CSMIP NEAR-REAL-TIME STRONG MOTION MONITORING SYSTEM: RAPID DATA RECOVERY AND PROCESSING FOR EVENT RESPONSE

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ABSTRACT

Recent developments in accelerographic instruments and communication technology have made possible significant advances in the monitoring and reporting of earthquake strong motion. The California Strong Motion Instrumentation Program (CSMIP) has developed and implemented an economical system for near-real-time data recovery from strong-motion stations in its network. The system can guide earthquake response and provide shaking data rapidly to emergency responders, engineers and seismologists. The system has extensive redundancy and can be easily expanded as more stations are added. The data recovered are automatically processed to produce the ground motion parameters most useful for engineering assessment of the earthquake impact. Distribution channels for the rapid strong-motion information continue to be developed and will include local and state emergency response officials as well as earthquake seismology and engineering agencies.

INTRODUCTION

During the minutes and hours after a strong earthquake in California, little information has been available on the levels of shaking that occurred. The traditional seismic monitoring networks (weak motion) have developed capabilities over the last five years that allow rapid determination of the earthquake epicenter and magnitude and rapid distribution of that information (e.g., Caltech USGS Broadcast of Earthquakes (CUBE) and the Rapid Earthquake Data Integration (REDI) system). However these networks are mostly comprised of instruments designed to record the thousands of small to moderate earthquakes that occur every year in California. These instruments can provide only limited information on large earthquakes because the shaking exceeds their measuring range.

In contrast, strong-motion networks do accurately measure the strong shaking, using instruments specialized for recording the strongest motions. However, these instruments were originally designed to provide data for strong-motion research, and not designed to provide the data they record quickly. As a result of these two aspects, very little strong shaking information has been available after an earthquake in a time frame useful to guide emergency response activities.

An example from the 1994 Northridge earthquake dramatizes the problem. The Santa Monica area was shaken with unexpected severity relative to neighboring areas. Yet this was not widely known for some time, since most attention was focused on the epicentral area and the San Fernando Valley. The strong-motion instrument on the grounds of the Santa Monica City Hall did accurately record the severe shaking. However, the data from that analog instrument could not be recovered and provided to regional and state officials for several days.

The 1989 Loma Prieta earthquake provided another example. The Santa Cruz and Watsonville areas were heavily damaged during the event, but that was not known for several hours because the focus was on the San Francisco Bay area. Oakland was more heavily shaken than could have been expected, while in contrast, San Jose, closer to the event, was shaken less. These shaking levels were all recorded by strong-motion instruments, but the data could not be provided in a timely enough manner to be useful in strategic coordination of the available response resources or in developing early earthquake damage estimates. With expansion of the system described here, the important information can be provided to emergency officials within a few minutes.

SEISMIC NETWORKS AND EARTHQUAKE DATA TIME SCALES

In order to clarify the difference between the system described here and the traditional seismic networks, some of their differences are highlighted. One aspect is the instrument type, as discussed below. Another key aspect is that seismic networks operate in real-time, while the strong-motion system described here operates in near-real-time. These two time scales are important to consider in post-earthquake data reporting.

Real-Time Real-time seismic data are available at a central location at the same time shaking at a field station occurs. This is data-as-it-happens, being recorded at a central site and available for processing. Real-time data requires a continuous, dedicated telemetry or other communication link from the station to the central site. Once data is available at the central site, the epicenter and magnitude can be quickly determined.

The development of techniques for rapid determination and dissemination of the location and magnitude of an earthquake was a significant improvement in seismic monitoring in California. The CUBE system initiated in 1990 in southern California was the pioneer project in this effort (Kanamori et al., 1993). In Northern California, the REDI system (Romanowicz, 1993), a joint project of UC Berkeley and the USGS, now parallels the CUBE capability.

