# THE STRONG MOTION INSTRUMENTATION PROGRAM AND DATA RECORDED DURING THE LOMA PRIETA EARTHQUAKE

A.F. Shakal and M.J. Huang
California Department of Conservation
Division of Mines and Geology

## ABSTRACT

The purpose of the Strong Motion Instrumentation Program (SMIP) is to improve methods to protect California citizens and property from earthquake-induced structural hazards. Toward this end, the program records strong earthquake shaking in structures and at ground response sites to obtain the data necessary for the improvement of seismic design codes. SMIP also promotes and facilitates the improvement of seismic codes through data utilization projects. The SMIP 1990 Research Review Seminar is a component of that effort. Several sets of data recorded during the Loma Prieta earthquake are the first measurements of the performance of several standard construction types during moderate and strong earthquake shaking, and these records will be the subject of data utilization studies in 1990.

## INTRODUCTION

SMIP was established after the 1971 San Fernando earthquake caused unexpectedly severe damage to structures that had been designed according to contemporary code standards. To acquire the data necessary to improve the prediction of strong motion and the detection of structural problems, many more strong-motion stations were needed than were provided by the existing federal program. SMIP was created to fill that need.

The program installs and maintains strong-motion instruments in representative structures and geological environments throughout California. Since the program's inception, over 480 installations of various types have been completed. Sites are selected for instrumentation on the basis of the recommendations of a committee of the California Seismic Safety Commission, called the Strong Motion Instrumentation Advisory Committee (SMIAC), comprised of leading engineers and seismologists from California universities, government and private industry.

Strong-motion data recovered from the instruments in the SMIP network are processed and made available to engineers and seismologists engaged in predicting or designing for earthquake shaking. A large number of earthquake records have been recorded and analyzed, including many from the 7.1 $M_L$ 1989 Loma Prieta earthquake [1], the 5.9 $M_L$ 1987 Whittier Narrows earthquake [2], and the very important records from the Imperial County Services Building, damaged during the 6.6 $M_L$ 1979 Imperial Valley earthquake.

## NETWORK STATUS AND INSTRUMENTATION OBJECTIVES

SMIP currently has a total of 480 stations installed at selected locations throughout the state of California. Table 1 summarizes the current and target numbers of ground-response, building, and lifeline installations.

Table 1. SMIP Network Status and Goals

| Installation Type | Total Network Plan | Installed To Date | Remaining High Priority | Remaining To Complete Network |
|---|---|---|---|---|
| Ground-Response | | | | |
| Isolated Sites | 500 | 344 | 104 | 156 |
| Dense Arrays | 20 | 2 | 8 | 18 |
| Buildings | | | | |
| All Types | 400 | 103 | 160 | 297 |
| Lifelines | | | | |
| Dams | 30 | 21 | 9 | 9 |
| Transportation | 40 | 8 | 15 | 32 |
| Water & Power | 25 | 2 | 13 | 23 |
| Total | 1015 | 480 | 309 | 535 |

**Ground-Response Instrumentation** An objective of ground-response instrumentation is to measure earthquake shaking in a range of geologic conditions including rock, deep and shallow alluvium, and liquefiable deposits. Recording the motion at specific locations with respect to the earthquake fault is also important to allow study of the rupture process and the attenuation of seismic waves radiated from the source region. A total of 344 ground-response stations have been installed. The instrumentation objectives for the next 15 years include adding an additional 104 isolated sites and 8 specialized dense arrays.

**Building Instrumentation** A primary objective in the instrumentation of a building is to effectively record selected modes of the building's motion during strong shaking. For each building type, specific modes of response or deformation are most important, and these determine where the sensors are located. As a result, building instrumentation systems have sensors located at key points throughout a structure, all connected to a centrally-located recorder. Typically, 12 to 15 sensors are located in a building. Since the motion at the base of the building may not accurately represent the input motion, an additional 3-sensor set may be located some distance from the building. As shown in Table 1, 103 buildings have been instrumented by SMIP. Objectives for the next 15 years include the instrumentation of an additional 160 high-priority buildings.

**Lifeline Instrumentation** Lifeline structures instrumented by SMIP include bridges, dams, and power plants. Table 1 lists the number instrumented in several categories and the number remaining in the highest priority categories. One of the most important records obtained to date is from the Vincent Thomas suspension bridge during the 1987 Whittier earthquake, which is discussed below.

