OVERVIEW OF THE STRONG MOTION INSTRUMENTATION PROGRAM
MAY 1989

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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 SMIP89 Seminar is a component of that effort.

INTRODUCTION

SMIP was established after the 1971 San Fernando earthquake caused unexpectedly severe damage to buildings 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 its inception, over 450 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. This advisory committee is made 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 1987 Whittier Narrows earthquake, and the very important records from the Imperial County Services Building damaged during the 1979 Imperial Valley earthquake.

Obtaining adequate recordings during the next major earthquake is essential for improving earthquake resistant design. Given the rarity of great earthquakes and the rapid growth in California, if the next event occurs without being adequately recorded another opportunity to gain the data necessary may not occur for many years and thousands of new structures will be built without that knowledge. This realization led to an acceleration in the program's instrumentation rate in 1988 through increased funding.

INSTRUMENTATION OBJECTIVES AND NETWORK STATUS

SMIP currently has a total of 450 stations installed at selected locations through the state of California, as shown on the map in Fig. 1. Table 1 summarizes the present status and target numbers of installations in each of three categories: ground-response, buildings, and lifeline structures.

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	328	120	172
Dense Arrays	20	2	8	18
Buildings				
All Types	400	91	170	309
Lifelines				
Dams	30	21	9	9
Transportation	40	8	15	32
Water & Power	25	1	14	24
Total	1015	451	336	564

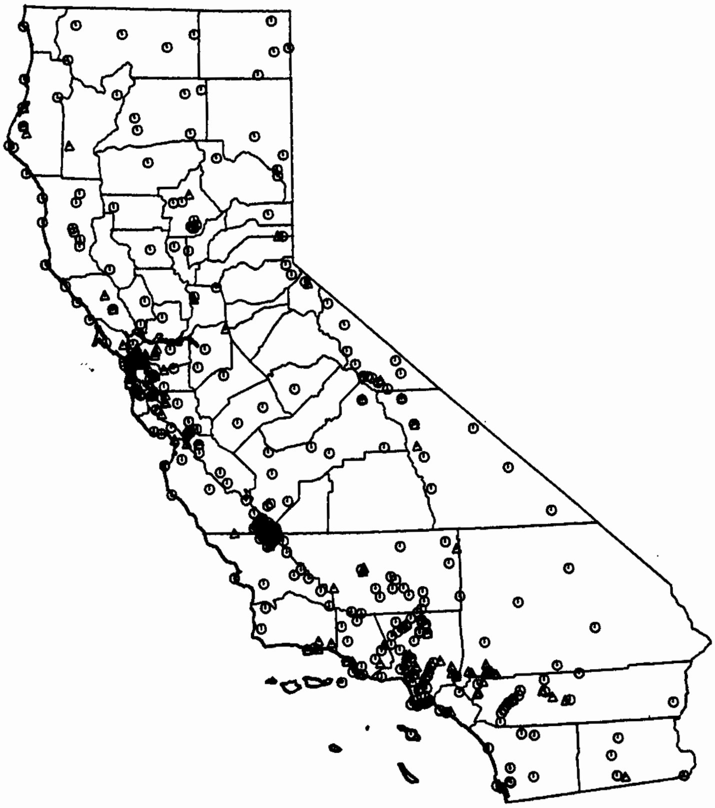

Fig. 1 Stations of the Strong Motion Instrumentation Program as of January 1989.

Ground-Response Instrumentation

The objectives of ground-response instrumentation are 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 details of the rupture process and the attenuation of seismic waves radiated from the source region.

A total of 328 ground-response stations have been installed. Many are in small 1-story buildings like schools and fire stations, but most have been installed in small, light fiberglass instrument enclosures approximately 1 meter high. The goal of the installation design is to minimally affect incoming seismic motion while providing adequate coupling to the ground and protection for the instrument. The instrumentation objectives for the installation of ground-response stations over the next 15 years include adding an additional 120 isolated sites and 8 specialized dense arrays.

