2. INVENTORY OF OPERATING AND PLANNED GEOTECHNICAL MONITORING SITES

2.1 CSMIP INSTRUMENTED GEOTECHNICAL ARRAYS

A. F. SHAKAL
P. HIPLEY
V. GRAZIER
California Geological Survey

INTRODUCTION

Data recorded by vertical subsurface (downhole) arrays with sensors installed at different depths in different geologic layers provide critical information for understanding the effects of local geologic conditions on strong motion at the surface. The California Strong Motion Instrumentation Program (CSMIP) in the California Geological Survey began instrumenting boreholes with strong-motion accelerometers in 1989. Since then CSMIP has been working with the California Department of Transportation (Caltrans) and other partners placing strong motion sensors at downhole arrays.

Twenty downhole arrays have been instrumented by CSMIP throughout the state, as of October 2004. More downhole arrays in various stages of completion will come online soon. Fourteen of the arrays were instrumented with the support, cooperation and assistance of the Caltrans. The others were installed with support of the National Science Foundation (NSF), Electric Power Research Institute (EPRI), U.S. Geological Survey (USGS), and University of California, Santa Barbara (UCSB). Nine of the arrays are located in Northern California and eleven are located in Southern California.

The downhole arrays are located in a variety of geologic structures ranging from deep soft soil (e.g., La Cienega, El Centro and Eureka) to fill and alluvium over rock (e.g., Treasure Island and San Francisco). The Treasure Island and El Centro geotechnical arrays are installed in areas that experienced liquefaction, during the Loma Prieta 1989 and the Imperial Valley 1979 earthquakes, respectively. More than 80 low amplitude recordings from earthquakes with $2.4<M<7.1$ have been recorded at these arrays. Analysis of some recently recorded data is included in a companion paper by Graizer and Shakal [1].

Data recorded at the CSMIP instrumented downhole arrays are available through the CISN Engineering Data Center at http://www.quake.ca.gov/cisn-edc/.

INSTRUMENTED SUBSURFACE ARRAYS

The twenty arrays instrumented by CSMIP are detailed in Table 1. Each array has sensors located at from one to six depths. There is a triaxial accelerometer package installed at each listed depth. The twenty arrays include a total of 75 sensor packages, for a total of 225 sensor channels. The deepest array sensor is at a depth of 252 m (over 750 ft), in the La Cienega array in Los Angeles, a deep alluvial site. As reflected in Table 1, the deepest sensors for most arrays are typically much shallower.

Subsurface arrays instrumented in cooperation with Caltrans are installed near important bridges in different geologic areas of Southern and Northern California. Most of these arrays represent deep soft alluvium sites (except for the Tunitas Creek array near Half Moon Bay) with sensors located at depths from a few meters up to 250 m. The instrumented subsurface arrays allow studying the response of the geologic profiles near the bridges to different levels and types of seismic shaking. As reflected in Table 1, several of the arrays have a significant number of recordings already, and some data have been analyzed in terms of site amplification, analysis with Shake and wave propagation studies [2][3]

TREASURE ISLAND

One of the early downhole arrays instrumented by CSMIP is the Treasure Island array near San Francisco. This array has the greatest number of sensors in the CSMIP network, 21 sensors at 7 depths (surface, 7 m, 16 m, 31 m, 44 m, 104 m, and 122 m). The deepest two sensor packages are in rock. Besides the accelerometers there are several pore pressure sensors in the liquefiable layers, installed by T. Leslie Youd of the University of Utah, and monitored by Pedro de Alba of the University of New Hampshire and CSMIP. The array is the result of a multi-agency partnership, including the NSF, the EPRI, the USGS, the University of Utah, and the University of New Hampshire. The early records form this array showed the limitations of the original 12 and 16-bit instrumentation. All of the original recorders have been replaced by CSMIP with 19-bit recorders, and the data quality is remarkably better. The difference is an important lesson for downhole arrays.

In general, because subsurface motion are smaller, and sometimes much smaller, than the surface motion, recorders and configurations appropriate for surface instrumentation are much less effective recording subsurface motion. It is most effective to either use a recorder with higher resolution; a lower resolution recorder, could be used in conjunction with an amplifier to raise the signal levels (although this risks clipping, in the event of an earthquake with significant motion). Similarly, while 4*g* sensors may be an appropriate, conservative policy at the surface, to avoid exceeding the sensor capacity, using 2*g* sensors at subsurface depths seems more appropriate, and adequate.

