

# Strong Motion Instrumentation and Recent Data Recorded at Dams

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## Abstract

The measurement of strong motion has made significant advances in the last two decades. This paper reviews past and present instruments and techniques in strong-motion measurement, especially for dam instrumentation. Some of the most important recent strong-motion records obtained in California are reviewed for their impact in the earthquake instrumentation and response of dams.

This paper also considers current developments in instrumentation. Near-real-time strong-motion recording, which is an important emerging development that will see greater application in the future, is also reviewed.

## Introduction

The 25 years since the 1971 San Fernando earthquake have seen significant advances in strong-motion measurements. The California Strong Motion Instrumentation Program (CSMIP) in the Department of Conservation's Division of Mines and Geology, was started shortly after that earthquake. The program now has a total of 650 strong-motion stations throughout California. These stations include 350 free-field stations, 150 buildings, 35 bridges and 20 dams. The review and conclusions made in this paper are based on the experience and knowledge gained in the maintenance and expansion of this network.

## Overview of Strong Motion Instrumentation

Strong-motion recorders currently in wide use can be grouped in several categories:

1. Analog Accelerographs. Film-based analog strong-motion recorders (e.g., SMA, RFT) are functionally similar to, though much improved from, the first accelerographs developed in the 1930's. There are many of these instruments in the United States because they were the commonly available units when the number of instruments was significantly increased in the 1970's following the 1971 San Fernando earthquake. As a result, these instruments represent a

large part of the installed instrument base. Analog instruments share the following characteristics:

- Analog instruments are quite reliable, for the most part, and have low maintenance requirements. They require little power and will generally perform well despite receiving only infrequent maintenance (every 6 months or year).
- Records from analog instruments are expensive to utilize. The necessary digitization of the film records requires extensive work by skilled individuals with specialized equipment, if reliable results are to be obtained. Recent PC-based scanning methods have reduced the equipment costs, but still require skilled efforts.
- The recording range of analog instruments (nominally 1 g) has been exceeded by the shaking that occurred at locations within 20 km of several earthquakes in the last ten years. There is no practical method to increase the recording range.
- Triggering is generally caused by the vertical motion in analog instruments. The vertical component is usually the smallest, and if a vertical trigger is set to turn on the instrument at 1% g, ground shaking may occur with as much as 5% g on the horizontal without being recorded. In addition, the complete ground shaking, including the P-wave arrival before the trigger, cannot be recorded by analog instruments.

In regions of low likelihood of shaking, where few records are expected in the lifetime of an instrument, it can be argued that analog instruments still represent a good investment of resources, although rapid use of the data is not possible.

2. Early Digital Accelerographs. The first digital accelerographs were introduced in the late 1970's and record data on magnetic tape. Unlike the analog film recorders, good arguments can be made for replacing existing instruments of this type. For these instruments:
  - High maintenance requirements are necessary to achieve adequate reliability.
  - Using the data recorded on digital tape media requires unique equipment and highly skilled efforts which can be comparable in difficulty to digitizing a film record.
3. Intermediate Digital Accelerographs. The solid-state digital recorders introduced in the 1980's were the first instruments to approach analog instruments in performance and reliability. Although these instruments have

some minor problems with inadequate signal filtering and susceptibility to electrostatic discharge (ESD) and radio frequency interference (RFI), they generally have adequate performance. These instruments are now comparable in cost to film recorders. However, their power consumption is much higher than the analog units so they are not as easy to deploy at dams or other remote sites without AC power. These instruments are generally 12-bit, so they have a dynamic range of 72 dB (i.e., resolution of 1 part in 4,000). This is a significant advance over the film recorders, which typically have a dynamic range of about 55 dB (resolution of 1 part in 500).

4. **Modern High-Resolution Digital Accelerographs.** In the last few years high-resolution digital accelerographs have become available. These units have a resolution of one part in 64,000 (96 dB), since they record with 16 bits. These units have been dropping in cost, and are now comparable in cost to the early 12-bit units, but they typically require significantly more power. Because of their high resolution, they are even useful in some traditional seismology applications. Also, because of the dynamic range, previously unobservable problems with sensors become recordable and potentially problematic.

**Strong-Motion Sensors.** The standard sensor used in strong-motion instrumentation, the force balance accelerometer (FBA), has seen wide application in conventional, above-ground deployments. Measuring acceleration or other parameters at depth has proven to be more difficult. However, measuring acceleration at depth can presently be done with much more reliability than 10 years ago. Sensors are now more reliable, and techniques to deploy accelerometers at depth and lock them in location while still allowing recovery for servicing have been developed (e.g., Shakal and Petersen, 1992). These approaches also focus on minimizing the effects of the deployment and locking devices on the recorded data.

In contrast to acceleration, the measurement of subsurface pore pressure remains more difficult. New techniques have been employed at Treasure Island near San Francisco, which is one of the National Geotechnical Test Sites (Benoit and de Alba, 1988). Eight downhole pore-pressure sensors are being recorded at the site, in cooperation with L. Youd, P. de Alba and others. Economical pore pressure sensors with long-term reliability, or a means to retrieve the units for repair, are in a state of advance and development.

**Other Sensors.** New sensor technology has been introduced in recent years:

- **New-technology Accelerometers.** New acceleration sensors have been developed in recent years partly because of the need to sense the deceleration which triggers vehicle air bags. These hold promise for reducing seismic sensor costs because of the economies of volume. Several technologies are being pursued, but these units do not yet have performance comparable to that used in strong motion. Of course, since the cost of sensors is only a small

fraction of the cost of a typical record, which includes the costs of years of maintenance as well as the initial costs of the recorder and its sensors, the sensor economy will not cause a proportional reduction in total costs.

- **Relative-Displacement Sensors.** The determination of actual ground displacements has long been a goal in strong motion. The recent use of relative displacement sensors is a step in that direction. Although these sensors can only measure the relative displacement between two nearby points, the sensors are approaching the reliability levels required in strong motion. In some cases knowing the relative displacement between two points is more important than knowing the absolute displacement of either point.