Building Instrumentation

The objectives for the instrumentation of buildings are to effectively record selected modes of the response of specific building types during strong shaking. For each type of building, certain modes of response and deformation are most important, and these determine where the sensors are located. Since the motion at the base of the building may not accurately represent the input motion, an additional recording site may be located on the ground at some distance from the building.

Building instrumentation systems have sensors located at key points in a structure and connected to a centrally-located recorder. At the time of the 1971 San Fernando earthquake, instrumented buildings usually had only three separate accelerographs -- one located on the top floor, one at mid-height, and one on the ground floor -- as called for by the Uniform Building Code. The San Fernando data indicated that the records would be more useful if the sensors were interconnected and recordings were obtained from more than just three points in the building. With a modern central-recording system sensors can be located almost anywhere within a building and be connected, via shielded cabling, to a central recording unit that records all of the signals simultaneously.

As indicated in Table 1, 91 buildings have been instrumented by SMIP. Building instrumentation objectives over the next 15 years include the instrumentation of an additional 170 buildings. Typically, 12 to 15 sensors are located in a building. The sensors are positioned in the structure so that specific measurement objectives will be achieved. An example showing part of the sensor layout for a structure is given in Fig. 2. The building (the Law and Justice Center of San Bernardino County) is base-isolated, with rubber isolators placed between the foundation and the 5-story super-structure. Sensors were placed to record the relative motion across the isolators, as well as the motion of the super-structure itself. Several records have been obtained in the building, but no base motion stronger than 0.05 g has been recorded. The records are interesting nonetheless (Fig. 2), since they show a reduction in high frequency motion across the isolators.

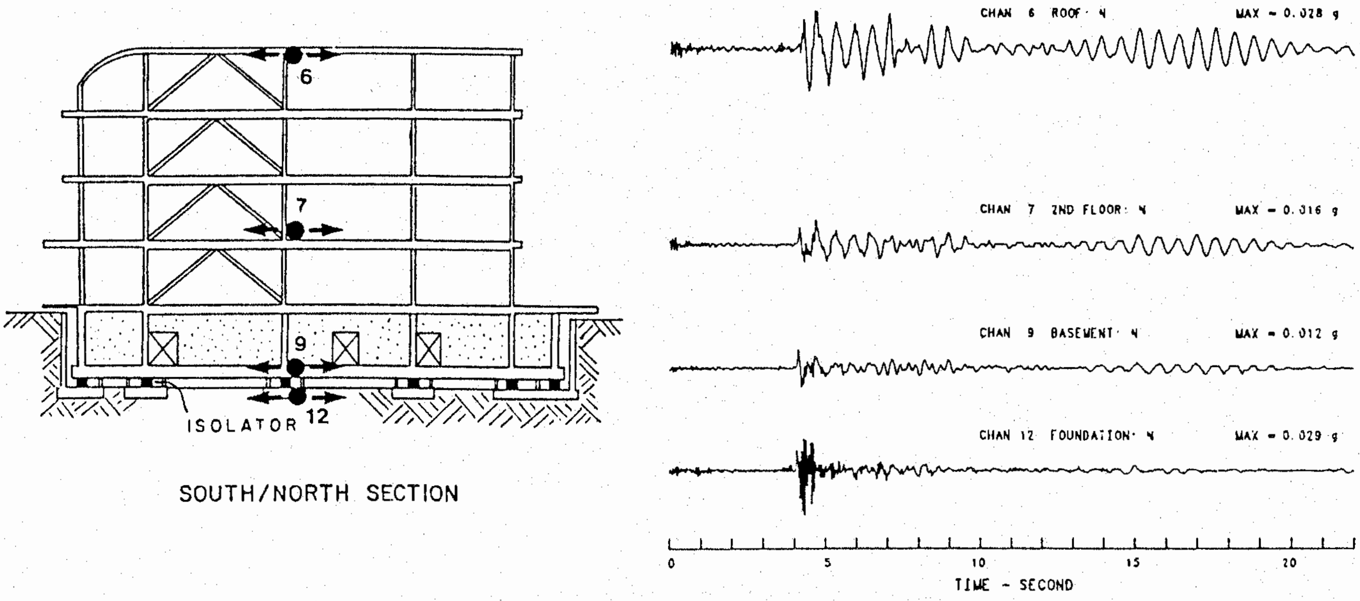

Fig. 2 Cross-section of the base-isolated San Bernardino County Law and Justice building (left) and accelerograms obtained from sensors at the roof, the 2nd floor, and above and below the isolators during the Redlands earthquake of October 2, 1985.