**Network Maintenance** Thorough training of personnel and regular, careful servicing are key elements of an effective maintenance program. For a program like SMIP, continually installing new instruments as well as maintaining previously installed instruments, the budget balance between installation and maintenance is important. An instrument installed one year increases maintenance costs for subsequent years. In addition, about 1-2% of SMIP stations have to be abandoned and re-installed each year due to change of property ownership or changing physical conditions at the site.

**Accelerogram Processing** SMIP's in-house digitizing facility is patterned after that developed by Trifunac and Lee [3]. In this system, the film accelerogram is scanned, while mounted on a rotating drum, by a laterally-moving photodensitometer. Studies of the system noise are used to develop signal-to-noise ratios to guide filtering during processing. SMIP is currently investigating the accuracy and feasibility of a PC-based scanning system for replacing the existing system.

**Data Utilization through Directed Research** An effort to increase the application of the data collected to the improvement of building codes was recently initiated. Studies are funded for analysis of strong-motion data by researchers, working when possible with graduate students and with the engineers who designed the structure being studied. These projects are aimed at answering specific questions about the response of the structures or the ground through utilization of strong-motion data. The results of these studies are presented in annual seminars and published in technical journals.

## IMPORTANT DATA FROM THE 1989 LOMA PRIETA EARTHQUAKE

The Loma Prieta of October 17, 1989 produced a large set of strong-motion data from a magnitude 7.1 earthquake. These data are very important because most previous strong motion data are from earthquakes of magnitude 6 or less. SMIP obtained records from a total of 94 stations, including 53 ground-response stations and 41 extensively-instrumented structures [1]. The structures include 34 buildings, 2 dams, 2 freeway overpasses, a wharf, a tunnel, and a rapid-transit bridge.

Recorded peak horizontal acceleration values from SMIP stations are plotted on the map in Fig. 1. Stations in the epicentral area had accelerations as high as 0.64 g. Peak acceleration data from ground-response stations (or buildings with less than three stories) from the SMIP network [1] and the USGS [4] are plotted against distance in Fig. 2. The peak accelerations are higher than would be predicted by a standard model [5], and the values from many stations are more than 2 standard deviations above the median. The geologic conditions at a site can be important in causing local amplification, but Fig. 2 indicates that surficial geology is not the only factor causing the variation. The ability to more accurately predict peak ground motion for a given earthquake is a focus of data utilization studies.

The stations at Yerba Buena Island and Treasure Island were installed over 15 years ago specifically as a rock - soil station pair, respectively. Treasure Island is a man-made island, built of fill on a shallow sand spit north of Yerba Buena Island. Amplification of the motion recorded at the soft soil site compared to the rock site is clearly shown in the acceleration records and the response spectra (Fig. 3).

A particularly interesting record was obtained at a 47-story office building in San Francisco. The building, instrumented with 18 sensors, has a moment-resisting steel frame in the longitudinal direction, and a braced steel frame in the transverse direction. The peak acceleration was 0.48 g on the 44th floor and 0.16 g at the base level. The acceleration records were dominated by motions of higher modes, but the computed displacements clearly show the response in the fundamental mode. Fig. 4 shows the displacements in the longitudinal direction at the 44th floor, 16th floor, and the "B" level.