**Record Timing.** Recording the time with an accelerogram has become increasingly common in recent years. Time facilitates the association of a recording with an earthquake and increases the value of the data. The classic approach is to record the WWVB radio time signal. A special internal clock has also been used, when WWVB can not be received well or when drift is not very important. The recently available timing signal from the Global Positioning System (GPS) has better reliability of reception, and the cost of GPS receivers has recently become comparable with other methods of timing, making GPS a better option in many cases.

**Event Response,** a new utilization of strong-motion data. The value of strong-motion data is no longer limited to design verification and improvement. The use of strong-motion data to guide emergency response is a new expansion of its value which increases the usefulness of the investment on an immediate basis. This in turn can make the investment more attractive to an agency or jurisdiction. For this application the accelerograph needs to have a near-real-time capability, discussed further below.

**Summary.** From the above overview, it can be seen that new strong-motion deployments should incorporate digital instruments, of at least moderate resolution (12-16 bit), have GPS timing (if any), use tested and reliable sensors, and have a viable long-term commitment to maintenance and data recovery.

### **Recent Strong-Motion Data from Dams**

Many dams were subjected to strong ground shaking during the Northridge earthquake of January 17, 1994. Table 1 lists the maximum accelerations recorded at 10 dams within 55 km of the epicenter. Although the epicentral distance is listed, the location of the dam relative to the rupturing fault is more important in affecting the intensity of shaking. In addition to the dam structure, the outlet towers at the Castaic Reservoir and the Los Angeles Reservoir were also instrumented and recorded a maximum horizontal acceleration of 0.83 g and 1.34 g, respectively. Processed data (acceleration, velocity and displacement) and spectra (response and Fourier) are available for many of these dams (e.g., Darragh et al., 1994; Lindvall Richter Benuska, 1994).

TABLE 1 - Strong-Motion Data from Dams - Northridge Earthquake

<u>Name of Dam</u>	<u>Agency Station No.</u>	<u>Structure Type</u>	<u>Epicentral Dist.(km)</u>	<u>Component</u>	<u>Max. Acceleration</u>	
					<u>Ground</u> <u>(g)</u>	<u>Crest</u> <u>(g)</u>
Los Angeles Reservoir Los Angeles Dam and Dike	LADWP	Earth dam* (15 sensors)	11	64	0.32	0.56
				Up	0.13	0.39
				154	0.28	0.43
Pacoima Reservoir Pacoima Dam	CSMIP 24207	Concrete arch dam (23 sensors)	19	360	0.54	1.76
				Up	0.43	>1.60
				270	0.49	2.01
Wood Ranch Reservoir Main Dam and Dikes	CSMIP 24251	Earth dam (12 sensors)	26	335	---	0.28
				Up	---	0.18
				245	---	0.39
Lake Piru Santa Felicia Dam	CSMIP 24280	Earth dam (6 sensors)	34	265	0.21	0.27
				Up	0.13	0.13
				175	0.27	0.30
Castaic Lake Castaic Dam	DWR	Earth dam* (9 sensors)	35	Long	0.23	0.35
				Up	0.20	0.24
				Tran	0.21	0.24
Castaic Lake Elderberry Dam	LADWP	Earth dam (6 sensors)	40	349	0.36	0.25
				Up	0.14	0.19
				79	0.35	0.45
Garvey Reservoir	USGS	Earth dam (6 sensors)	43	114	0.14	0.16
				Up	0.07	0.08
				24	0.12	0.18
Whittier Narrows Dam	USGS	Earth dam (6 sensors)	49	180	0.22	0.19
				Up	0.08	0.07
				270	0.15	0.21
Cogswell Reservoir Cogswell Dam	CSMIP 23210	Rock fill dam (9 sensors)	53	155	0.15	0.32
				Up	0.07	0.28
				65	0.11	0.35
Palos Verdes Reservoir	USGS	Earth dam (6 sensors)	53	210	0.15	0.12
				Up	0.10	0.07
				120	0.12	0.15

\* Outlet tower, not part of the dam structure, was also instrumented but the peak acceleration values are not listed.

The Pacoima Dam, a concrete arch structure northeast of San Fernando, had the most intense shaking of these dams during the Northridge earthquake. The instrumentation recorded very high accelerations, with peaks exceeding 2 g, which is above the instrument capacity and higher than would have been expected. Several aspects are unique for the dam: 1) the site was close to the fault, 2) the dam is a concrete arch structure with contraction joints, 3) the earthquake mechanism was thrust faulting, and 4) the site is on the upthrown block. Several cable runs in the instrumentation system were damaged by falling rocks during the strongest shaking, but fortunately adequate-length records were obtained before the damage occurred. One of the key lessons from the Northridge earthquake is that old instrumentation systems on some structures need to be upgraded if they are to adequately record strong shaking.

As shown in Figure 1, the upper left abutment instrument recorded accelerations of 1.47 g and 1.70 g on the horizontal components, and 1.36 g on the vertical component. Processing of this record presents several challenges. In general, the high amplitudes and the number of trace crossing make the record difficult to digitize and require careful attention to obtain the peak value. In addition, the base line shift in the record can only be corrected after special analyses (Shakal et al., 1994). Analysis of the record indicates that the site tilted about 3° to the northeast (downslope) during the earthquake. This is obtained by subtracting a simple tilt function determined from the record. The 3° is independently confirmed by level measurements at the site. The concrete pier to which the instrument is bolted appears to be well connected to the rock ridge, and there is no relative displacement apparent between the pier and the rock. In contrast to the pier, the gunite and thin concrete on the rock nearby broke up and shifted. Of course, the purpose of the accelerometers at the site is to measure the strong shaking during earthquakes. Special sensors such as tiltmeters should be deployed with the accelerometers if permanent tilt is important.