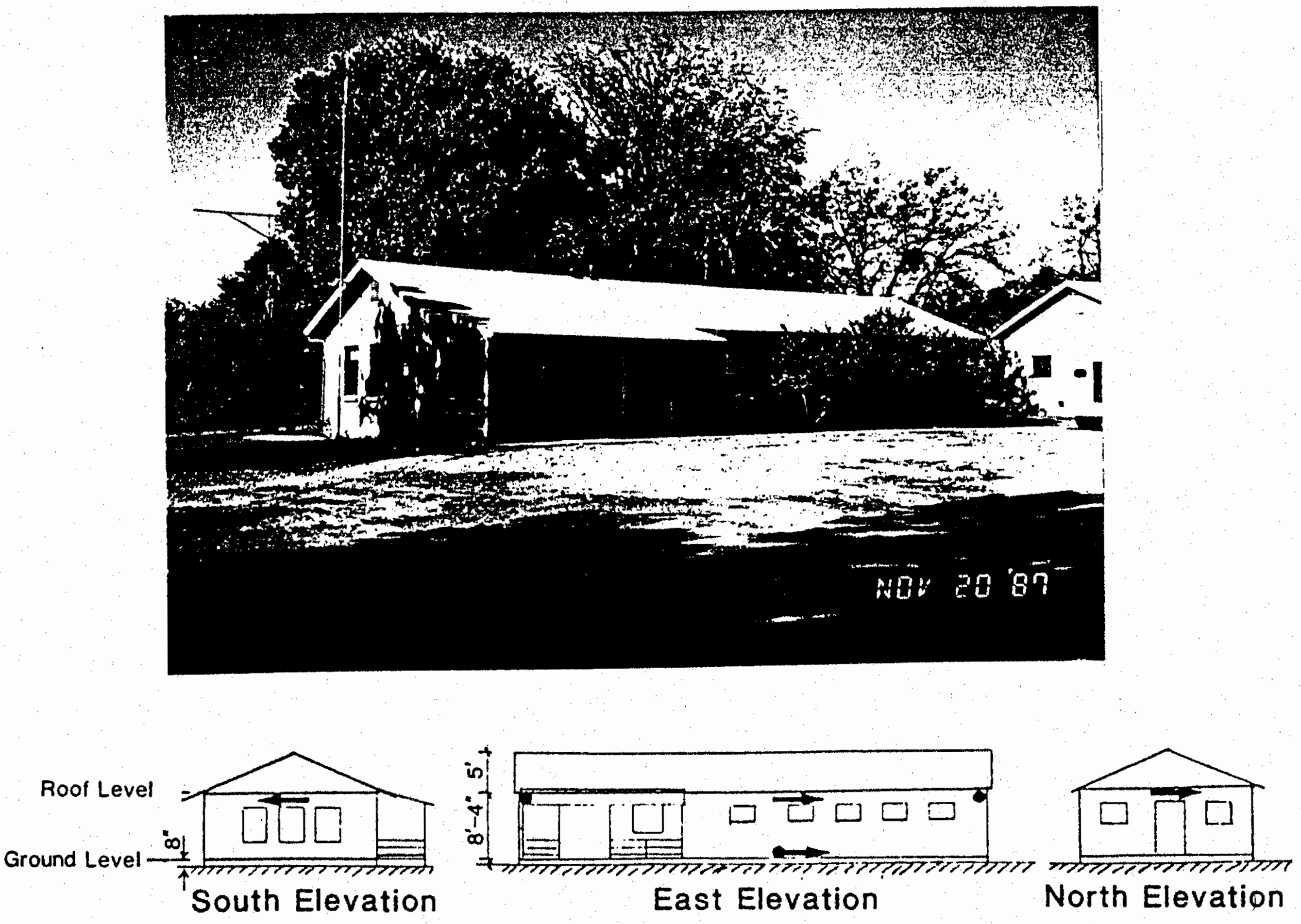

Fig. 3 The one-story masonry CDF dormitory building near Parkfield and the locations of the six sensors installed in the building.