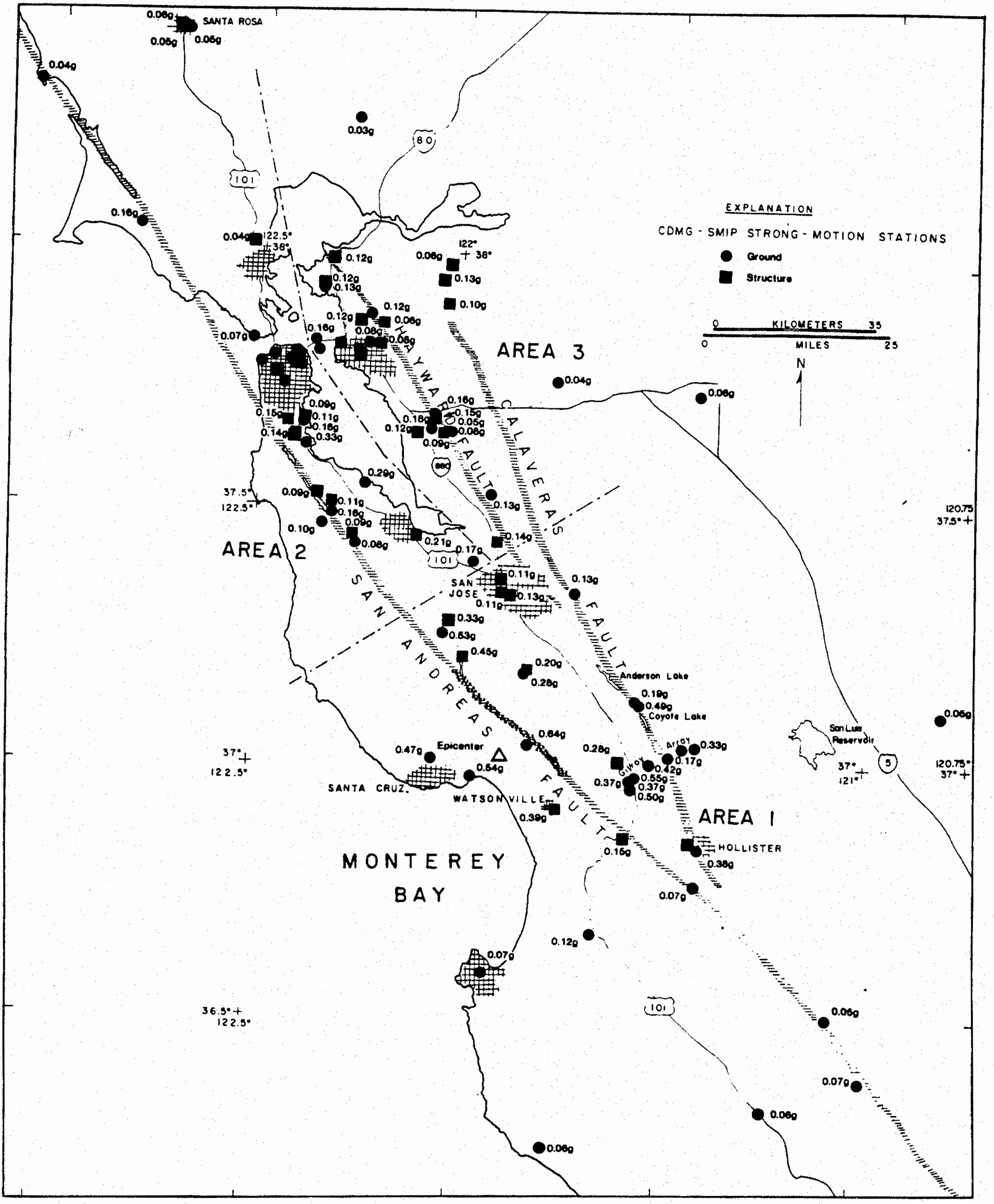

Fig. 1. Map of central coastal California showing the San Andreas fault, the epicenter and aftershock zone of the Loma Prieta earthquake, and the locations of SMIP stations that recorded the strong shaking. The peak horizontal acceleration recorded at each station is shown next to the station.

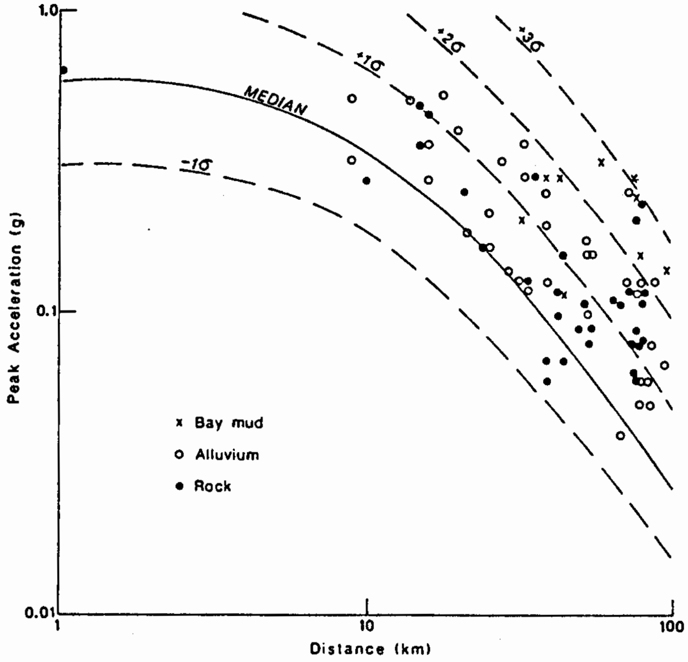

Fig. 2. Peak horizontal acceleration versus distance to the nearest point on the fault inferred from the aftershock distribution. Largest of the two horizontal components is plotted. Solid line is the median curve of Joyner and Boore, 1981, for a moment magnitude 6.9 earthquake. Dashed lines indicate -1, +1, +2, and +3 standard deviations. Site geology is shown in the key.