A profile of the acceleration transverse to the dam crest at the upper left abutment, at a point on the face of the dam at 80% of the dam height, at the dam base and at the downstream site is shown in Figure 2. The velocity records are also shown in the figure. It can be seen from the figure that the motion at the downstream site, a hard rock site in a steep canyon, and the dam base are quite similar. The motion at the dam structure and the upper left abutment are much larger, due to the response of the dam structure, the topographic amplification at the abutment, and the interaction between the dam and the thrust block.

Another feature of the response of the Pacoima Dam is the opening of the contraction joints in the concrete structure. Post-earthquake inspection showed that some of the 11 contraction joints had opened and closed during the earthquake. The joint between the arch and the thrust block on the left abutment was open about 2 inches after earthquake.

It may be expected that the opening and closing of the contraction joints during the strong shaking generated high-frequency spikes in the acceleration records. As a comparison, spikes have also been observed in bridge records. One example is in the

Pacoima Reservoir - Pacoima Dam  
(CSMIP Station No. 24207)

SENSOR LOCATIONS

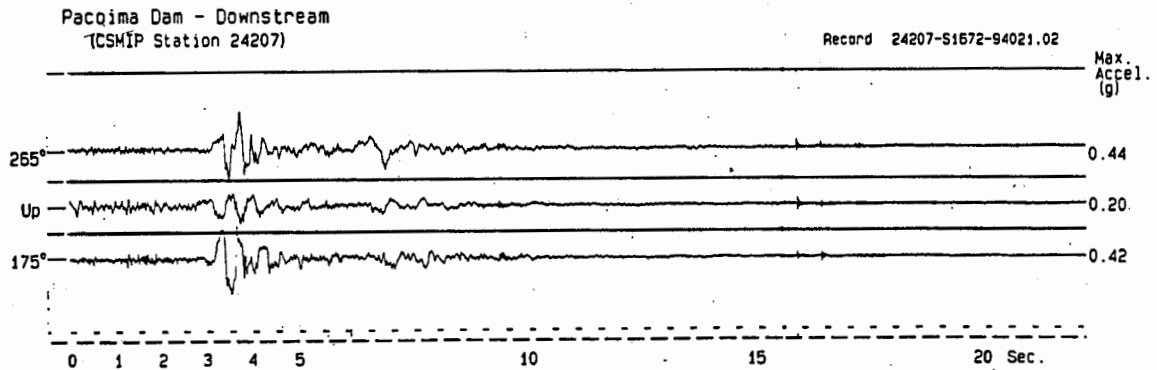
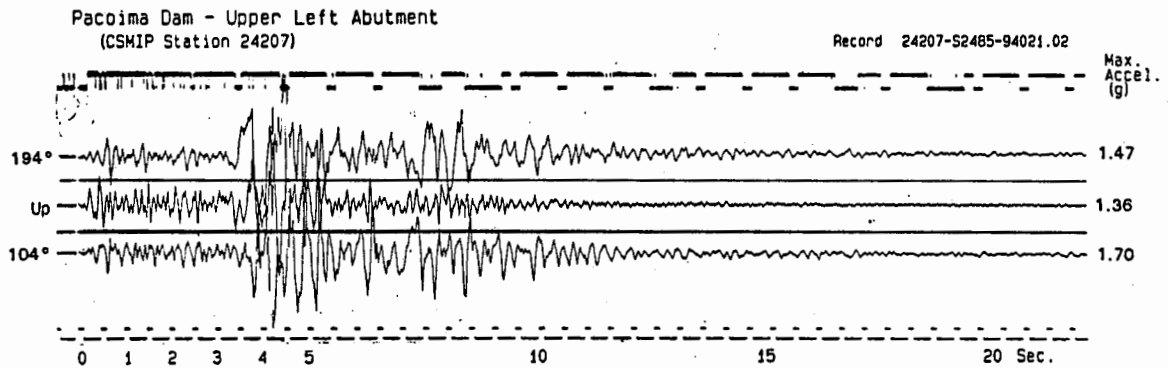
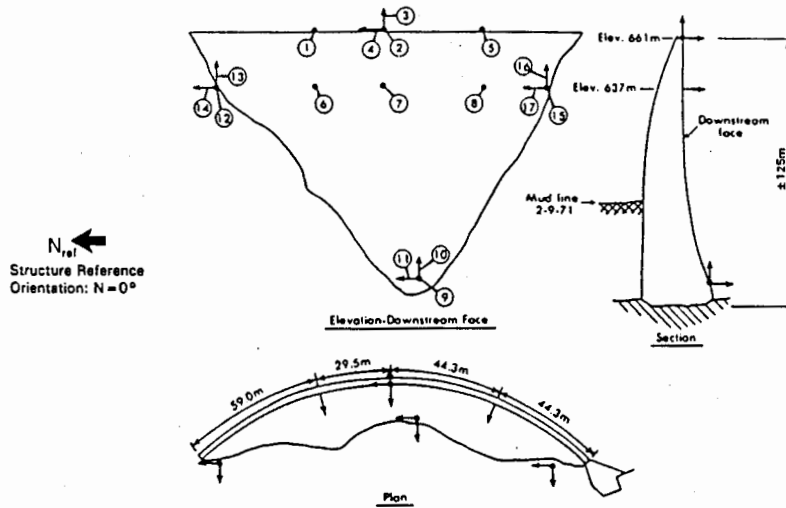
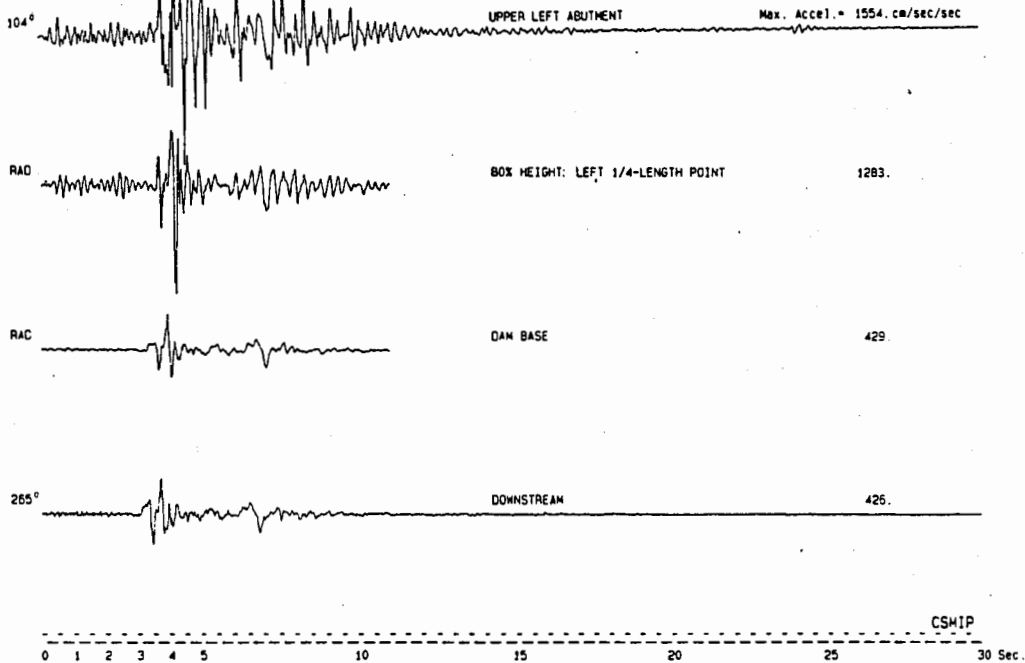