CUBE and REDI rely primarily on the existing real-time weak-motion seismic monitoring networks in California. These instruments and networks were designed to detect and locate small events on fault systems in California. For large earthquakes these sensitive instruments are overdriven and can provide little information beyond duration. The instruments go off-scale because of their limited dynamic range, and their narrow frequency response means they do not measure the long-period motion of larger events well. These instruments are not poorly designed, rather they are well designed for their original function, monitoring the seismicity of California. Much of what is known about the seismicity and deep geologic structure of California comes from analyses of the recordings made by these instruments. These weak-motion instruments are monitored continuously, transferring the data in real time, to a central site in both the CUBE and REDI approaches. As a result, these systems can determine very rapidly the locations of the many small earthquakes that occur in California. Speed is the strength of a real-time system, and the potentially high ongoing cost of the dedicated communication link is its price.

Near-Real-Time Near-real-time strong-motion data is available at a central facility not at the same time the shaking happens, but within seconds to minutes after earthquake shaking begins at a field station. The strong-motion monitoring system discussed here uses non-dedicated telephone links to transmit data that are recorded. The short delay, required for the data to be communicated via a non-dedicated telephone link, allows a major reduction in the cost of the information without reducing its value for many applications (Shakal et al., 1995).

The occurrence of strong shaking at a given station is quite rare in California. It is common for a period of several years to elapse between recordings of more than a few percent g at most strong-motion stations. This infrequency of significant data makes the high cost of continuous real-time data telemetry a deterrent. In contrast, the economy of near-real-time data transmission makes that approach cost effective for most strong-motion applications. This approach is the primary focus of the system described here. Before the system is described, certain characteristics of strong-motion instruments are reviewed.

DEVELOPMENTS IN STRONG-MOTION INSTRUMENTS

Until the introduction of modern designs, strong-motion instruments had little application for near-real-time seismic monitoring. Traditional accelerographs are analog, photographic-film recorders and thus they can make no contribution to rapid data recovery. Modern accelerographs are digital and store the record in solid-state memory. These instruments record the strong motion and, with minor auxiliary equipment, can transmit the record to a central facility by modem and telephone line. These instruments are very useful in a near-real-time system, since information on peak acceleration and other key parameters can be available within a few minutes after the shaking occurs. The full, complete record can also be transmitted within a few minutes. This capability can be obtained with a small incremental upgrade to existing digital instruments.

The most modern high-end accelerographs have a dual capability. They can record strong motion, like a classic accelerograph, while at the same time providing an output data stream to a digital telemetry system for continuous seismic monitoring, like a traditional weak motion system. Stations with these instruments can play a dual role, both as part of a strong-motion network and a traditional seismic network and they revolutionize strong-motion/weak-motion monitoring in that aspect. However, these units have been more expensive and have not yet been integrated into the CSMIP system described here.

CSMIP NEAR-REAL-TIME STRONG-MOTION MONITORING SYSTEM

The CSMIP strong-motion monitoring system uses the 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 personal computers (PCs) attached to modems and running monitoring code. The CSMIP system is illustrated schematically in Figure 1.

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 (the unit at the site performs the equivalent of taking the phone off 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 was unsuccessful in getting one of the PCs to answer because they were all busy or for some other reason, it tries again repeatedly after certain 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 dams through the U.S. (Viksne et al., 1995)

The design of the CSMIP monitoring system incorporates redundancy, since 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. These 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 50 CSMIP stations in California. The distribution of CSMIP stations and near-real-time stations are shown in Figure 2 for northern California.

AUTOMATED DATA PROCESSING

When a central computer has requested and received an accelerogram file from a field instrument, it begins unattended automated processing. The processing proceeds through several steps, each with careful quality control checks. The file is first uncompressed and converted from binary counts to raw acceleration data. The acceleration data is next integrated and high-pass filtered in the frequency domain to calculate the velocity. The data is once again integrated and high-pass filtered in the frequency domain to yield the estimated displacement. In normal processing selection of the optimal filtered bandwidth is a careful and time consuming process (e.g., Darragh et al., 1995). In contrast, automated processing in the near-real-time system assumes a more limited central bandwidth of 5 seconds period to 46 Hz.
At the completion of processing, the system provides through pagers the peak