LA CIENEGA DOWNHOLE ARRAY

To study the site response effect of a deep soil profile an array was installed near the Santa Monica freeway (I-10) at La Cienega Boulevard, 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. The site represents a deep soft soil geologic structure. Many earthquakes .have been recorded, with magnitude from 2 through 7.1 (Hector Mine). The largest acceleration yet

Table 1. CSMIP instrumented geotechnical arrays.

Station No.	Station Name	N.Lat, W. Long.	No. Depths (Sensors)	Sensor Depths (m)	Geology	Partner	No. of records
13186	Corona – I15/Hwy 91 Geotech Array	33.882 117.549	4 (12)	Surface, 8, 22, 42	Alluvium, rock	Caltrans	0
68206	Crockett – Carquinez Bridge Geotech Array #1	38.055 122.223	3 (9)	Surface, 46	Alluvium, rock	Caltrans	0
01794	El Centro - Meloland Geotechnical Array	32.773 115.447	4 (12)	Surface, 30, 100, 195	Deep alluvium	Caltrans	7
89734	Eureka - Geotechnical Array	40.819 124.165	5 (15)	Surface, 19, 33, 56, 136	Deep soft alluvium	Caltrans	10
58968	Foster City – San Mateo Bridge Geotech Array	37.573 122.263	4 (12)	Surface, 16, 22, 35	Alluvium, rock	Caltrans	1
58964	Half Moon Bay – Tunitas Geotech Array	37.360 122.395	4 (12)	Surface, 5, 12, 45	Alluvium, soft rock	Caltrans	1
58798	Hayward - San Mateo Br Geotech Array	37.617 122.153	5 (15)	Surface, 10, 23, 46, 91	Deep alluvium	Caltrans	1
24703	Los Angeles - La Cienega Geotech Array	34.036 118.378	4 (12)	Surface, 18, 100, 252	Deep soft alluvium	Caltrans	35
24400	Los Angeles – Obregon Park	34.037 118.178	2 (6)	Surface, 70	Alluvium, sandstone	UCSB	2
14785	Los Angeles - Vincent Thomas Geotech Array East	33.750 118.270	4 (12)	Surface, 18, 46, 91	Deep soft alluvium	Caltrans	0
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	2
36529	Parkfield - Turkey Flat #1	35.878 120.358	2 (6)	Surface, 24	Rock	CGS, Industry	7
36520	Parkfield - Turkey Flat #2	35.882 120.350	3 (9)	Surface, 10.7, 23.5	Alluvium, rock	CGS, Industry	6
68797	Rohnert Park – Hwy 101 Geotech Array	38.347 122.712	3 (9)	Surface, 10.7, 47	Alluvium	Caltrans	1
03192	San Diego – Coronado East Geotech Array	32.698 117.145	4 (12)	Surface, 13, 30, 91	Deep alluvium	Caltrans	2

Table 1: Continued

Station No.	Station Name	N.Lat, W. Long.	No. Depths (Sensors)	Sensor Depths (m)	Geology	Partner	No. of records
03193	San Diego – Coronado West Geotech Array	32.689 117.164	5 (15)	Surface, 12, 23, 42, 103	Deep alluvium	Caltrans	2
58961	San Francisco – Bay Bridge Geotech. Array	37.787 122.388	3 (9)	Surface, 14, 40	Fill, Alluvium, rock	Caltrans	2
58700	San Francisco - Golden Gate Bridge	37.818 122.477	1 (3)	152	Rock	Golden Gate Bridge District	2
24764	Tarzana - Cedar Hill B	34.160 118.534	2 (6)	Surface, 60	Soft rock	ROS-RINE	25
58642	Treasure Island - Geotechnical Array	37.825 122.373	7 (21)	Surface, 7, 16, 31, 44, 104, 122	Fill, alluvium, rock	NSF	11

recorded in CSMIP vertical arrays was recorded here, 0.49*g*, in a local earthquake. A plan view of the array layout is shown in Figure 1.

VINCENT THOMAS DOWNHOLE ARRAYS

Downhole arrays were instrumented at the east and west ends of the Vincent Thomas suspension bridge near Long Beach. These array sites 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. As an example, Figure 2 shows the location of the east array. The example is used to underscore that some arrays near important structures, such as major bridges, are uncomfortably close the structure, and motions can be influenced by the motion of the structure itself. This effect should decrease with depth, so the deepest sensors should be in many cases relative closely reflect the actual input. The practical aspects of property ownership, right-of-way, and use of the area by maintenance crews put practical, and sometimes significant, limits on where the array can.