Fig. 1. Sensor locations for the Pacoima Dam and acceleration records from the Pacoima Dam upper left abutment site and the downstream site in the narrow canyon below the dam. The records show dramatic differences in acceleration amplitudes and waveforms.

NORTHRIDGE EARTHQUAKE JANUARY 17, 1994 04:31 PST  
 PACOIMA DAM

INSTRUMENT-CORRECTED AND BANDPASS-FILTERED ACCELERATION

FILTER BAND: .08-.16 TO 23.0-25.0 HZ. 24207-S1672-94021.02 061794.0922-QN94A207



INSTRUMENT-CORRECTED AND BANDPASS-FILTERED VELOCITY

FILTER BAND: .08-.16 TO 23.0-25.0 HZ. 24207-S1672-94021.02 061794.0922-QN94A207

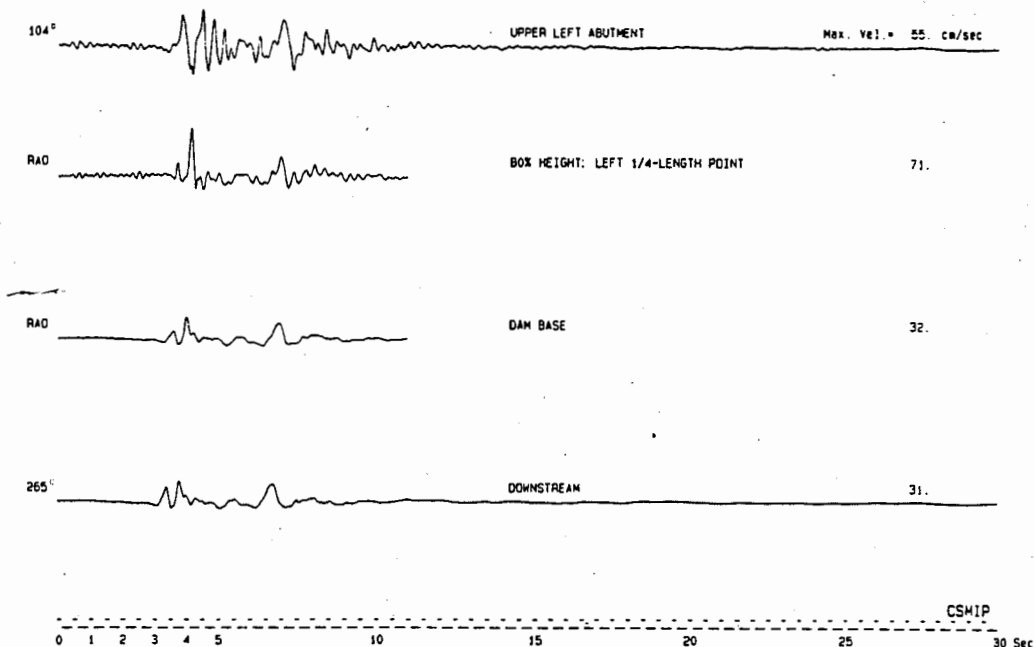


Fig. 2. Accelerations and velocities in the radial direction at the Pacoima Dam upper left abutment, 80% height, the dam base and the downstream for the Northridge earthquake.



data from the Interstate 10/Interstate 215 interchange bridge near San Bernardino. This is a multiple-span, 2540-foot concrete box-girder bridge instrumented with 34 accelerometers by CSMIP in cooperation with the California Department of Transportation. A striking aspect of the response is the presence of sharp spikes in nearly all of the acceleration records from sensors near the separation joints in the concrete structure (Huang and Shakal, 1994). Figure 3 shows the accelerations recorded by four sensors at a joint during the 1992 Landers earthquake. Spikes as high as 0.7 g are noticeable. Analysis of these records indicates that the spikes were caused by the forces generated at separation joints by impacts between adjacent bridge segments and the forces of impacts are directly proportional to the size of the spikes, and can be estimated by using a simple formula (Malhotra et al., 1995). In recent bridge instrumentation, CSMIP has begun using 4 g accelerometers to measure potential large spikes and relative displacement sensors to supplement the accelerometers at the joints.