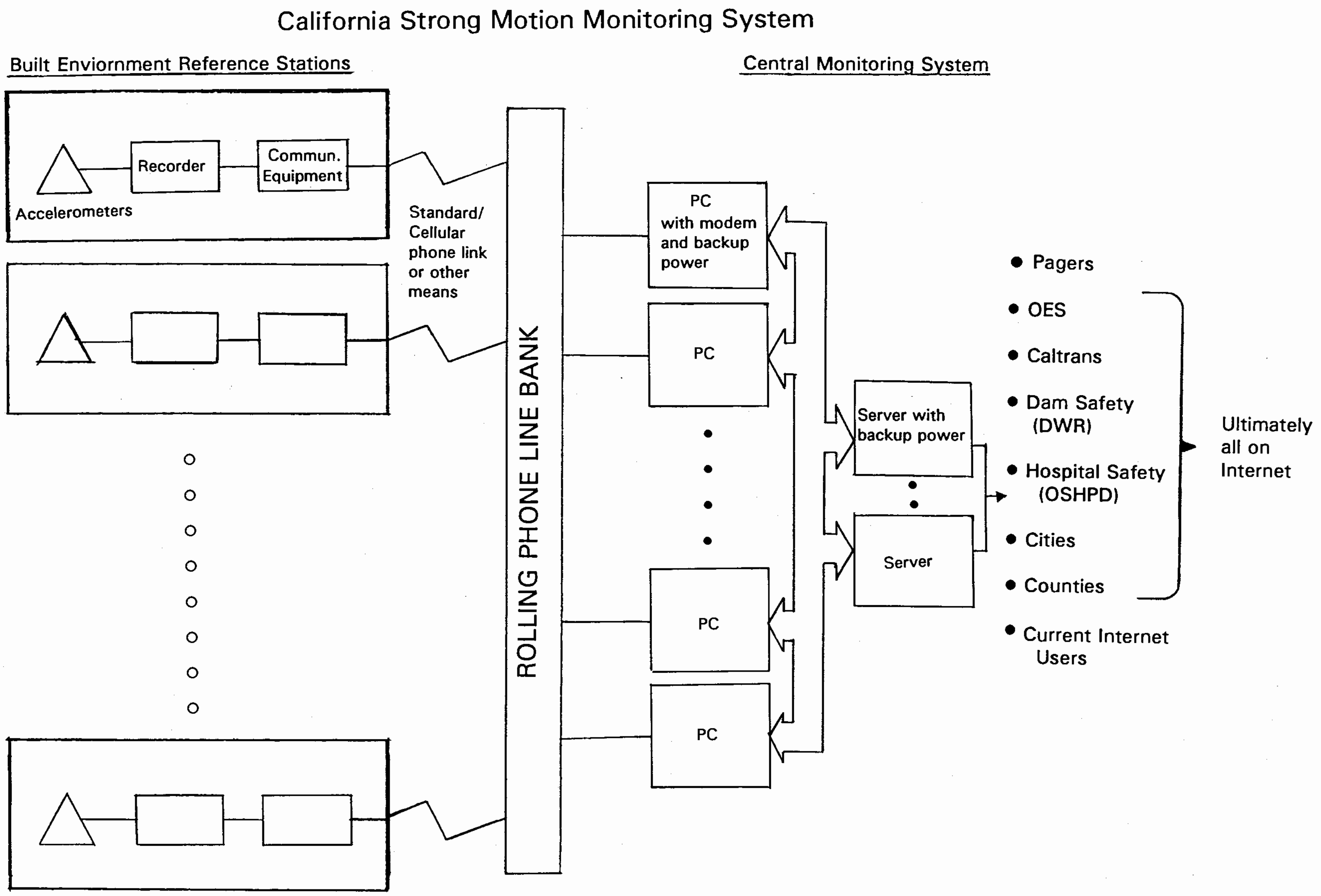


Fig. 1. Schematic of the CSMIP near-real-time strong motion monitoring system.

