STRONG-MOTION DATA RECORDED BY CDMG/CALTRANS SUBSURFACE ARRAYS AND MODELING USING SHAKE PROGRAM

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Abstract

Data recorded by downhole (subsurface) arrays with sensors installed at different depths and geologic layers provide critical information for studies of local site amplification effects. California Department of Conservation, Division of Mines and Geology (California Geological Survey)/CSMIP has been working with Caltrans for several years placing strong motion sensors at downhole arrays. Eight downhole arrays were instrumented throughout the state with more downhole arrays to come online soon. More than 50 low amplitude recordings from earthquakes with 2.4<M<7.1 were recorded at these arrays.

Large (up to 10 cm) long-period (up to 8 seconds) displacements were recorded at the La Cienega, El Centro and Long Beach arrays during the M_w7.1 Hector Mine earthquake at epicentral distances of 200 - 220 km. Use of downhole array data provides an opportunity to identify surface Rayleigh waves at the La Cienega and Long Beach Vincent Thomas Bridge arrays. Surface waves from big earthquakes can produce damage to large structures.

Comparison of empirical and theoretical site amplification effects at La Cienega and Tarzana were performed using SHAKE91 modeling motion separately in the longitudinal and transverse directions. Most of data recorded at downhole arrays so far represent low amplitude motions, not exceeding a few percent g. Processed data recorded at the geotechnical arrays are available at the website: ftp://ftp.consrv.ca.gov/pub/dmg/csmip/GeotechnicalArrayData

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 December 2001 thirteen downhole arrays are operational, and installation of few new arrays is planned for 2002. Eight arrays were 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., 2000a, 2000b). At each site there is a triaxial accelerometer package installed at each of the listed depths.

Instrumented Subsurface Arrays

Subsurface arrays instrumented by Caltrans/CDMG project are installed near important bridges in different geologic areas of southern and northern California (Table 1). Most of these arrays represent deep soft alluvium sites (except for the recently instrumented Tunitas Creek array in Half Moon Bay) with sensors located at the depths from a few meters up to 250 m. Instrumented

subsurface arrays allow studying response of different geologic structures to different levels and types of seismic shaking.

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

								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	4	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
8	58964	Half Moon Bay – Tunitas Geotech Array	37.360	122.395	4	12	Surface, 5, 12, 45	Alluvium, Soft Rock

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 show small lakes and marshy ground on the surface near the site of the collapsed Santa Monica freeway (Graizer et al., 2000b) (La Cienega means "the swamp" in Spanish).

Table 2. Earthquakes recorded at La Cienega Geotechnical Array

									PGA, g
1	6/26/95	08:40:28.9	5.0	34.390	118.670	13.3	47.6	145	0.011
2	9/27/96	21:34:60.0	1.9	34.090	118.360	5.5	6.2	196	0.009
3	3/18/97	15:24:47.7	5.1	34.970	116.820	1.8	176.7	235	0.004
4	4/4/97	09:26:24.5	3.3	33.980	118.350	4.2	6.7	337	0.078
5	4/4/97	09:35:09.5	2.4	33.990	118.360	4.5	6.4	342	0.010
6	4/5/97	14:33:25.3	2.5	33.990	118.360	4.1	6.4	342	0.022
7	4/26/97	10:37:30.7	5.1	34.370	118.670	16.5	45.8	144	0.015
8	4/27/97	11:09:28.4	4.9	34.380	118.650	15.2	45.7	147	0.007
9	1/12/98	06:36:24.9	3.4	34.190	118.470	11.3	19.1	154	0.009
10	4/15/98	20:13:21.6	3.2	34.100	118.260	9.2	13.0	237	0.014
11	5/5/98	18:14:08.6	1.9	34.050	118.390	9.2	1.9	144	0.012
12	6/17/99	01:11:50.1	3.0	34.010	118.220	8.5	15.2	275	0.012
13	6/29/99	12:55:00.8	3.8	34.010	118.220	8.0	15.2	275	0.042
14	10/16/99	09:46:44.1	7.1	34.594	116.271	6.0	203.6	253	0.035
15	10/16/99	09:59:35.1	5.8	34.682	116.285	5.8	205.0	250	0.007
16	11/30/99	18:27:02.1	3.3	34.121	118.417	2.8	10.1	159	0.017
17	11/30/99	18:46:27.1	3.1	34.125	118.416	2.8	10.5	160	0.011
18	8/1/00	19:53:18.2	3.0	33.927	118.359	15.9	12.2	352	0.038
19	9/16/00	13:24:41.3	3.3	33.976	118.424	12.2	7.9	33	0.064
20	1/14/01	02:26:13.0	4.3	34.293	118.403	6.1	28.6	175	0.021
21	9/9/01	23:59:18.0	4.2	34.059	118.387	4.9	2.7	162	0.490