EL CENTRO DOWNHOLE ARRAY

A downhole array (surface and two depths) was installed near El Centro, at the Meloland Road Overpass on Interstate 8. 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 [4]. P-wave and S-wave velocity surveys of the drilled borehole were performed by Caltrans. Although no significant records have yet been obtained, this area, like Treasure Island, is a potentially liquefiable site and of particular interest.

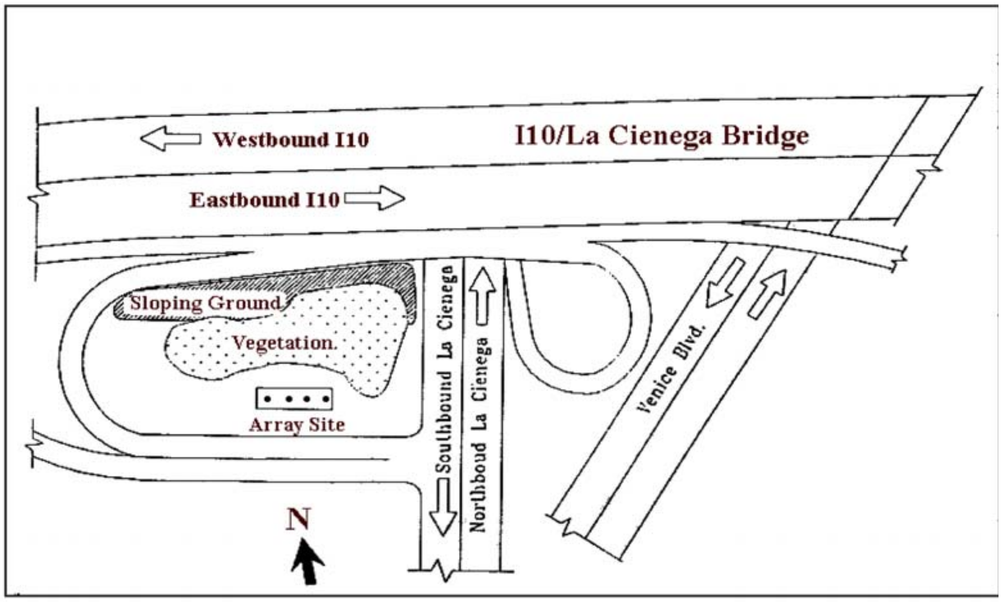

Figure 1. Plan view of the La Cienega strong motion array at near the La Cienega Boulevard intersection with Interstate 10 in Los Angeles. The array has accelerometers at the surface and at depths of 18 m, 100 m, and 252 m.

FUTURE PLANS

It is expected that future deployments will follow the most recent approaches. Caltrans has a clear need to understand the ground shaking input to bridges, especially in areas of soft soil and/or strongly changing geology. The appropriate different inputs to various points of an extended structure like a major toll bridge can only be obtained by multiple measurements. The new San Francisco Oakland Bay Bridge has important vertical arrays planned. The Golden Gate Bridge has an additional downhole array underway at the north end of the bridge. After a long evolutionary process of continual improvement of fielding techniques, the present approach is quite effective and major changes are not expected on that front. Some of the most difficult and expensive verticals are the deepest; we do not expect many more arrays with the depth of La Cienega, 252 m (nearly 800 ft), except in special situations.

INSTRUMENTATION OBJECTIVES AND TECHNIQUES

The primary goal of downhole strong motion instrumentation is obtaining quality recordings of *in situ* strong motion at depth. In the CSMIP approach, this entails several subsidiary goals, as discussed in Shakal and Peterson [5].

Seismic Transparency

A subsurface sensor/instrument package should move with the medium it is embedded in, in a transparent way. The total sensing unit should not be more rigid than the surrounding medium, to effectively move with it. In addition, the sensor package should not, due to loose component rattling during strong shaking, add noise to the signal.