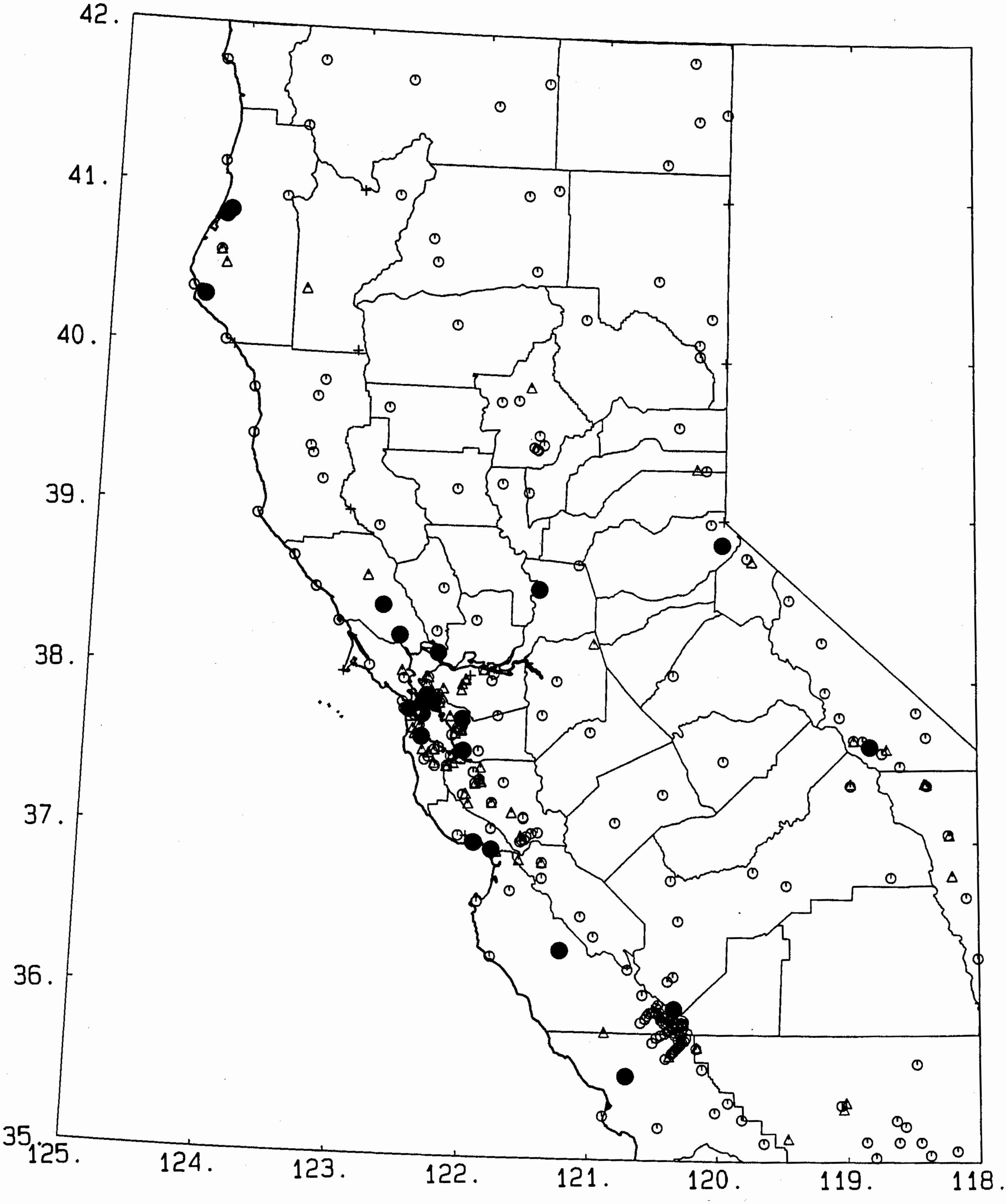


Fig. 2. CSMIP stations in northern California. Stations in the near-real-time network are shown as closed circles. Open circles and triangles are CSMIP ground-response and structure-response stations, respectively.

acceleration, velocity and displacement as well as spectral levels at selected periods to key personnel.