These records show that after about 30 seconds the building oscillated in free vibration with an amplitude of about 30 cm (one foot) and a period of about 6 seconds. The damping ratio, as estimated from the record, is about 3%. Similarly, the record shows that the fundamental mode in the transverse direction has a period of about 5 seconds. Detailed analysis of the record will allow determination of important building response parameters and allow the evaluation of seismic design provisions for tall buildings.

The record obtained at a 4-story concrete shear wall building in Watsonville is also interesting. The building was designed in 1948 and 1955. A peak acceleration of nearly 1.25 g was recorded on the roof, and about 0.4 g was recorded at the ground floor. It is clear from the record in Fig. 5 that the building vibrated at a period of about 0.35 second and this period was not changed dramatically during the shaking. The record also shows that the building experienced some torsional motion. The computed displacements [6] at three different levels in the east-west direction are also shown in Fig. 5. Note that these displacements are very similar because the building is very stiff. The relative displacement between the roof and the ground floor is less than 4 cm. Comparison to Fig. 4 illustrates the expected flexibility of a steel frame structure.

## DATA FROM OTHER RECENT EARTHQUAKES

Important records have also been obtained during other recent earthquakes. One example is the record obtained at the Vincent Thomas suspension bridge near Los Angeles during the 1987 Whittier earthquake. The acceleration records from 26 sensors are shown in the SMIP Whittier report [2]. The processed data revealed that the periods of first lateral and vertical modes of the bridge deck were about 7 and 4.5 seconds, respectively. Fig. 6 shows