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, according to the classification by Boore et al., 1993).

More than twenty 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 nine 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 0.49 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 2. Acceleration (short period motion) at the surface is amplified 2.5-3 times relative to the motion at depth, but the displacement at all depths was almost the 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 these long-period waves from this distant large earthquake (Graizer et al., 2002). Figure 3 demonstrates the surface site amplification effect (the ratios of the 5 percent damped response spectra). These ratios are flat for periods of 3 seconds and higher (3-15 seconds), and show that long-period motions are not amplified from depth to the surface (because those wavelengths are much higher than sensor location depths).

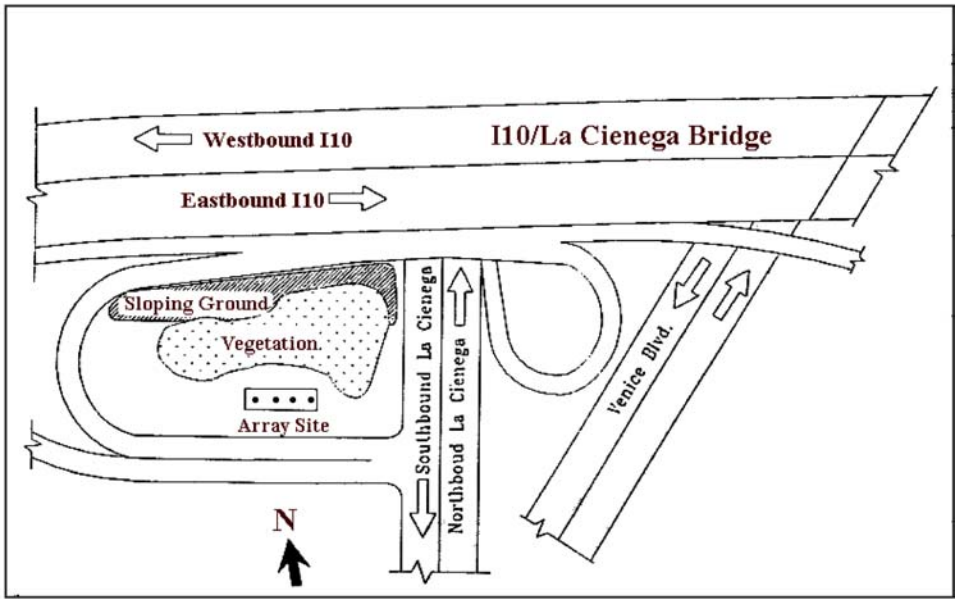
Records of the Hector Mine earthquake provide an opportunity to identify Rayleigh waves (Shakal et al., 2001). Particle motion variations at different depths show clear Rayleigh wave type motion (polarized in the radial direction, and retrograde at the surface and depths of 18 and 100 m, and prograde at the depth of 252 m). The differences in spectral ratios along the East-West (radial) and North-South (tangential) components in Figure 3 are due to the polarized 1.8 second Rayleigh wave.