The motions have so far been too small to excite the non-linear response of the isolation system.

The most important building records recorded by SMIP are those from the Imperial County Services Building. These records from the 16 sensors installed in the building document the strong shaking and the resulting structural failure of a modern multi-story building during the 1979 Imperial Valley earthquake. Several studies have analyzed these data to study the details of the failure process [1].

The instrumentation of smaller structures typically involves fewer sensors. As an example, Fig. 3 shows a 1-story masonry structure instrumented in Parkfield, in the vicinity of an earthquake predicted by the USGS. Six sensors have been installed to record the motions of this structure; no data have yet been recorded at this site.

Records obtained from buildings can be used to estimate the earthquake forces in a building. For example, the lateral force at each level can be estimated by multiplying the weight of each floor by the acceleration. These values are listed in Table 2 for a 10-story building in San Jose for the motion recorded during the 1984 Morgan Hill earthquake. For comparison, the original design forces reported in the ATC-2 report at each level and the total base shear in each direction are also listed. The dynamic earthquake forces are between 25 and 160 percent greater than the static design forces. The base shear is about 1.5 times the design shear in the longitudinal direction and 2 times in the transverse direction. This example illustrates the value of strong motion data in comparing actual earthquake forces to those used in design.

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. The most important record from a lifeline obtained to date is from the Vincent Thomas suspension bridge, discussed in detail below.

NETWORK OPERATION AND MAINTENANCE

Maintenance techniques for strong-motion instruments have been developing since the early 1930's. Thorough training of personnel and regular, careful servicing are the key elements of an effective maintenance program. For a program like SMIP, which is 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 the maintenance costs for subsequent years. Component parts of the total budget for SMIP, including installation and maintenance, are shown in Fig. 4 projected for the next 15 years.

In addition to instrument maintenance, a maintenance aspect not readily apparent is station maintenance. Stations must occasionally be moved and reinstalled at the request of the property owner. Experience indicates that 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.

Table 2. Maximum lateral forces estimated for a 10-story concrete building in San Jose during the 1984 Morgan Hill earthquake.

		Longitudinal(NS) Direction (at t=19.36 sec. in the record)			Transverse(EW) Direction (at t=17.82 sec.)		
Floor Level	Weight (kips)	Acceleration (g)	Earthquake Force (kips)	Design Force (kips)	Acceleration (g)	Earthquake Force (kips)	Design Force (kips)
Roof	2700	0.18 *	486	384	0.20 *	540	332
10	2400	0.17	408	311	0.19	456	269
9	2400	0.16	384	282	0.18	432	244
8	2400	0.15	360	253	0.17	408	219
7	2400	0.13	312	224	0.16	384	194
6	2400	0.12	288	195	0.14	336	169
5	2400	0.11 *	264	166	0.13 *	312	144
4	2400	0.10	240	137	0.12	288	119
3	2400	0.09	216	109	0.10	240	94
2	2400	0.07 *	168	85	0.08	240	73
Total Base Shear			3126	2146		3588	1857
Percent of Total Weight			13%	9%		15%	8%

Footnotes: Design forces are from ATC-2 report (1974).
* -- Maximum acceleration values from the record; the maximum accelerations for other levels are estimated by linear interpolation between the values at the levels recorded.