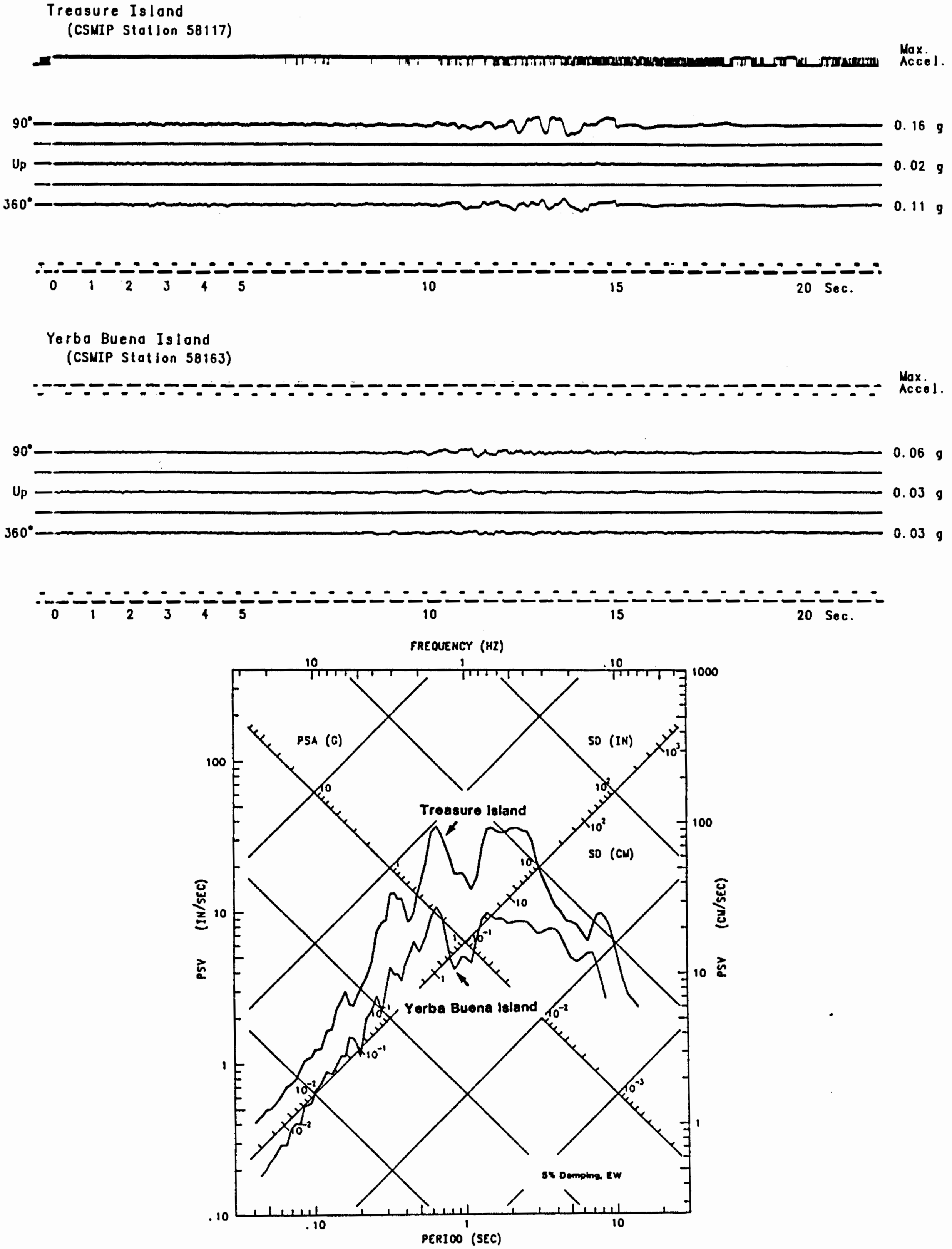

Fig. 3. Comparison of accelerations and response spectra for the Treasure Island (soft-soil site) and Yerba Buena Island (rock site). The Treasure Island spectrum is amplified by a factor between 2 to 4 for the range of periods shown.

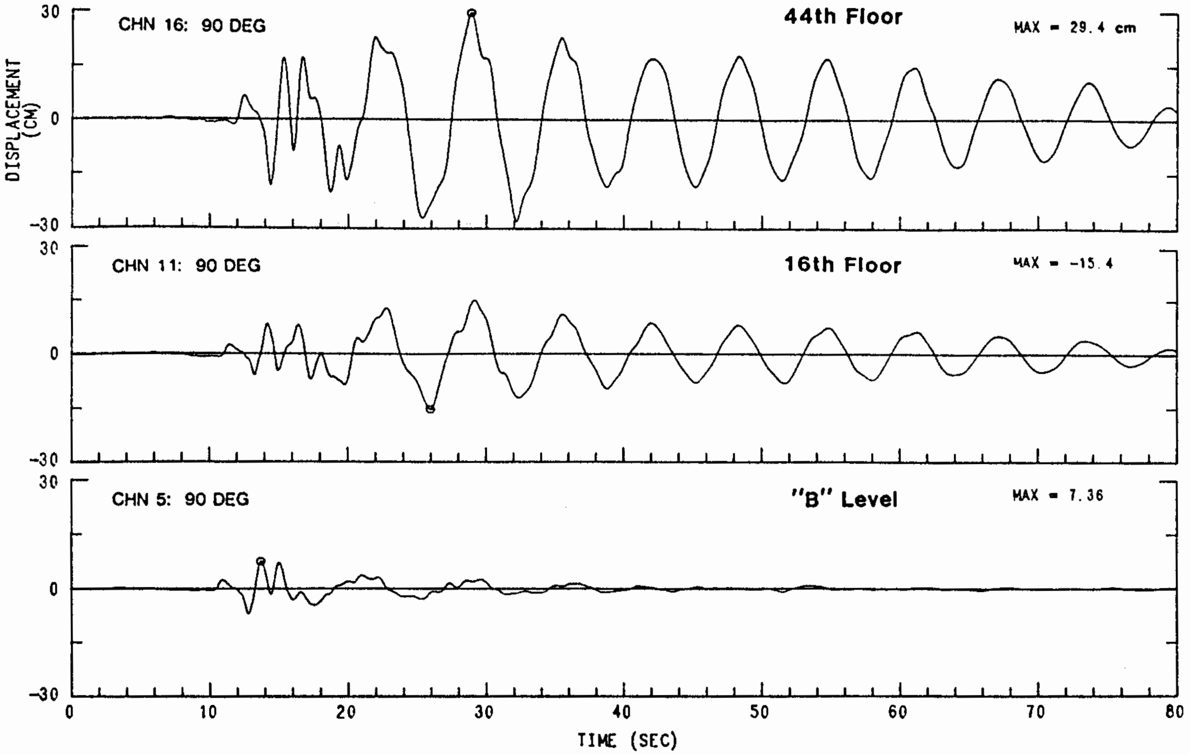

Fig. 4. Displacements computed from the accelerations recorded at the 44th floor, 16th floor, and base level in the longitudinal direction of a 47-story steel office building in San Francisco. Note that the building oscillated in free vibration with amplitude of 30 cm after the ground motion stopped.

the lateral displacement and the torsional motion of the deck. Note that the torsional motion of the bridge deck at the side span has a period of about 1 second, and the motion of the side span is larger than that of the center span. In lateral motion, the main span shows a longer period of about 7 seconds with an amplitude of about 4 cm. Studies underway will extend the analysis of the response and compare it to modelling results.