Acceleration, velocity and displacement recorded during the M4.2 earthquake of September 9, 2001 are shown in Figure 4. The hypocenter of this relatively small event was located almost under the array, and produced maximum acceleration of almost 0.5 g at the surface. The duration of the signal was very short, and as a result, displacement amplitude was less than 1 cm. Comparison of the ground motion from the large distant (Figure 2) and the small close event (Figure 4) demonstrates differences in the site response to the different type of the input signal. In contrast to the long-period motion produced by a distant large earthquake that excites deep geologic structure (displacements in Figure 2), the short-period motion produced by a small event demonstrates significant differences in response of different layers at different depths (Figure 4). Displacement recordings from the small event at depths of 18, 100 and 252 m demonstrate double peaks, with the second peak associated with the S-wave reflected from the surface.

Modeling Ground Motion

Ground motion at the La Cienega array was modeled at different elevations by using the program Shake91. The shear wave velocity model provided by J. Gibbs (written communication) was chosen. In this model shear wave velocity increases gradually from 163 m/s at the ground surface to 653 m/s at depth of 250 m (Figure 1). However, some low velocity layers between higher velocity layers are detected and considered. Uniform density per layer was considered for all the layers. The soil model was represented by horizontal layers over a half space at the depth of 252 m. The dynamic soil properties of the layers from the ground surface to depth of 23.5 m are modeled by using the Seed & Sun (1989) relationship for clay layers. The lower layers are modeled as sand using the Seed & Idriss (1970) relationship

Schematic location of La Cienega array



P- and S-wave velocities and generalized soil profile

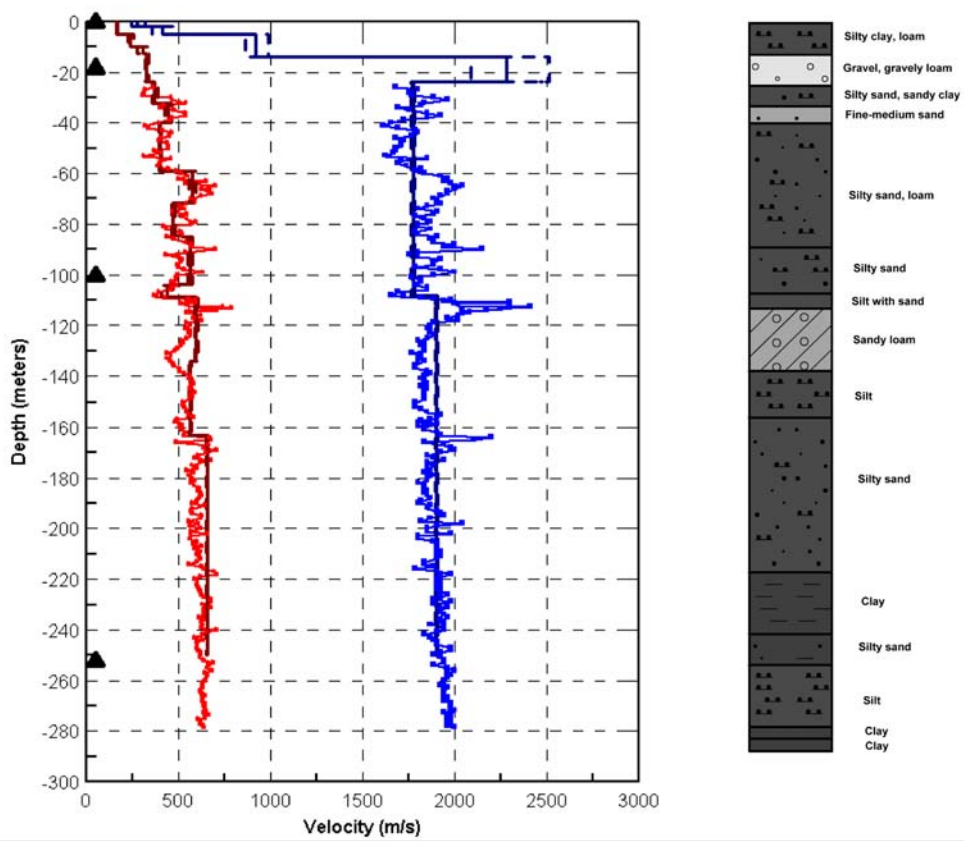


Figure 1. La Cienega downhole array: schematic location of the array, P- and S-wave velocities, sensor location, and lithology.

