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Paper No. 1566. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

NEAR-REAL-TIME CSMIP STRONG MOTION MONITORING AND REPORTING FOR GUIDING 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 activities and provide shaking data rapidly to emergency responders, engineers and seismologists. The system has inherent 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.

A magnitude 5 earthquake occurred near Castaic in southern California and provided the first real-life test of the system operation. The system recovered and processed data from the 13 stations that were triggered by the event within 30 minutes without problems. The recovery and processing time will be reduced as a larger number of central processing components are added. Distribution channels for the rapid strong-motion information continue to be developed.

KEYWORDS

Strong-motion; accelerograph; accelerograph; near-real-time; earthquake response.

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 (weak motion) networks in California have developed capabilities over the last five years that allow rapid determination of the earthquake epicenter and magnitude and also provide rapid distribution of that information (e.g., Caltech-USGS Broadcast of Earthquakes (CUBE) and the Rapid Earthquake Data Integration (REDI) system of UC Berkeley and the USGS). 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 that they record quickly. As a result of these two aspects, very little strong shaking information has been available after an earthquake in a timeframe useful to guide emergency response activities.

An example from the magnitude 6.7 Northridge, California earthquake of January 17, 1994 dramatizes the problem. The Santa Monica area, approximately 25 km southwest of the epicenter was shaken with unexpected severity relative to neighboring areas. Yet this fact was not widely known for some time, since most attention was focused on the epicentral area and the Northridge area in the San Fernando Valley. There was a strong-motion instrument on the grounds of the Santa Monica City Hall, and it 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.

Time Scale of Earthquake: Real-Time vs Near-Real-Time

In order to clarify the difference between the system described here and the traditional seismic networks, some of the differences between the two are highlighted. One aspect is the instrument type, discussed further 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 that 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. With the data 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.

Systems like 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 in California. For large earthquakes these sensitive instruments are overdriven and can provide little information in addition to the onset time and the duration of shaking at the station. 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 large 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 studies of the recordings made by these instruments.

Traditional weak-motion instruments are monitored continuously, and they transfer the data in real-time to a central site. 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 are 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 the recorded data. The short delay, required for the data to be communicated via a non-dedicated 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 quite common for several years to elapse between recordings of more than a few percent g at most 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 accelerographs had little application in 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 obtained within a few minutes. This capability can be obtained with a small incremental upgrade to many existing solid-state 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, functioning both as part of a strong-motion network and as part of a traditional seismic network. These instruments revolutionize strong-motion/weak-motion monitoring in that respect. However, these units have been more expensive and have not yet been integrated into the CSMIP system described here.

NEAR-REAL-TIME STRONG-MOTION MONITORING SYSTEM

The CSMIP strong-motion monitoring system 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 that do not have land-line phone service. The ancillary equipment at the station consists of a high-speed modem and logic controls. The equipment at the central site in Sacramento includes a bank of standard personal computers (PCs) attached to modems and running monitoring software.

The 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 (i.e., the unit at the station 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 by other 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 which continues monitoring strong motion at the site. The PC then begins automatic processing of the record, discussed further below. If it should happen that a field station is unsuccessful in getting one of the PCs to answer because they were all busy or for some other reason, the station tries again repeatedly after certain delays. Some of the key logic components are also used in a similar system developed by the U.S. Bureau of Reclamation in Denver for strong motion instruments located at dams through the United States (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 an uninterruptible power system (UPS) for backup power. This design also allows the recovery and processing of the shaking data from multiple stations to occur simultaneously. The system is also 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 stations for maintenance activities. This approach yields reduced maintenance costs through more targeted maintenance work, and results in higher overall network performance levels. Near-real-time strong ground motion data are now available from 50 of the CSMIP stations in California.

AUTOMATED PROCESSING

When a central computer has requested and received an accelerogram file from the field instrument, it begins unattended automated processing. The processing proceeds through several steps, each with careful quality control checks. The file is first uncompressed (if necessary) and converted from binary counts to raw acceleration data. The acceleration data are next integrated and high-pass filtered in the frequency domain to calculate the velocity. The data are 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. It is not intended that this processing will supplant the traditional processing except for rapid usage and small events. For high amplitude and important records the careful processing will still be performed.