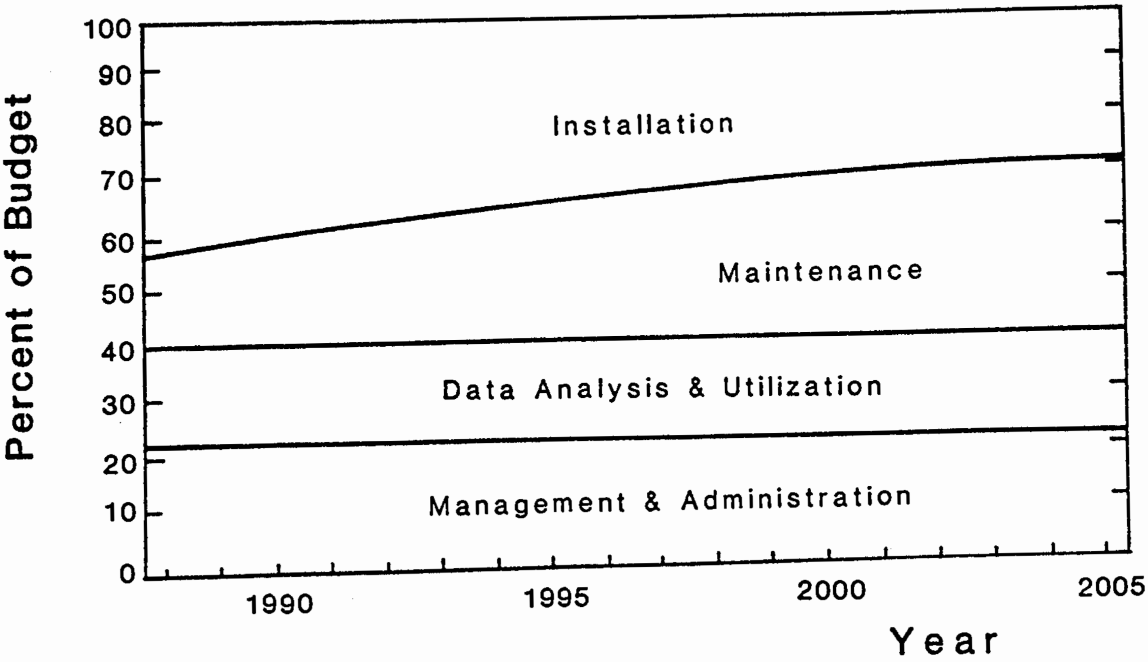

Fig. 4 Component parts of the SMIP budget projected for the next 15 years.

Accelerogram Processing

SMIP developed an in-house digitization capability in 1981 which is patterned after that developed by Trifunac and Lee in 1979 [2]. In this system, the film accelerogram is scanned, while mounted on a rotating drum, by a traveling photodensitometer. The processing procedure is described in reports produced by the program. Analyses of the system noise are used to develop signal-to-noise ratios to guide record filtering during processing.

Data Utilization

An effort to increase the application of the data collected by SMIP to the improvement of building codes was recently initiated. Studies have been funded for analysis of strong-motion data by researchers, working with graduate students (as a part of their professional training) and with the engineers who initially designed the structure being studied. These projects are aimed at answering specific questions regarding the response of the structures or the ground through utilization of existing strong-motion data. The results of these studies will be presented in annual seminars such as SMIP89 and published in technical journals.

IMPORTANT DATA FROM THE 1987 WHITTIER NARROWS EARTHQUAKE

The Whittier Narrows earthquake of October 1, 1987 was a moderate magnitude (5.9 M_L) event recorded by many strong-motion stations. Over 100 stations of the SMIP network, including 63 ground-response stations, 27 buildings, eight dams, and one suspension bridge recorded the event.

On average, the recorded peak accelerations are higher than predicted by the Joyner-Boore model [3] for a magnitude 6 event. The data of the SMIP network [4] and the U.S. Geological Survey stations [5] are plotted against epicentral distance in Fig. 5. The mean and +/- 1 standard deviation curves of Joyner and Boore have been included for comparison. The distribution of the Whittier data is biased high compared to the Joyner-Boore curves. The ability to more accurately predict peak ground motion will be increased by the study and understanding of this difference.