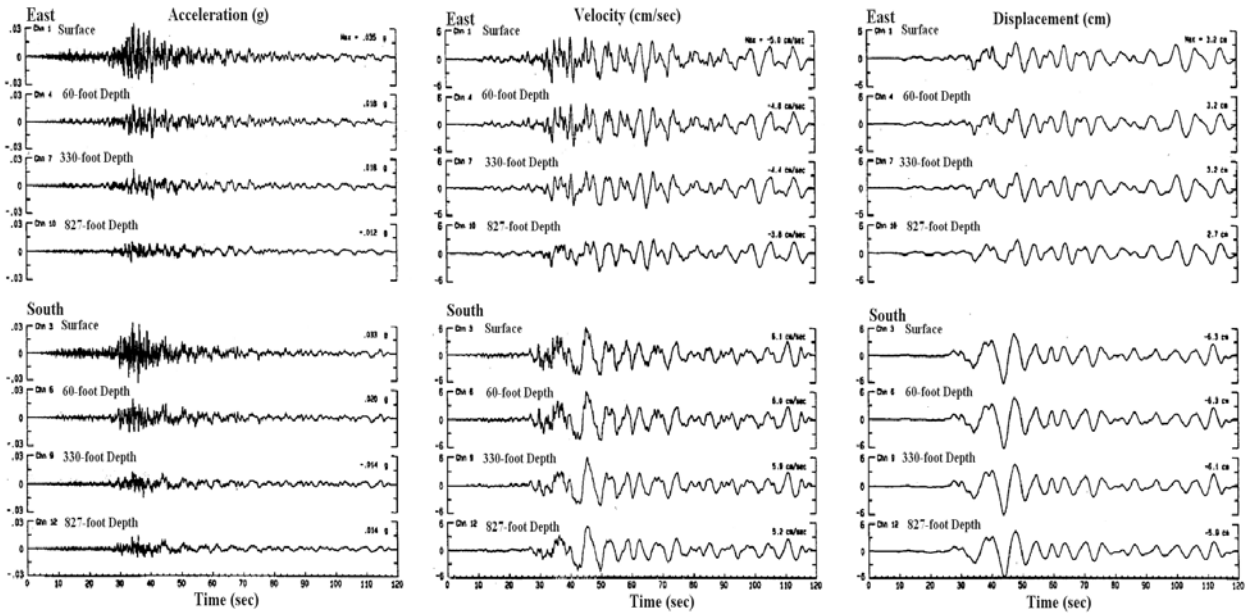


Figure 2. Acceleration, velocity and displacement recorded at the La Cienega array during the M7.1 Hector Mine earthquake, at the surface and depths of 18, 100, and 252 m. The maximum displacement is about 6 cm, at all depths.