Another important record was obtained during the 5.5 $M_L$ Upland earthquake of February 28, 1990 at the base-isolated Law and Justice Center of San Bernardino County. Several records were obtained in the building since it was instrumented in 1985, but the previous events all had very small motion at the site. As shown in Fig. 7, the peak accelerations recorded at the foundation level (below the isolators) and the basement (above the isolators) were 0.14 g and 0.05 g, respectively. The peak acceleration at the roof was 0.16 g. Comparison of the records above and below the isolators shows that high-frequency horizontal motion was filtered by the isolator, which was also observed in the records from other earthquakes. The period of the structure during this event was near 0.75 second; this is longer than the 0.6 second period present in other low-amplitude records. The differences in the horizontal motions at different levels in the structure can also be compared in the response spectra, which show a reduction at high frequency as well as amplification at the structural period.

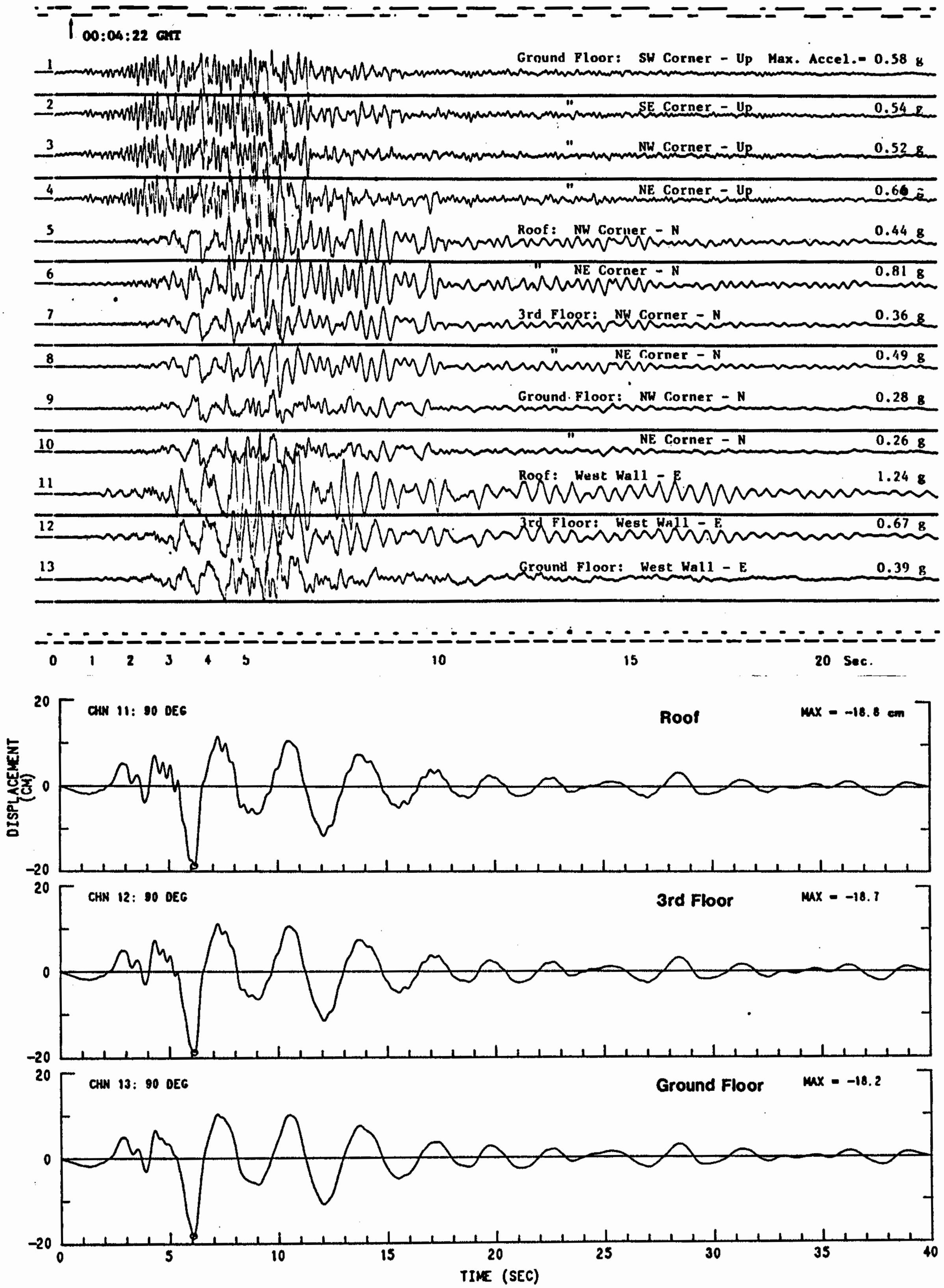

Fig. 5. Recorded accelerations from a 4-story concrete shear wall building in Watsonville (top), and the computed displacements at the roof, 3rd and ground floors in the EW direction (bottom). Note that the displacements are very similar because the building is relatively stiff. The building response is seen as the high frequency motion between 3 to 6 seconds in the roof and 3rd floor displacements.