As an example of output of the automated system, Figures 3 and 4 show standard 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 during the final preparation of this paper. 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 field stations, which being remote, has a cellular phone connection running at a much slower baud rate than conventional phone connections.

Figure 3 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 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 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 4. Spectral acceleration is plotted up to a period of 4 seconds, and the design curve from the Uniform Building Code (ICBO, 1994) is plotted for convenient comparison.

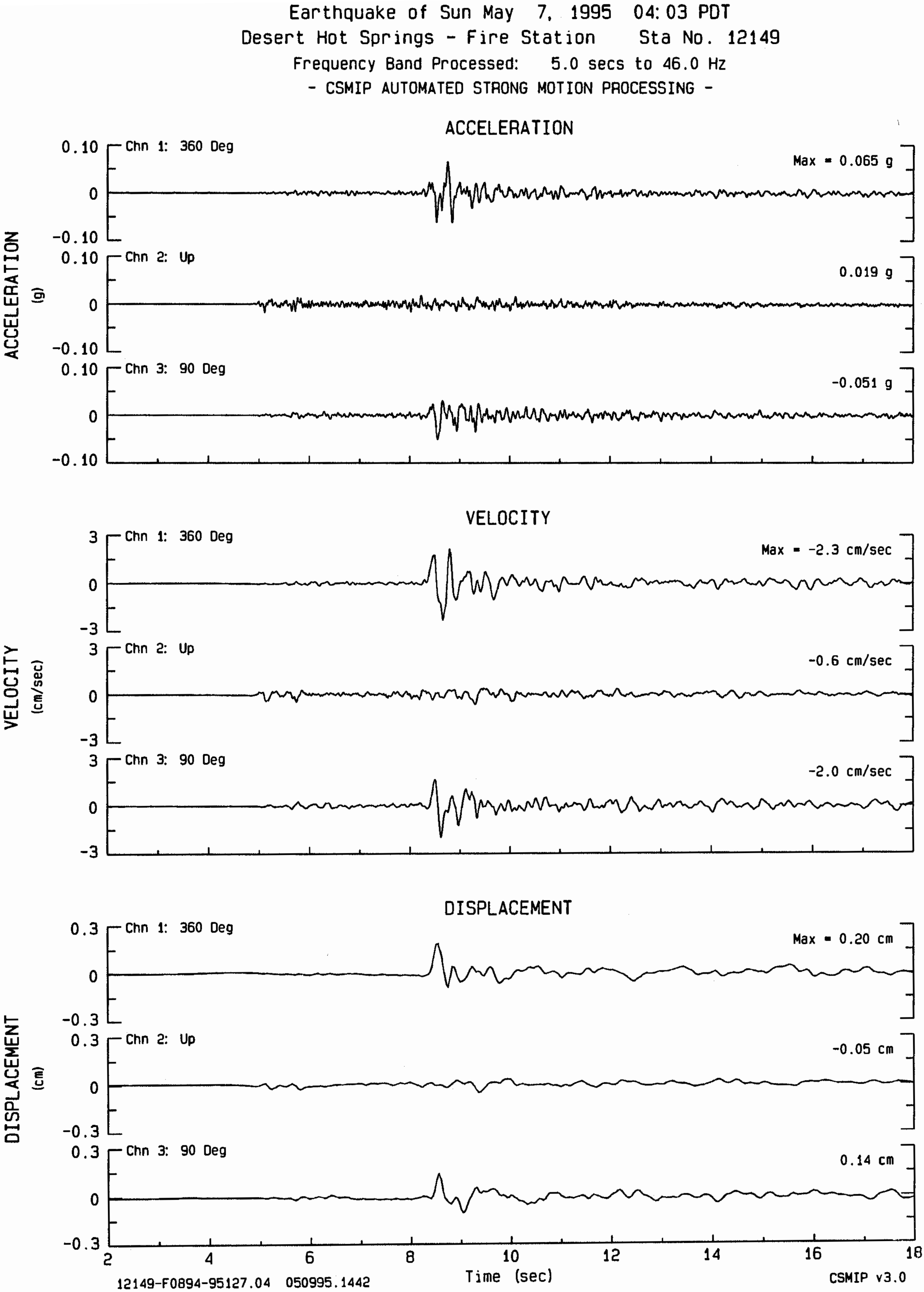
DATA DISTRIBUTION METHODS

The most effective means of disseminating the near-real-time strong motion data results continue to be developed. Present plans include providing the data parameters to CUBE and REDI within minutes after the earthquake, as part of cooperative data exchange agreements. The data will be provided via automated Internet e-mail message or file transfer, or other electronic means, to target directories on the CUBE, REDI and possibly other computers. Peak strong motion parameters are currently being automatically sent to pagers of key personnel. Automatic data distribution methods will continue to be developed.