An interesting record was recovered at the Tarzana station, 44 km from the epicenter. A peak acceleration of 0.62 g was recorded although many stations even in the epicentral area recorded smaller peak values. In addition, stations in the vicinity of the Tarzana station recorded values of about 0.15 g. The site is located in a region of low rolling hills between the alluvial San Fernando Valley and the Santa Monica Mountains. The site is underlain by shallow soil over siltstone; soil depth has been estimated to be less than 10 m. The cause of the unusual record is not yet known but is important to understanding earthquake strong motion.

The record obtained at the Administration Building of the California State University at Los Angeles (CSULA), a 9-story reinforced concrete structure about 9 km from the epicenter is particularly interesting. The structure has a "soft first story" design very similar to the 6-story Imperial County Services Building in El Centro which suffered column failure in the 1979 Imperial Valley earthquake. The locations of the sensors in the

CSULA building and the accelerogram recorded in the Whittier Narrows earthquake are shown in Fig. 6. The maximum acceleration was about 0.40 g at the base and 0.50 g at the roof. For comparison, the 1979 Imperial County Services record had a peak value of 0.35 g at the base, and 0.60 g at the roof, and was longer in duration. The CSULA administration building suffered some damage in the earthquake. A cast-in-concrete steel column and two shear walls had some cracks which were repaired with epoxy.

The Vincent Thomas suspension bridge near Long Beach, south of Los Angeles and 40 km southwest of the epicenter, was instrumented with 26 sensors in 1981, with cost sharing from the federal government. Fig. 8 shows the locations of the sensors on the bridge structure. The record is the first significant strong-motion record ever obtained from a long-span suspension bridge. The maximum acceleration at the base of the towers was 0.08 g, while the acceleration of the suspended deck in the side-span reached 0.28 g. At the center of the side span the deck edges moved about 10 cm vertically as the deck oscillated in torsion with a period of about 1 second. The longer central span underwent little torsional oscillation in the first 20 seconds of the motion, after which it began oscillating in torsion with a period of approximately 1 second. Analysis of these data will allow theoretical models of the bridge response during strong shaking to be improved.