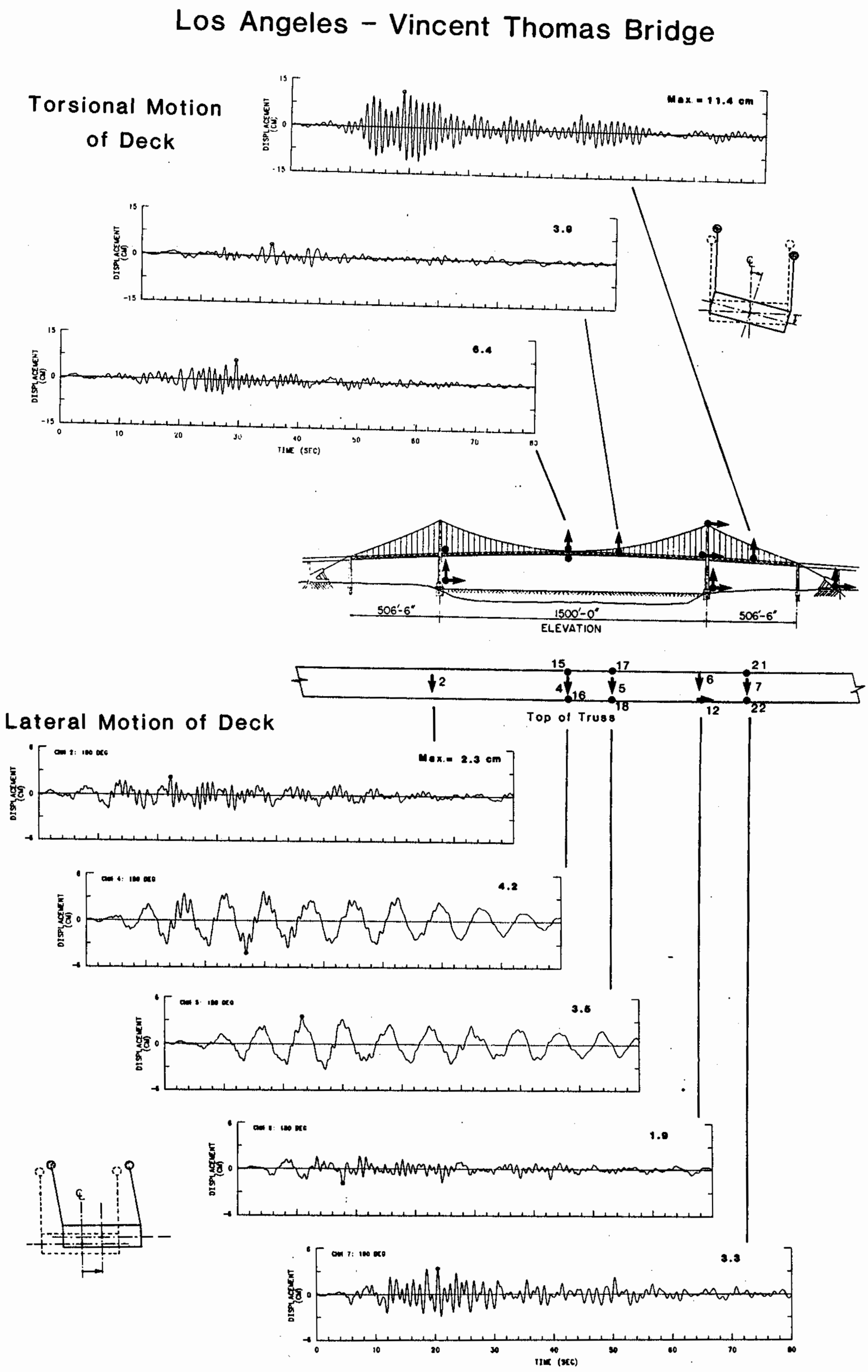

Fig. 6. The torsional and lateral displacements of the deck computed from the accelerations recorded at the Vincent Thomas bridge during the 1987 Whittier earthquake. A 7-second period can be seen in the center span lateral displacements. The torsional motion of the deck is dominated by a 1-second oscillation which has maximum displacement at the middle of the side span.