At the completion of processing, the system transmits, through a pager system, the peak acceleration, velocity and displacement as well as spectral levels at selected periods to pagers of key personnel.

Example Output As an example of output of the automated system, Figures 2 and 3 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,

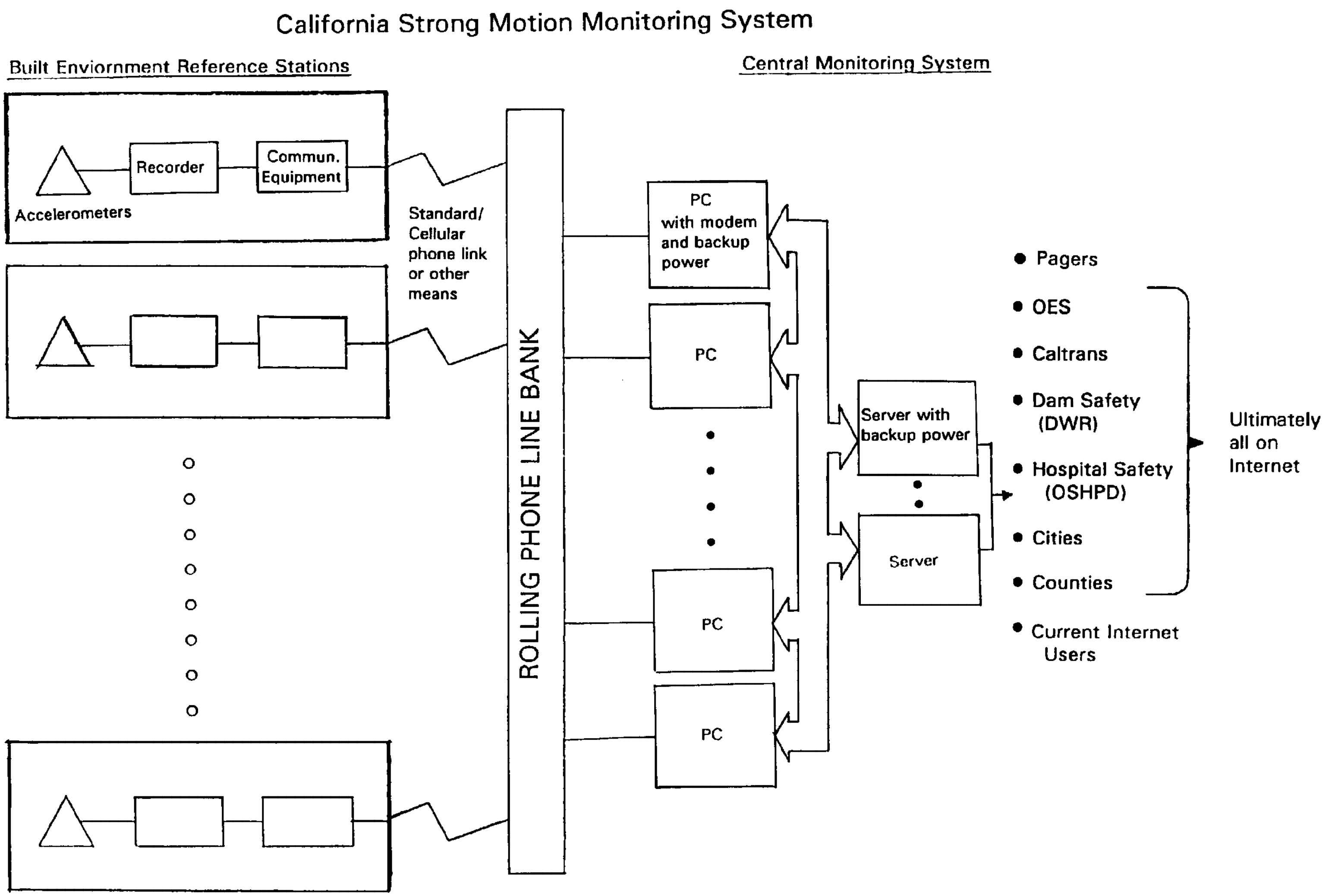

Fig. 1. Schematic of the CSMIP near-real-time strong motion monitoring system.