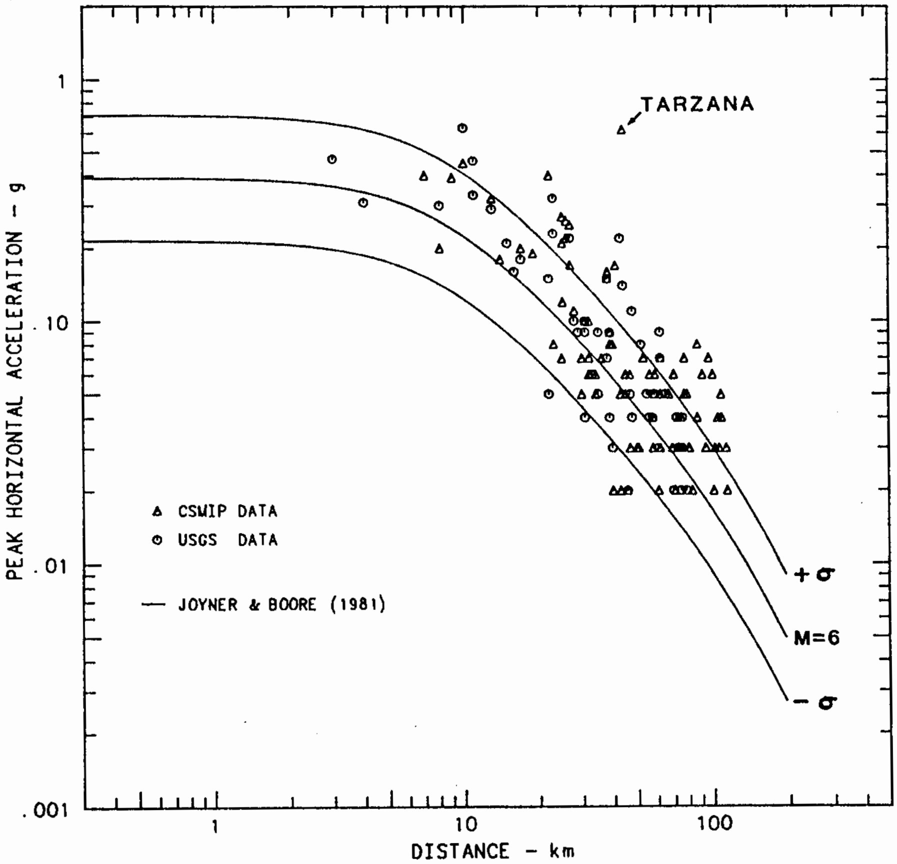

Fig. 5 Peak acceleration data for the Whittier Narrows earthquake plotted against epicentral distance.