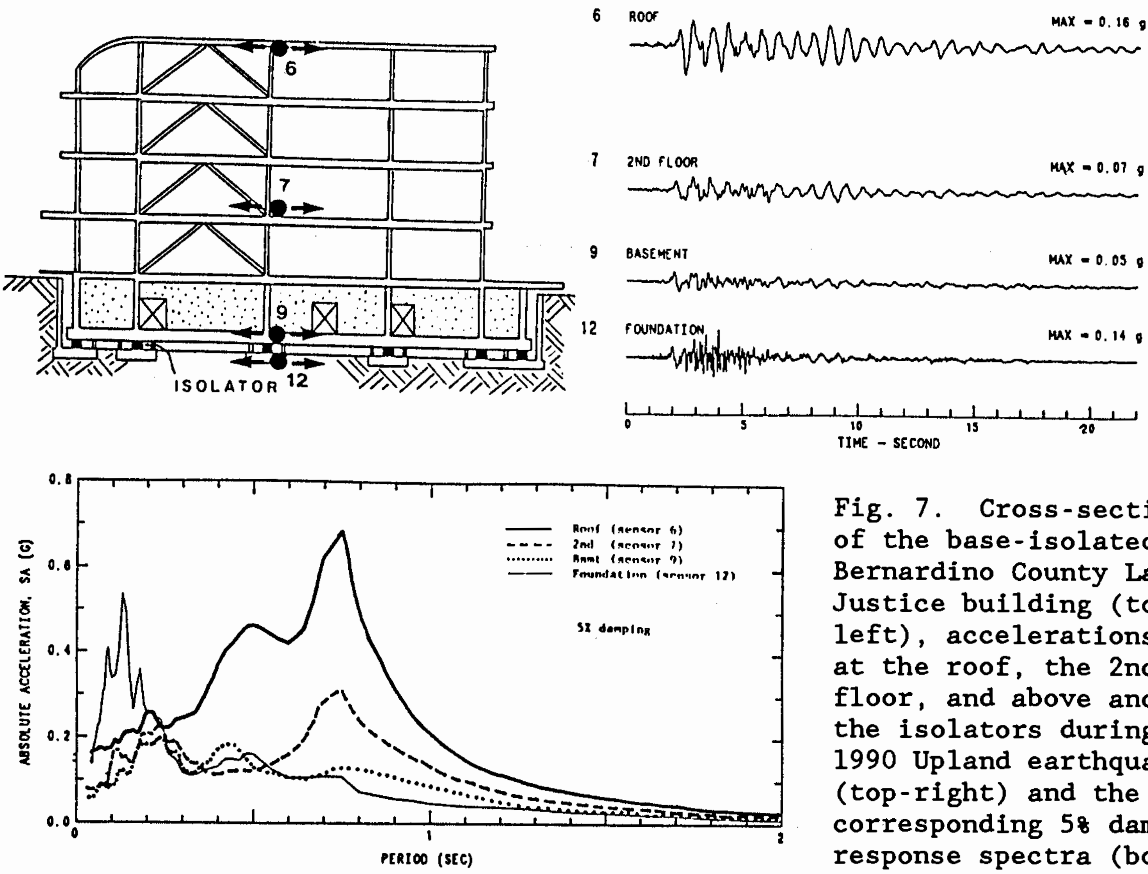

Fig. 7. Cross-section of the base-isolated San Bernardino County Law & Justice building (top-left), accelerations at the roof, the 2nd floor, and above and below the isolators during the 1990 Upland earthquake (top-right) and the corresponding 5% damping response spectra (bottom).

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