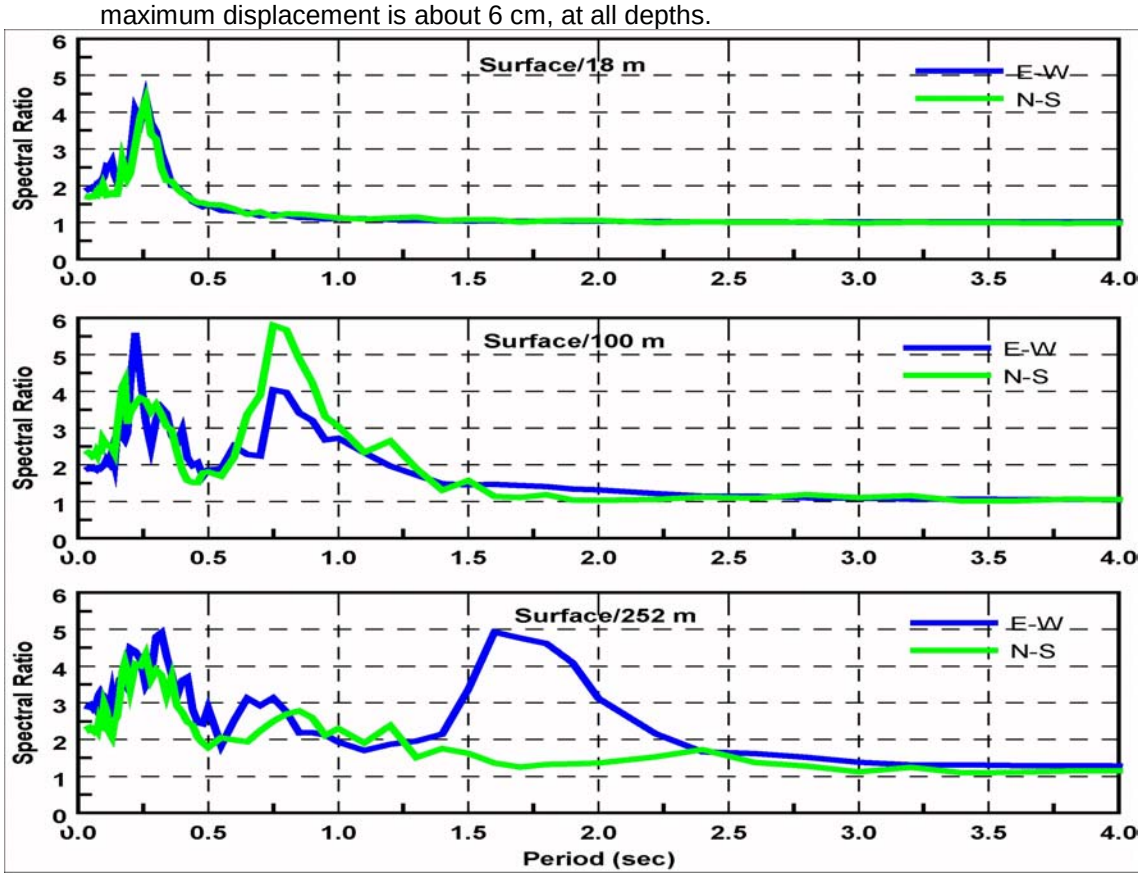


Figure 3. Spectral ratios of the response spectra (5 percent damped) at La Cienega array for the Hector Mine earthquake. Ratios of: surface to 18 m depth, surface to 100 m depth, surface to 252 m depth.