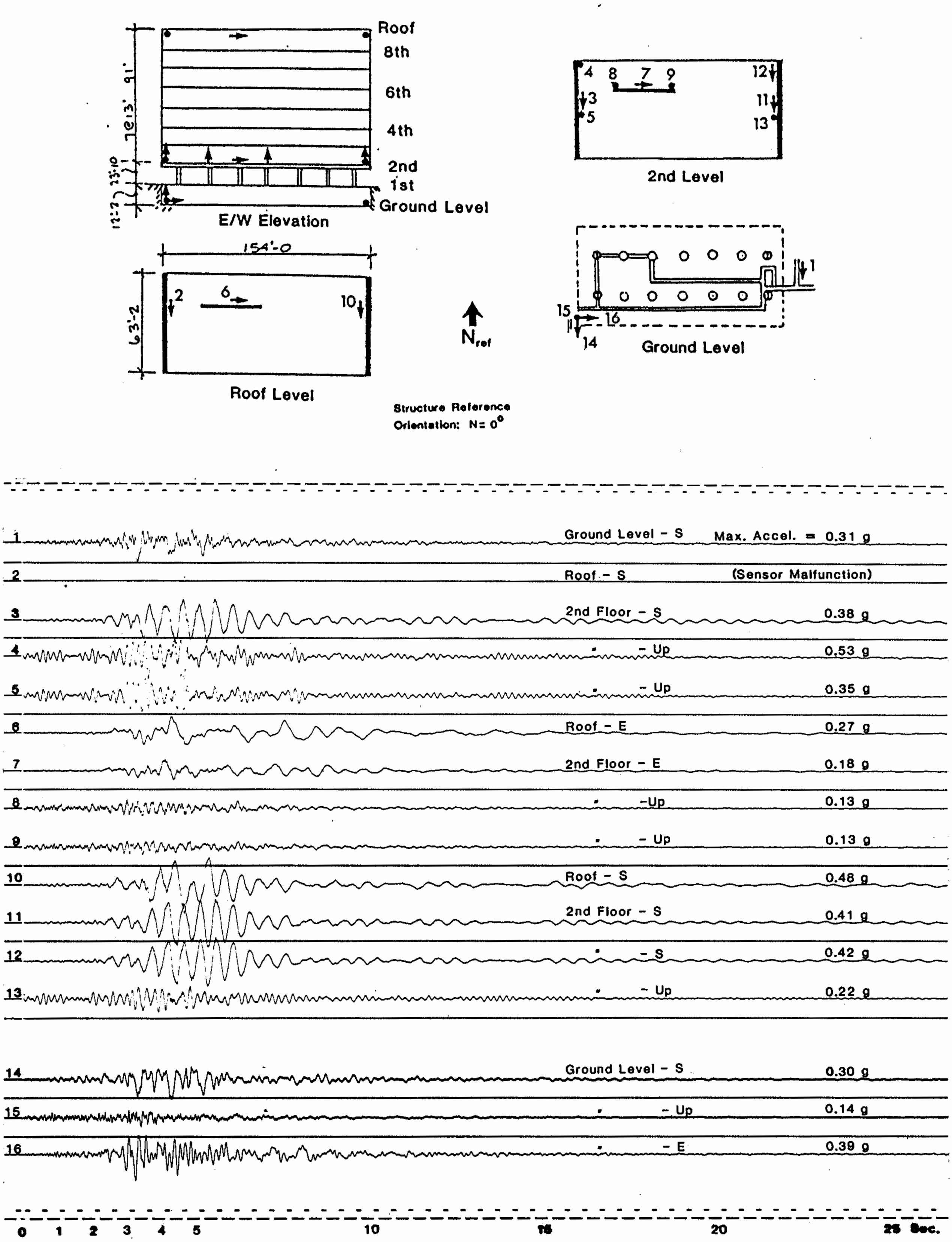

Fig. 6 Sensor locations and accelerogram recorded at the CSULA Administration building during the Whittier Narrows earthquake.

CONCLUSION

In its 16-year history, SMIP has made important contributions to our understanding of strong motion, in particular regarding the response of soft-story structures and the attenuation of seismic waves in California crustal geology. Since the number of SMIP installations will double in the next 15 years, and with the implementation of a data interpretation and utilization component to SMIP, the program's contributions will grow. A crucial cause of the success of SMIP is the extensive advice given by California engineers, seismologists and public officials.

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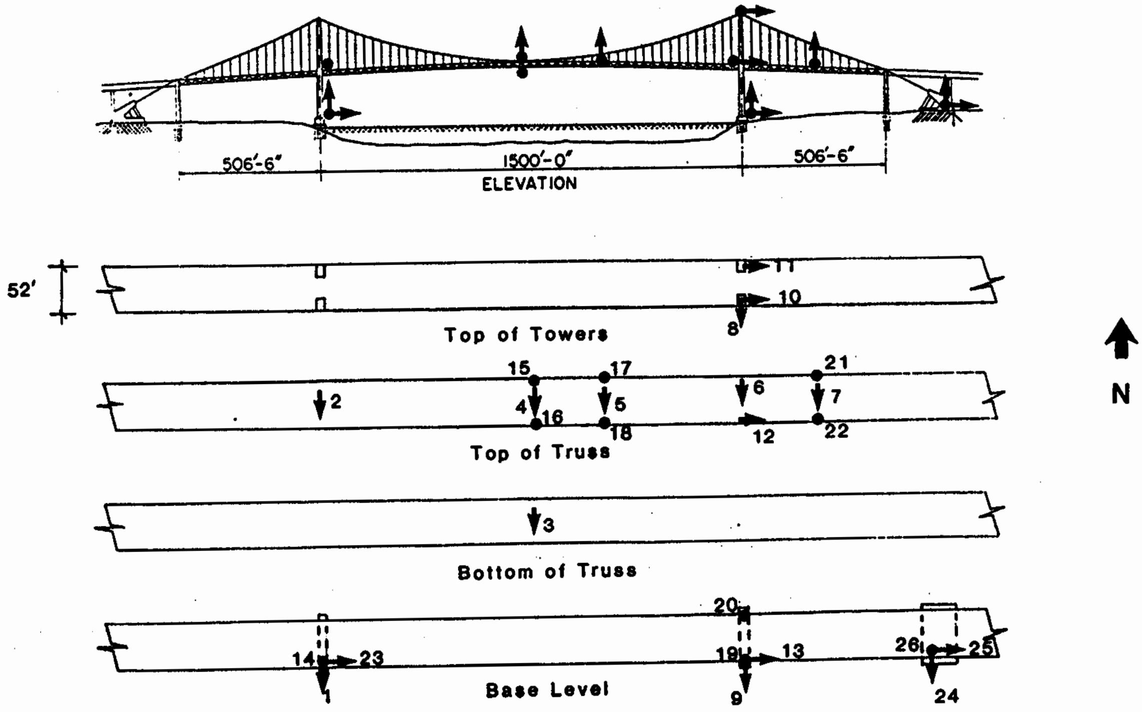

Fig. 7 Locations of sensors on the Vincent Thomas suspension bridge.