To serve cities, counties, state, and local jurisdictions more effectively, a more personnel-oriented approach will be used. The near-real-time information capability will be augmented by automated phoned voice messages to emergency response officials and agency staff members. These prepared messages will report the level of shaking in the community in standardized, easily-understood words. Effectively advising local communities is a central part of these plans.

BENEFITS

The ability to distribute near-real-time strong-motion data provides important benefits to the State. Post-earthquake information provided to the Office of Emergency Services (OES), cities and counties would, for the first time, contain extensive information on strong shaking amplitudes rather than being primarily limited to magnitude and location. Strong-motion instrumentation will be able to handle the largest earthquakes, complimenting the existing weak-motion seismic network instruments which will be off-scale.


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 -
ACCELERATION
ACCELERATION (g)
0.10
0
-0.10
Chn 1: 360 Deg
Max = 0.065 g
Chn 2: Up
0.019 g
Chn 3: 90 Deg
-0.051 g
VELOCITY
VELOCITY (cm/sec)
3
0
-3
Chn 1: 360 Deg
Max = -2.3 cm/sec
Chn 2: Up
-0.6 cm/sec
Chn 3: 90 Deg
-2.0 cm/sec
DISPLACEMENT
DISPLACEMENT (cm)
0.3
0
-0.3
Chn 1: 360 Deg
Max = 0.20 cm
Chn 2: Up
-0.05 cm
Chn 3: 90 Deg
0.14 cm
2
4
6
8
10
12
14
16
18
Time (sec)
12149-F0894-95127.04 050995.1442
CSMIP v3.0