### Near-Real-Time Strong-Motion Record Recovery

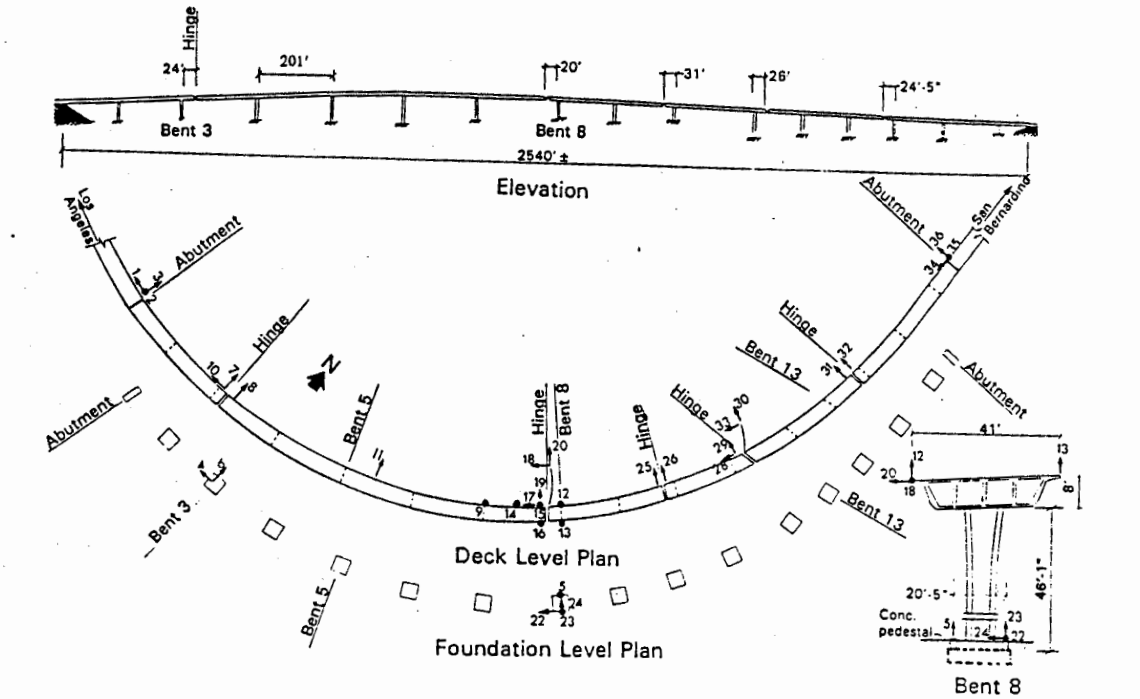
Recent developments in accelerographs and communication technology have made possible significant advances in the monitoring and timely reporting of earthquake strong motion. CSMIP has developed and implemented an economical system for near-real-time data recovery from strong-motion stations in its network. The near-real-time system uses non-dedicated dial-up communication links from stations at remote sites to central monitoring personal computers (PCs) in Sacramento, using cellular and conventional phone lines.

The 5.0  $M_L$  Northridge aftershock that occurred on June 26, 1995 was the first earthquake recorded by a significant number of CSMIP near-real-time stations. Within minutes after the event, accelerograms from 13 stations were automatically transmitted and processed. The first record was recovered and processed within 3 minutes after the earthquake. Staff were alerted by pager messages containing peak acceleration, velocity and displacement and response spectrum levels at key periods. Record recovery and processing for all 13 strong-motion stations was completed within about 30 minutes after the event, which occurred during the night.

The CSMIP strong-motion monitoring system (described more fully in Shakal et al., 1995) uses standard digital accelerographs at field stations throughout the State. These stations transmit data via high-speed dial-out communication links to Sacramento using conventional phone lines. Cellular phone links are used at remote strong-motion stations without land-line phone service. The ancillary equipment at the station consists of a high-speed modem and logic controls. The equipment at Sacramento includes a bank of standard PCs attached to modems and running monitoring code. The CSMIP system is illustrated schematically in Figure 4.

At the onset of strong shaking (P-wave arrival) at a station, the field instrument system establishes a telephone connection with the central monitoring system in Sacramento (i.e., the unit at the site performs the equivalent of taking the phone off

San Bernardino - I10/215 Interchange  
 (CSMIP Station No. 23631) **SENSOR LOCATIONS**



**Longitudinal Direction**



**Transverse Direction**

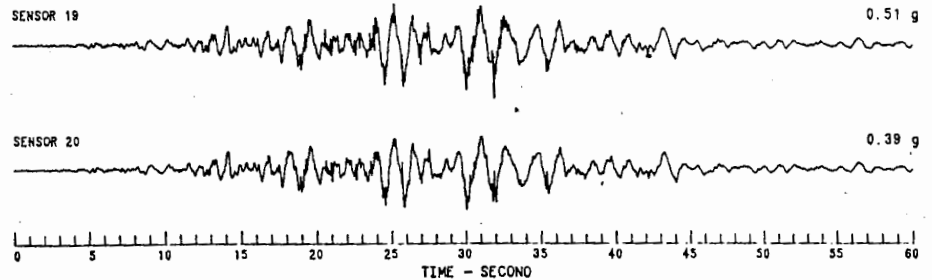


Fig. 3. Plan and elevation views of the I10/215 interchange bridge near San Bernardino and acceleration records from sensors at the hinge near Bent 8 during the 1992 Landers earthquake. Spikes are noticeable.