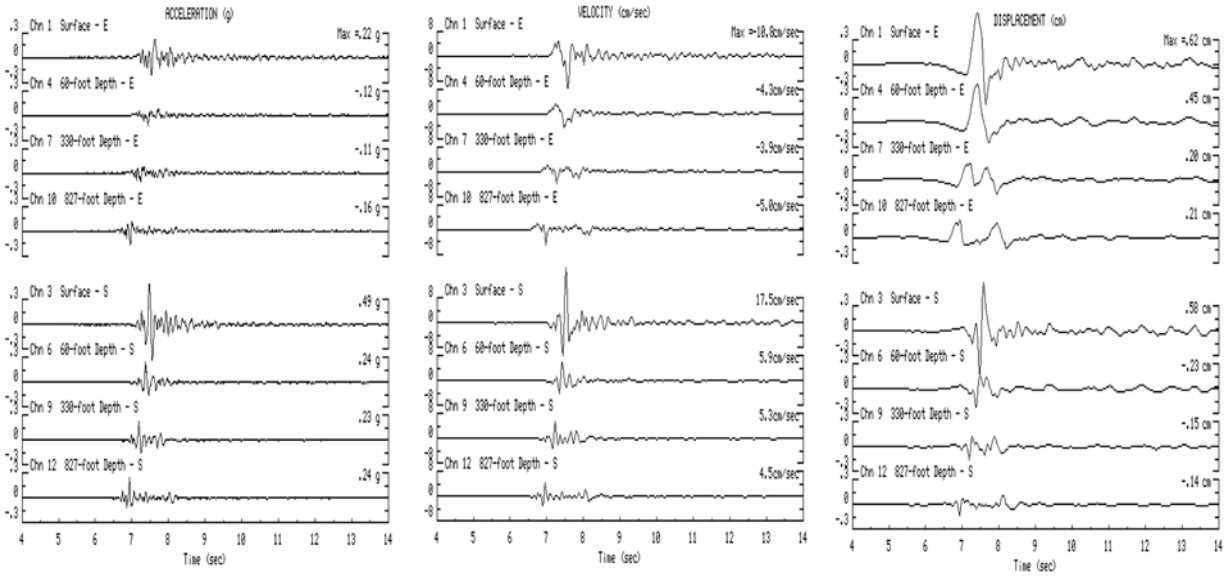


Figure 4. Acceleration, velocity and displacement recorded at the La Cienega array during the M4.2 earthquake of September 9, 2001, at the surface and depths of 18, 100, and 252 m.

Ground motion recorded during the September 9, 2001 earthquake at depth of 252 m was used as an input motion. The hypocenter of this event is located almost under the station, and vertical wave propagation serves as a good approximation. Output motions were generated using Shake91, and compared with the actual recordings at the ground surface (Figure 5), 18 m and 100 m depths. Use of the velocity model of J. Gibbs demonstrated pretty good agreement between modeled and recorded data. Figure 5 shows the portion of the record from 5 to 12 seconds, and demonstrates good agreement of amplitudes and phases of the modeled and recorded motions.

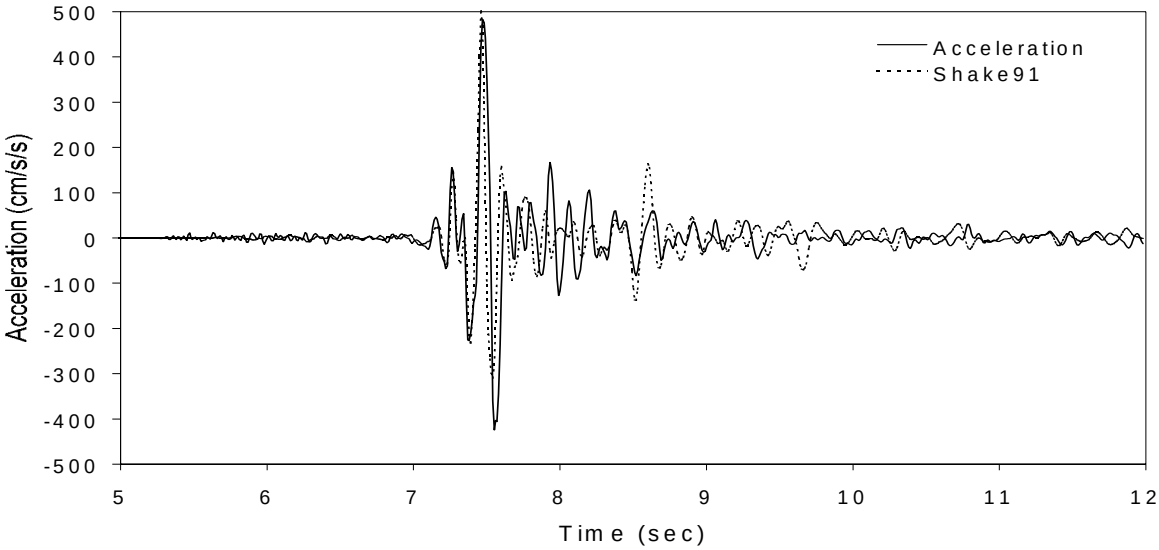


Figure 5. Comparison of the acceleration recorded at the surface with the output of Shake91 for the M4.2 earthquake of September 9, 2001, and using motion at the depth of 252 m as an input.