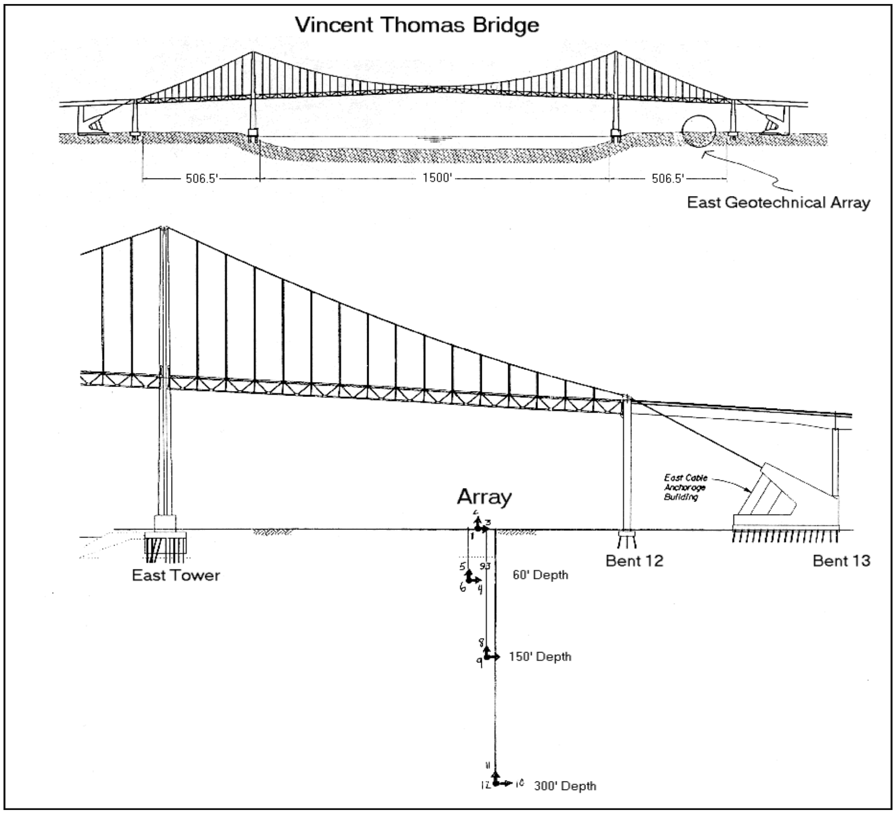

Figure 2. Schematic layout of the geotechnical array at the east end of the Vincent Thomas Bridge near Long Beach. To address issues such as right-of-way, community issues and property ownership, the array is deployed between the East Tower and Bent 12, in the longitudinal direction, and between the east and west bound roadways on the deck structure.

Orientation Control

The sensor orientation should be controllable, and known without the use of data recordings. Determining orientation through mathematical analysis of the data depends having confidence about the waves propagating past the emplacement at depth, and potential three-dimensional effects of the deep geologic structure. Although sometimes it may be unavoidable, the CSMIP approach generally determines and controls the orientation independent of the recorded data. Downhole electronic compasses have become available to measure orientation, which makes this goal easier to achieve. Finally, if the locking device includes a pin to control orientation relative to the casing, orientation repeatability is obtained.

Retrievability

On a very practical level, any deployed instrument will fail, the only variable being the time to failure. Improvement in technology ion the last ten years have significantly increased the time to failure, but it is still an important consideration, given the average time between occurrences of strong shaking at a site. It is not unusual for twenty years to pass between significant records from a strong motion recorder. An approach allowing the retrieval of a sensor for repair/replacement is a CSMIP design goal.

Repeatability

Because of the demonstrated high variability of subsurface motion, it seems important to control as much variability as possible. Once a sensor package ahs been retrieved and repaired, the redeployment should, if at all possible leave the instrument at the same depth in the hole, and oriented the same as during the previous period. Otherwise the data will have some new difference from the prior data, which may mask or interfere with signal variations form earthquake-to-earthquake, azimuth-to-azimuth, and so forth.

SUMMARY

The CSMIP has partnered with Caltrans and other institutions and agencies in the deployment of vertical arrays. The costs of drilling boreholes, casing them successfully, and grouting the annular space around the casing in a way that meets scientific objectives, as well as the regulations of the local water district of county health departments can be difficult. By partnering with agencies already drilling holes, an important part is taken care of, leaving CSMIP to focus on the instrumentation aspects. This also significantly reduces the total cost of vertical arrays for CSMIP. The partner agency also gains with the approach, since most or all of them do not maintain strong motion instrumentation as part of their normal activity.

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* . This allows relatively representative studies of linear response of the soil profiles.

One import lesson so far is that for large, distance events, vertical arrays indicate there is almost no near-surface amplification for velocity and displacement, that the displacement looks the same at 200-m depth as it does at the surface. This is reasonable form wavelength and wave propagation effects, but observing this is still surprise. This means of course, that for these events and long periods, Shake cannot be used to model the motion at a soil site using the motion and a nearby rock site. For large distance events, the motion is dominated by horizontally probating was, which may be surface waves and basin waves.

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