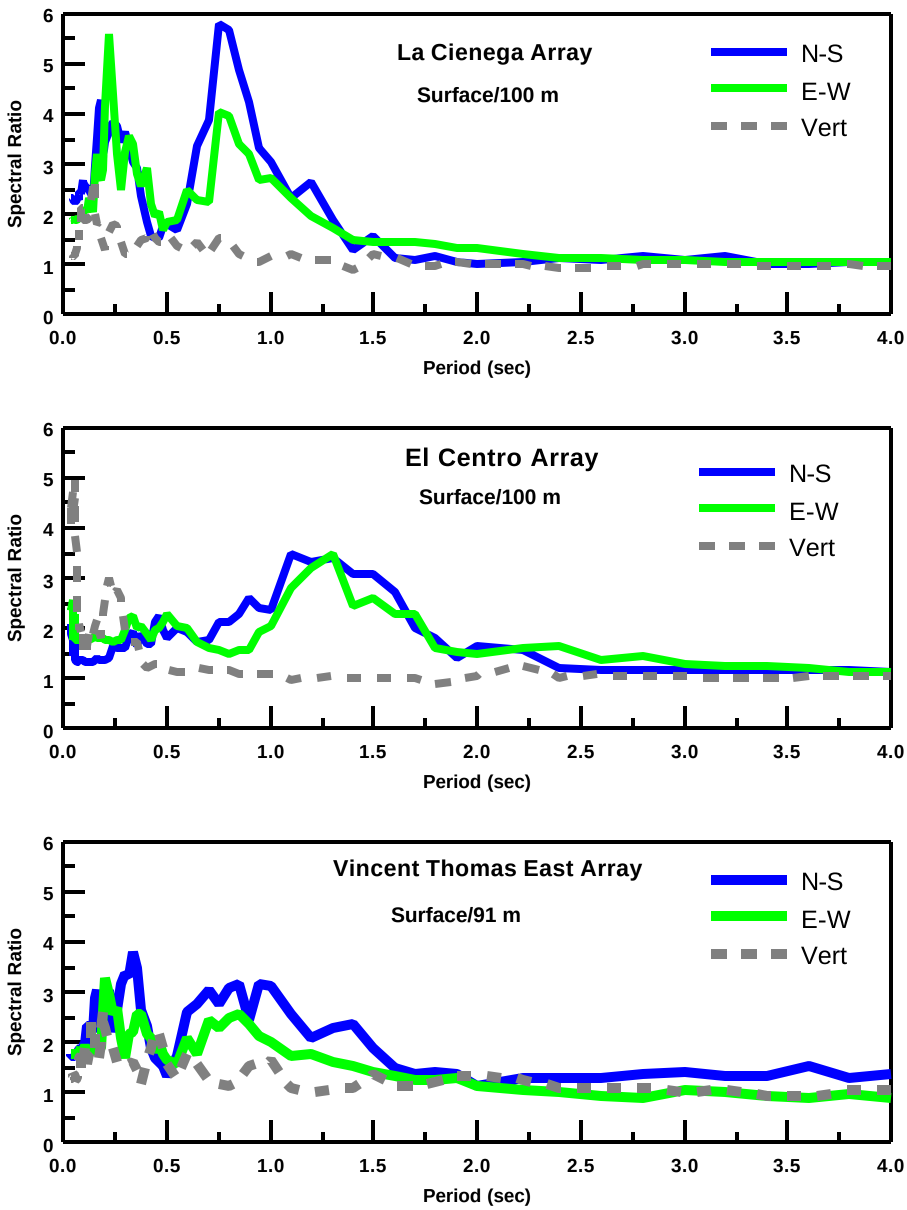

Figure 6. Comparison of horizontal and vertical surface site amplifications (surface/~100 m depth) during the Hector Mine earthquake at the three arrays.

SUMMARY

An important set of downhole geotechnical arrays have been instrumented at several locations. Data recorded at the downhole arrays so far represents only low amplitude motions, not exceeding a few percent g (Tables 2-3). 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 Caltrans/CDMG: La Cienega in Los Angeles, Vincent Thomas Bridge (East and West ends) near Long Beach, and Meloland in El Centro. These geotechnical arrays represent deep soft alluvium sites.

Long-period (up to 8 seconds) large amplitude (up to 10 cm) displacements were recorded at these 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. In contrast to the data for small local events, the data recorded at the four arrays during the Hector Mine earthquake shows that for the displacements and velocity curves there is practically no near-surface site amplification.

In the case of large distant events like the Hector Mine earthquake, surface and basin waves may dominate. Large amplitude long-period waves from distant, large earthquakes provide enough energy to excite the deep sedimentary basin structure. In contrast to a large earthquake, local events with M<5.0 generate relatively short period waves having enough energy to excite thin layers locally, but not the whole basin structure.

Further downhole studies are necessary to investigate site amplification effects during larger levels of shaking and different types of motion. This will allow the generation of empirical site amplification relationships taking into account nonlinear effects, distance to the source, and the effects 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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