Shake91 is designed to model vertically propagating SH waves. It demonstrates good agreement between recorded and modeled data for the small earthquakes, and flat topography. In case of large distant event, like the M7.1 Hector Mine earthquake, big portion of ground motion consists of surface waves. Modeling surface waves requires more sophisticated technique, and as a result Shake91 can not be applied in this case.

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 6. 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.

High amplitude of displacements and very long duration (120-150 seconds) of motions characterize the Hector Mine records obtained at the deep sedimentary basin sites. This type of motion appears to be shear and surface 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.

Hector Mine earthquake ground motion at the La Cienega and Vincent Thomas arrays clearly demonstrate much higher amplitudes and longer duration of surface wave motions at the deeper basin site in the Long Beach area (Vincent Thomas arrays). At deep alluvial sites surface waves produced by the distant large earthquake can be dominant part of the strong shaking at longer periods

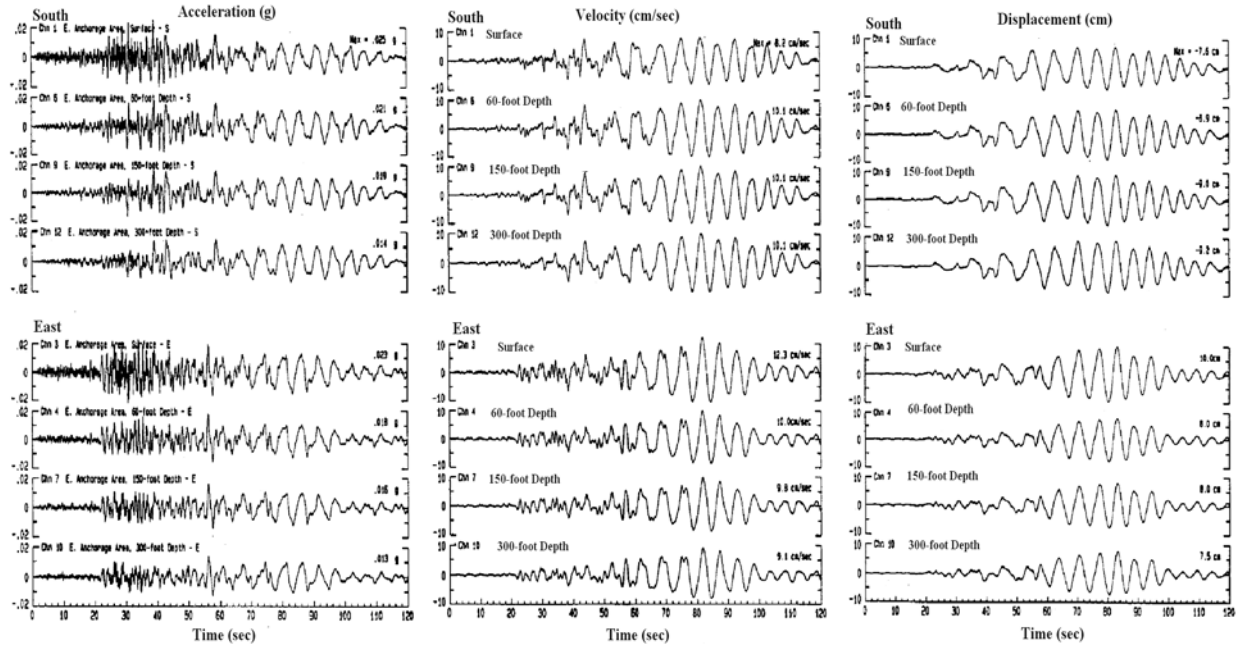


Figure 6. Acceleration, velocity and displacement recorded at Los Angeles –Vincent Thomas Geotechnical array East during the M7.1 Hector Mine earthquake, at the surface and depths of 18, 46 and 91 m. The maximum displacement is 8-10 cm, at all depths.