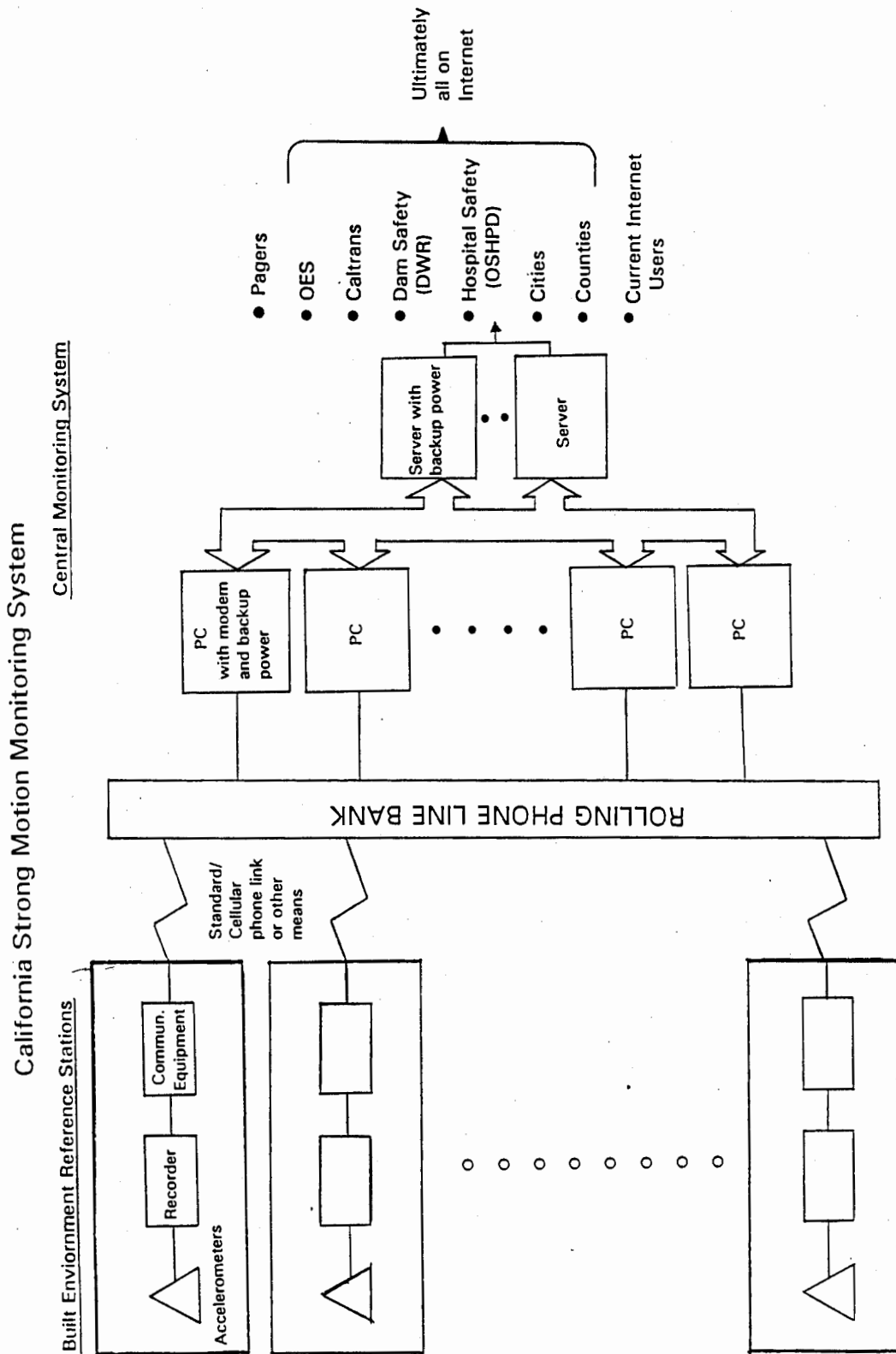


Fig. 4. Schematic of the CSMIP near-real-time strong motion monitoring system.

the hook and dialing a number). This ensures that a connection is established before the phone system is compromised or saturated with calls. The central monitoring system has a rolling phone line bank with the lines connected to a series of PCs with modems and backup power. When a field station calls in, the next available PC answers the call and begins to interrogate the instrument. The PC directs the instrument to identify itself and transmit a compressed file of the recorded accelerogram. Once the accelerogram has been transmitted, which may take 30-60 seconds, the PC releases the field instrument to return to monitoring strong motion at the site. The PC then begins automatic processing of the data, discussed further below. If the field instrument is unsuccessful in getting one of the PCs to answer because they are all busy or for some other reason, it tries again repeatedly after certain randomized delays. Some of the key logic components are also used in a similar system developed by the Bureau of Reclamation in Denver for strong-motion instruments located at federal dams (Viksne et al., 1995).

The design of the CSMIP monitoring system incorporates redundancy, in that the PCs function in parallel and independently, and each operates with uninterruptible power systems (UPS) for backup power. This design also allows the recovery and processing of the shaking data from multiple stations to occur simultaneously. The entire system is scalable, and as the number of field instruments increases the central monitoring system is easily expanded by the proportional addition of more PCs.

The communication links being used in this project already existed at many of the recently-installed CSMIP stations. The phone lines were in use because of their value in communicating with the stations for maintenance activities. This approach yields reduced maintenance costs through more targeted maintenance work and higher overall instrument performance levels.

Near-real-time strong ground motion data is now available from 65 CSMIP stations in California. The distribution of CSMIP stations and near-real-time stations are shown in Figure 5 for northern California.

As an example of output of the automated system, Figures 6 and 7 show standard time history and spectra output plots for a record recovered and processed by the near-real-time system. The data are from the magnitude 5 earthquake that occurred about 25 km east of Palm Springs at 4:04 am on May 7, 1995. Three CSMIP near-real-time stations recorded this event and the data from these stations were transmitted and processed within about 8 minutes after the occurrence of the earthquake. This time includes the delay for one of the remote field station which has a cellular phone connection running at a much slower baud rate than conventional phone connections.