1995. Three CSMIP near-real-time stations recorded this event and the data from these stations was 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 2 shows the record recovered from the Desert Hot Springs stations, 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, for convenience of interpretation by 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 were 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 3. 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.

Test Event A magnitude 5.0 earthquake on June 26, 1995 near Castaic, California, in the Northridge aftershock area, was the first earthquake recorded by a significant number of CSMIP near-real-time stations. The system automatically recorded, transmitted and processed data from the 13 stations that were triggered by the 1:30 AM event. The first record was processed within 3 minutes, and all the remaining records were recovered and processed within 30 minutes after the event without a problem. No human intervention was required, although CSMIP staff were paged with peak parameters for each record as it was processed. The recovery and processing time will be reduced as a larger number of processing components are added in Sacramento. The data were not of engineering significance (<2% g) but the event provided a good test of the system.

Practical Application The largest event recorded by the near-real-time system was the magnitude 7.2 earthquake of September 1, 1994 located 145 km offshore of Eureka in northern California. This earthquake was recorded at a bridge instrumented as part of a California Department of Transportation (Caltrans) - CSMIP statewide bridge instrumentation project currently underway. Peak motions at the station 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 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.

SUMMARY

A near-real-time strong motion system has been developed which allows strong motion data to be made available very rapidly after the occurrence of an earthquake. The system does not impede the original long term goal of the instrumentation, the recording of strong shaking for the purpose of verifying and improving designs and building codes. The system provides waveform data and processed strong motion (velocity, displacement and spectra) 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 when required rather than twice per year, normally the practice.

The CSMIP near-real-time system has successfully recorded and transmitted to Sacramento the strong shaking data from dozens of earthquakes. Near-real-time strong ground motion data are now available from 50 CSMIP stations in California. This expanding network is cost-effective compared to a real-time strong-motion network. 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.