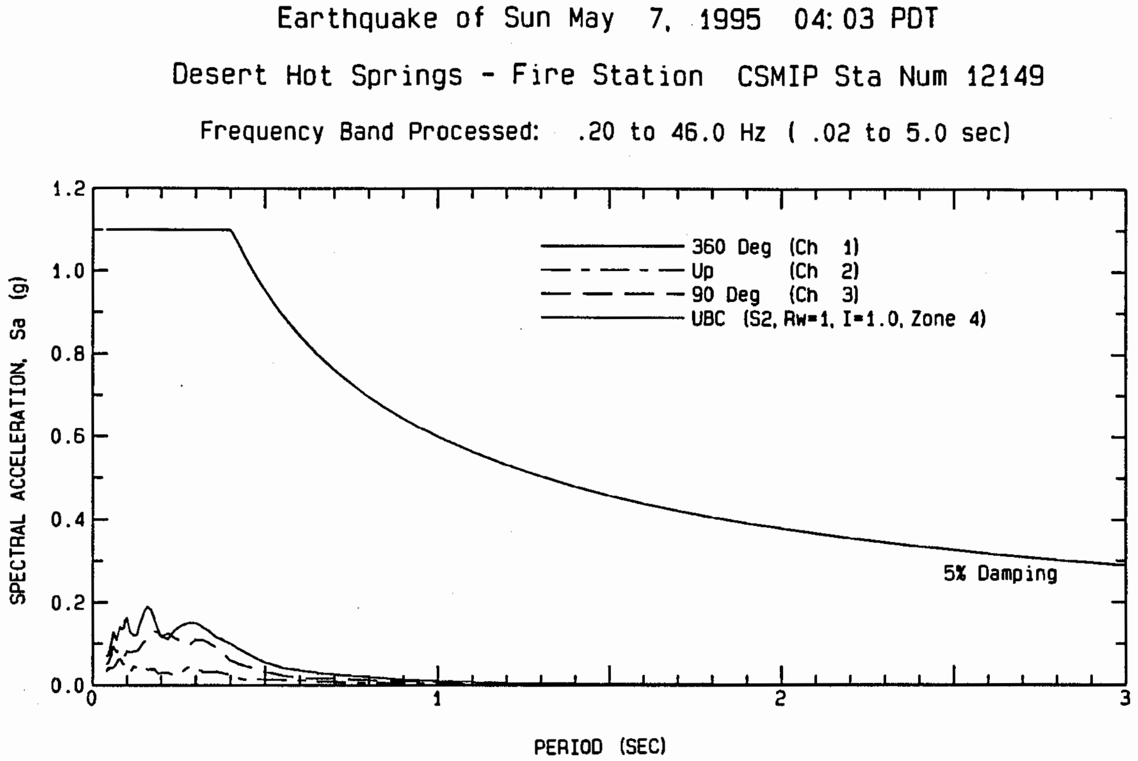


Fig. 4. Three components of band-passed spectral acceleration (5% damping) at Desert Hot Springs for the magnitude 5 earthquake of May 7. The design curve (Rw=1, for an S2 site in Zone 4) from the UBC is plotted for convenient comparison.

Systems like CUBE/REDI can be more effective in locating large earthquakes rapidly with this strong-motion information. For example, the strong-motion signal can be analyzed and the magnitude estimated from the first few tens of seconds of the acceleration. In contrast, the signals from weak-motion instruments may continue at a maximum clipped level for minutes before returning to unclipped levels so that a duration magnitude can be determined.

With the collaboration of CSMIP and CUBE/REDI, California earthquake response information can be significantly improved. More rapid, confident decisions can be made in deploying resources in the early period after an event. For example, this system would mitigate a Santa Monica situation, where unexpected localized damage occurred that unknowingly required focusing of emergency response resources. Finally, CSMIP stations located on dams, bridges, and other lifeline structures will quickly provide data on the shaking of these structures. Responsible public agencies can evaluate the hazard of these structures to the community if the measured data indicates severe shaking. Conversely, if the data indicates light shaking of the structure, that information is also important in guiding post-earthquake prioritization of responsibilities.

Fig. 3. (facing page) Three components of band-passed acceleration, velocity and displacement at Desert Hot Springs for the magnitude 5 earthquake of May 7.

SUMMARY

The CSMIP near-real-time system has successfully recorded and transmitted to Sacramento the strong shaking data from dozens of earthquakes. The largest event was a magnitude 7.2 earthquake on September 1, 1994 that was located 145 km offshore of Eureka, California. This earthquake was recorded at a bridge in the near-real-time network instrumented as part of a California Department of Transportation (Caltrans) - CSMIP statewide bridge instrumentation project currently underway. Peak motions at these stations were less than 0.1 g in acceleration, 8 cm/sec in velocity and 3 cm of displacement. The shaking and spectral information were distributed rapidly to Caltrans emergency response personnel after the earthquake. This information allowed Caltrans engineers to rapidly decide not to send inspectors to the Eureka area, 500 miles from Sacramento, to inspect their bridges in the area.

Near-real-time strong ground motion data is now available from 50 CSMIP stations in California. This expanding network is cost-effective compared to a real-time strong-motion network. Waveform data and processed strong motion (velocity, displacement and spectra) are available within a few minutes after shaking occurs at the station. In addition, both maintenance and post-earthquake data recovery costs are decreased because the station is only visited as required rather than twice per year as had been CSMIP practice. CSMIP plans to increase the number of stations in the near-real-time network both by adding new stations and by upgrading existing stations. Development of the most effective methods of transmitting the processed information to emergency response officials, building officials and the engineering and seismology agencies are underway.

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