Figure 6 shows the record recovered from the Desert Hot Springs station, approximately 22 km west of the epicenter. It shows the three components of band-passed acceleration, velocity and displacement. The plotting scale is approximately 1 cm/second, like that of classic analog accelerographs, to expedite the interpretation for individuals accustomed to working with accelerograms. For the same reason, the

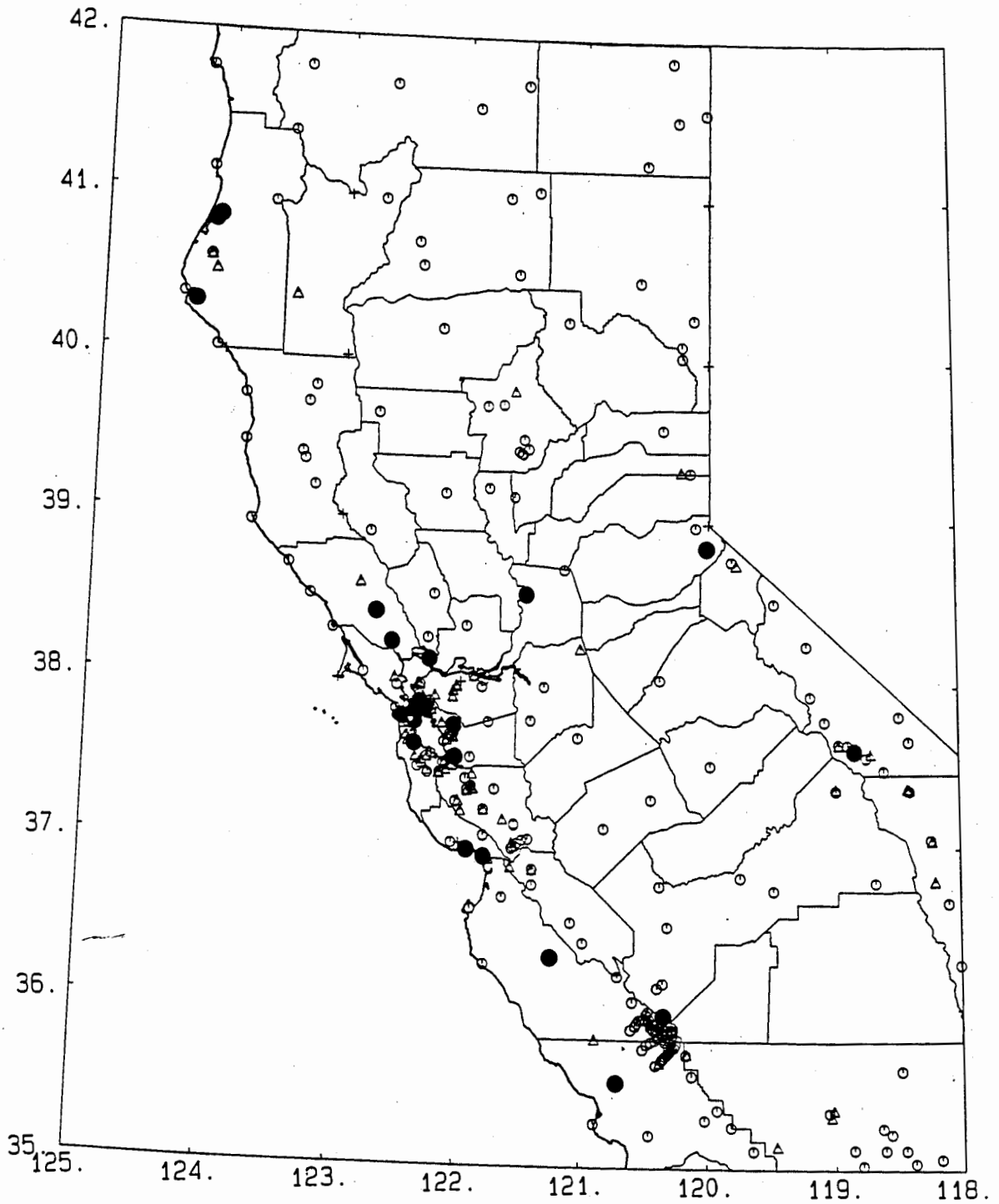


Fig. 5. CSMIP stations in northern California. Stations in the near-real-time network are shown as closed circles. Open circles and triangles are CSMIP ground-response and structure-response stations, respectively.

Earthquake of Sun May 7, 1995 04:03 PDT  
 Desert Hot Springs - Fire Station Sta No. 12149  
 Frequency Band Processed: 5.0 secs to 46.0 Hz  
 - CSMIP AUTOMATED STRONG MOTION PROCESSING -