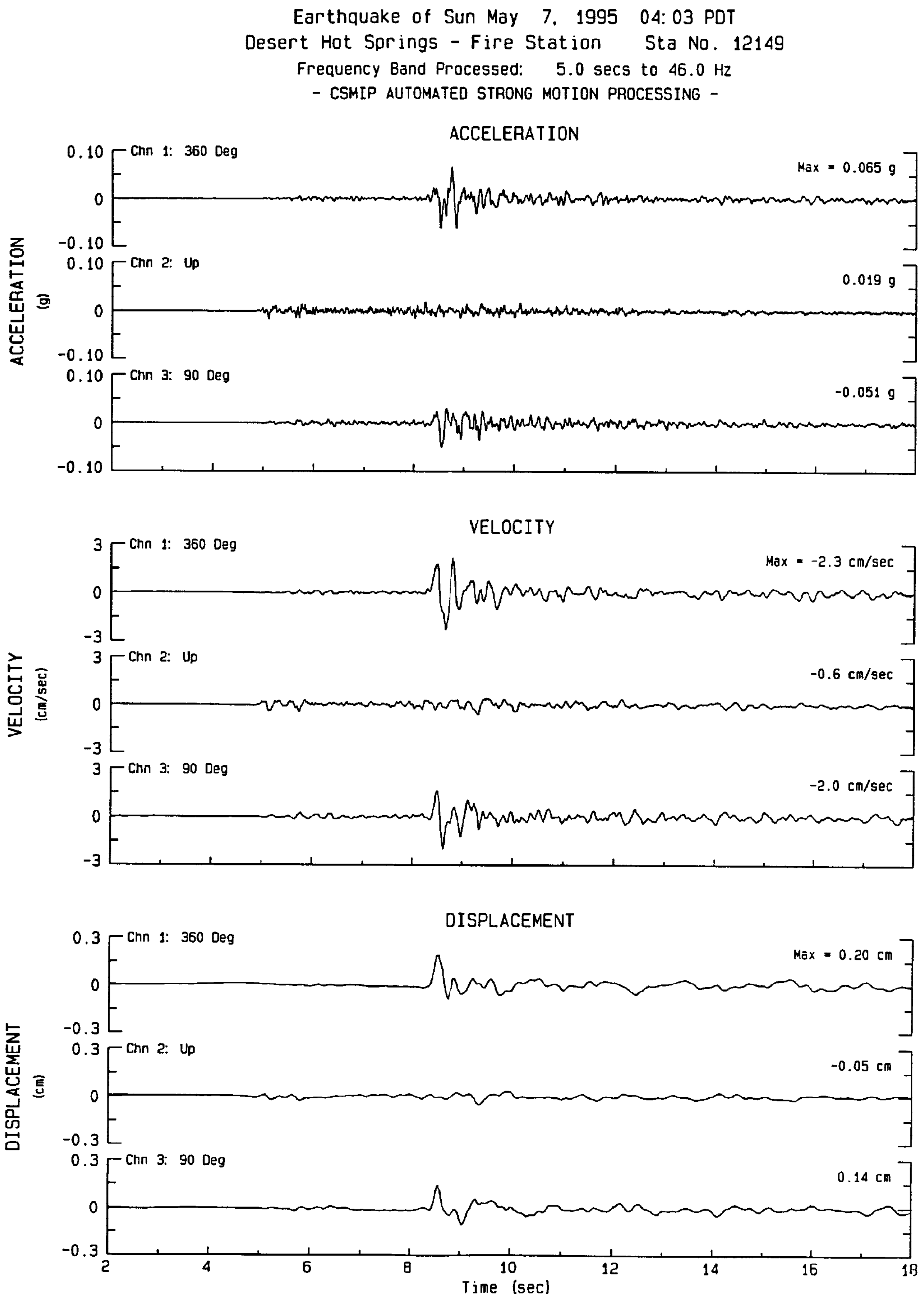

Fig. 2. Three component of band-passed acceleration, velocity and displacement at Desert Hot Springs for the magnitude 5 earthquake of May 7, 1995.

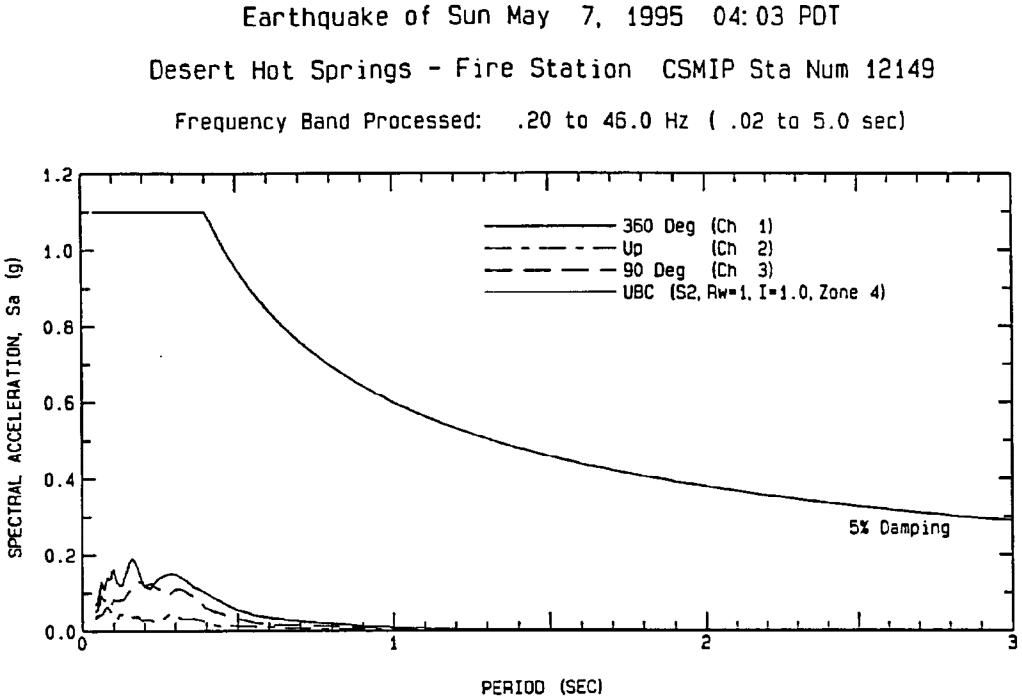

Fig. 3. Three components of band-passed spectral acceleration (5% damped) at Desert Hot Springs for the magnitude 5 earthquake of May 7, 1995. The design curve ($R_w = 1$ for an S2 site in Zone 4) from the UBC is plotted for comparison.

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