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

									PGA, (g)
1	7/24/99	02:01:26.0	3.9	32.770	115.560	15.4	10.6	88	.015
2	10/16/99	09:46:44.1	7.1	34.594	116.271	6.0	216.0	159	.016
3	4/9/00	10:48:09.7	4.3	32.692	115.392	10.0	10.4	330	.043
4	6/14/00	19:00:20.0	4.2	32.896	115.502	5.1	14.6	159	.015
5	6/14/00	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 7. Acceleration (short period motion) at the surface is amplified approximately 2 times relative 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 three depths is less than 10%. There is almost no near-surface amplification for the displacement or velocity (Figure 7).

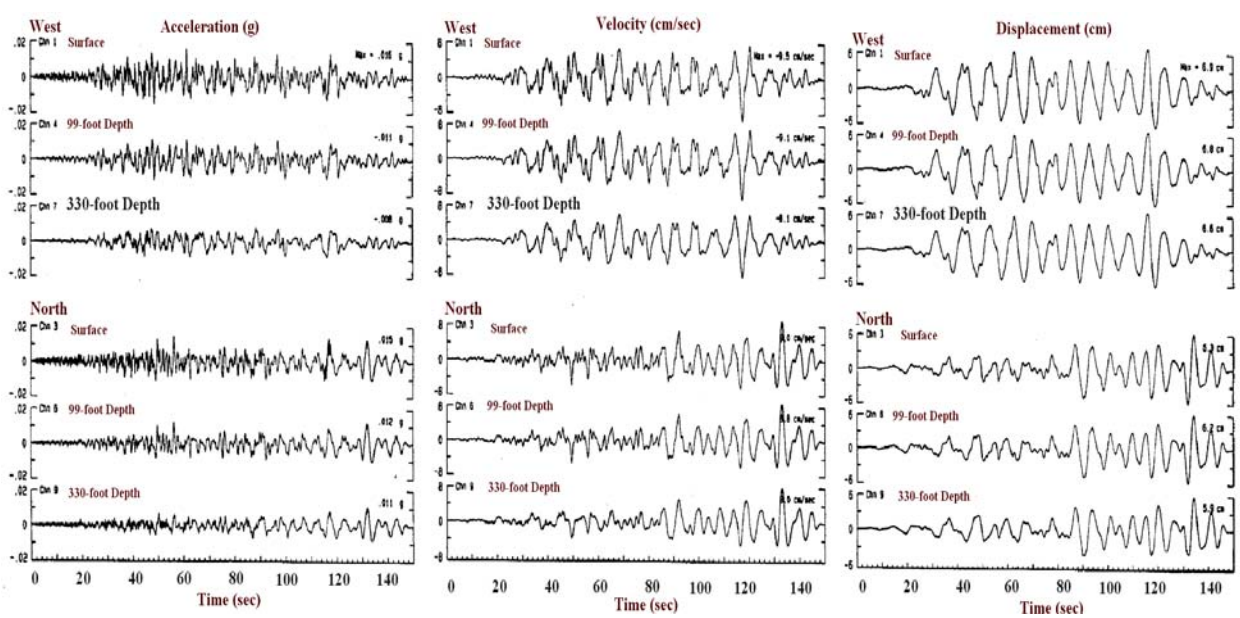


Figure 7. Acceleration, velocity and displacement recorded at the El Centro array during the M7.1 Hector Mine earthquake, at the surface and depths of 30, and 100 m. The maximum displacement is about 7 cm, at all depths.

Summary

An important set of downhole geotechnical arrays has been instrumented at several locations. Data recorded at the downhole arrays so far represents mostly low amplitude motions (except for one record of almost 0.5 g obtained at La Cienega array), 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: La Cienega in Los Angeles, Vincent Thomas Bridge (East and West ends) near Long Beach, and Meloland in El Centro. These geotechnical arrays were instrumented by Caltrans/CDMG, and 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 displacement 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.

Seismic response of the alluvium geologic structure to the small earthquake was successfully modeled using Shake91 program. The shear wave velocity model with average velocities corresponding to different geologic layers (Gibbs et al., 1996) and uniform density was chosen.

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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