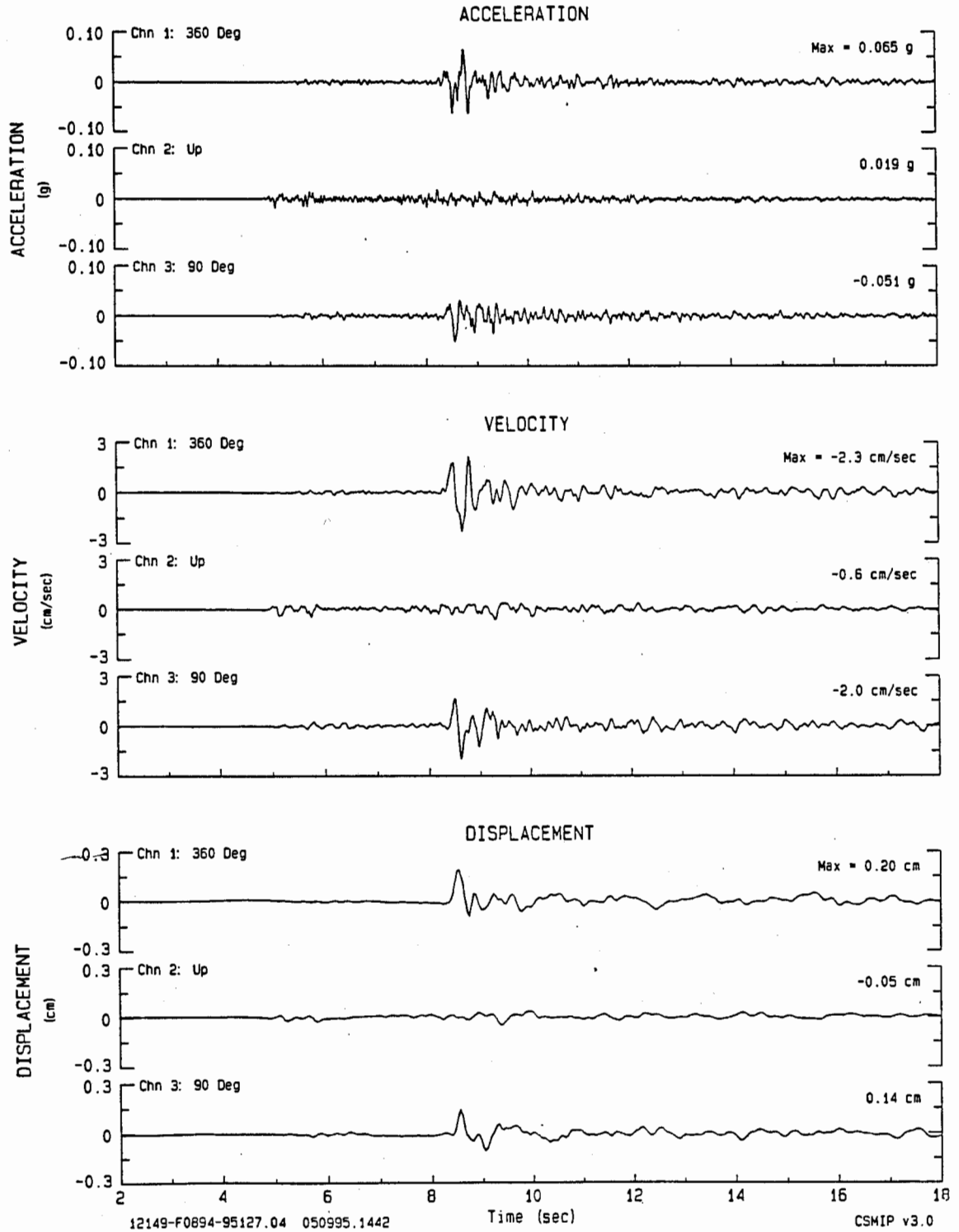


Fig. 6. Three components of band-passed acceleration, velocity and displacement at Desert Hot Springs for the magnitude 5 earthquake of May 7, 1995.

channels are all plotted with the same vertical scale. The peak ground motions at this station are 0.065 g, 2.3 cm/sec and 0.20 cm. The response and Fourier spectra are also calculated automatically, and the response spectra for 5% damping are shown in Figure 7. Spectral acceleration is plotted up to a period of 4 seconds, and design curves from the Uniform Building Code (ICBO, 1994) are plotted for convenient comparison.

Benefits. Near-real-time recovery adds a significant new dimension to strong-motion data. Rapid availability provides important benefits without reducing the value of the data in longterm design verification and improvement. Near-real-time recovery can guide earthquake response by providing shaking data rapidly to emergency responders, safety officials and engineers. The response spectra can be useful for dam engineers for comparison with design forces and in determining whether an inspection of the dam is needed following an earthquake. Post-earthquake information can, for the first time, contain knowledge of the strong shaking amplitudes rather than being limited to the magnitude and location of the event.

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Earthquake of Sun May 7, 1995 04:03 PDT  
 Desert Hot Springs - Fire Station Sta No. 12149  
 Frequency Band Processed: 5.0 secs to 46.0 Hz

SPECTRAL ACCELERATION,  $S_a(T)$

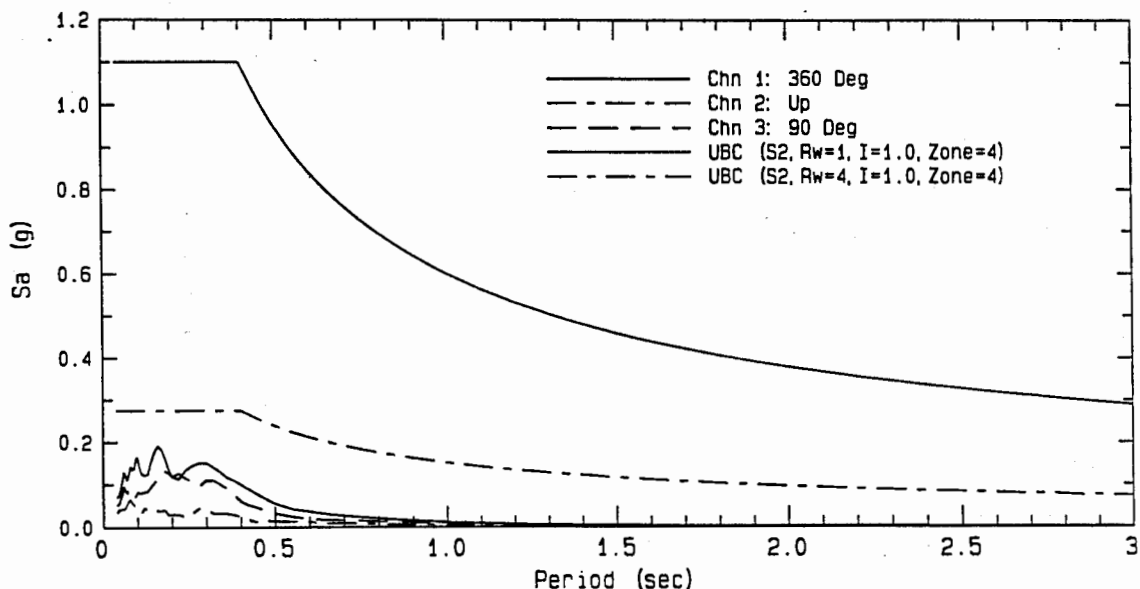


Fig. 7. Three components of spectral acceleration (5% damping) at Desert Hot Springs for the magnitude 5 earthquake of May 7, 1995. Design curves ( $R_w=1$  and 4, for an S2 site in Zone 4) from the Uniform Building Code are plotted for convenient comparison.

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# *Earthquake Engineering for Dams*



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*Association of State Dam Safety Officials*

*April 11-12, 1996  
Red Lion Hotel  
Sacramento, California*

## **PROCEEDINGS**