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THE CALIFORNIA STRONG MOTION INSTRUMENTATION PROGRAM: OBJECTIVES, STATUS, AND RECENT DATA

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SUMMARY

In the last 15 years the California Strong Motion Instrumentation Program has instrumented over 450 sites, including ground-response sites, buildings and lifeline structures. Many records have been recorded and analyzed, including the very important records from the County Services Building in El Centro, California, a fully-instrumented building that was damaged during the 1979 Imperial Valley earthquake. To increase the application of the data recorded to the reduction of earthquake hazard in California, a data utilization project has been initiated. The program is entering an accelerated phase to complete the instrumentation of all the most important sites and structures by shortly after the year 2000.

INTRODUCTION

The California Strong Motion Instrumentation Program (CSMIP) was established following the destructive 1971 San Fernando earthquake to increase the limited set of data on strong earthquake shaking. The program installs and maintains strong-motion instruments in representative structures and geological environments throughout California. Strong-motion data recovered from the instruments are processed and made available to engineers and seismologists involved in predicting or designing for earthquake shaking. The goal of the strong-motion program is to provide the data necessary to improve seismic design codes and increase seismic safety.

Since the inception of the program over 450 installations of various types have been completed. Ground-response sites and structures are selected for instrumentation on the basis of the recommendations of an advisory committee which is part of the California Seismic Safety Commission. The committee is made of leading engineers and seismologists from universities, government, and private industry. Various organizations and professional groups also provide input to the advisory committee.

The basic goals and objectives of the program were recently re-evaluated. Given the probability of a major earthquake occurring in the next 20 years, generally accepted to be 50% or greater, the advisory committee realized that most of the sites and structures targeted for installation would probably not be instrumented by the time of the next major earthquake. This lead to a call for an increase in the instrumentation rate by the program through increased funding. It is now projected that all high-priority sites and structures will be instrumented by the year 2005.

OBJECTIVES OF THE PROGRAM

The strong-motion characteristics of major earthquakes is a primary data need in earthquake engineering. Several earthquakes of magnitude near 6 have been well recorded in the last 15 years. The Whittier, California earthquake of October 1, 1987 is the most recent example and selected data from that event are considered in this paper. However, no matter how well moderate-magnitude earthquakes are recorded, little knowledge is obtained on how to improve design guidelines for withstanding a magnitude 8 event. The period range and duration are expected to be very different from those observed in moderate magnitude earthquakes. Therefore, obtaining adequate recordings in buildings and geological conditions during the next major earthquake is of the greatest importance in the effort to improve earthquake resistant design. Given the rarity of major earthquakes in California, if the next event occurs and is not adequately recorded, another opportunity may not occur for another 100 years.

The objectives for ground-response instrumentation include measuring the earthquake shaking in a range of geologic conditions including rock, and deep and shallow alluvium, and liquefiable deposits. Locating stations geometrically relative to the earthquake source is also important since the details of the rupture process must be understood to interpret the ground motion which is radiated from the earthquake zone to buildings and other structures distant from the earthquake epicenter. These and other aspects were considered at length by a ground-response advisory group to the program and subsequently published in a report edited by Borcherdt (Ref. 1). In quantitative terms, the specific objectives for ground-response sites are that an additional 120 isolated sites and 8 highest-priority dense arrays be installed within a 15 year target period.

The objectives for the instrumentation of buildings are to effectively record the response of typical building types during strong shaking. There are many structurally distinct types of buildings, and there are significant differences in response even within a given type, depending on building height. For each type of building, specific modes of response and deformation are most important, and these determine where the sensors are deployed when the building is instrumented. Since several data sets have indicated that 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. An advisory group focusing on building instrumentation priorities recommended that an additional 170 buildings should be instrumented within the next 15 years.

STATUS

Presently, CSMIP has a total of 451 stations installed at selected locations through the state of California, as shown on the map in Fig. 1. In general, strong-motion installations can be divided into three types: ground-response, buildings, and lifeline structures. Tables 1 summarizes the present status and target numbers of installations in each category.

Ground-Response Instrumentation A total of 328 ground-response stations have been installed, many in small buildings such as schools and fire stations. In the last decade records have shown that even small buildings may influence the motion recorded. Therefore, most recent ground-response stations have been installed in special small, light fiberglass instrument enclosures approximately 1 meter high. The enclosure is mounted on a 1.2 meter square concrete pad, approximately 10 cm thick, which often has a central raised surface on which the instrument is mounted. Under each corner a concrete pier approximately 20 cm in diameter extends into the soil to a depth of about 45 cm. The goal of the design is to minimally affect incoming seismic motion while at the same time provide adequate coupling to the ground and protection for the instrument.

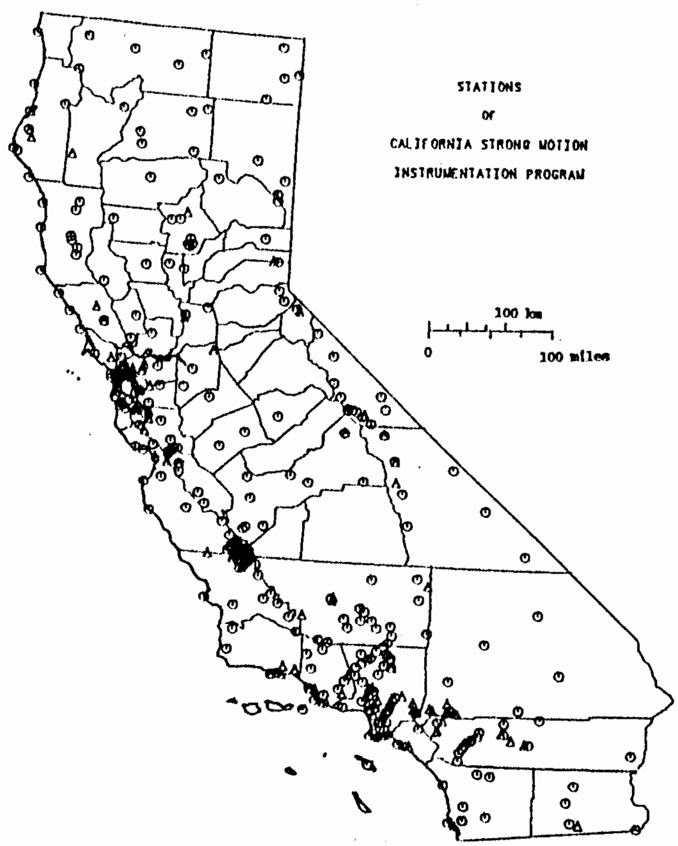

Fig. 1 Stations of the California Strong Motion Instrumentation Program installed as of July 1988.

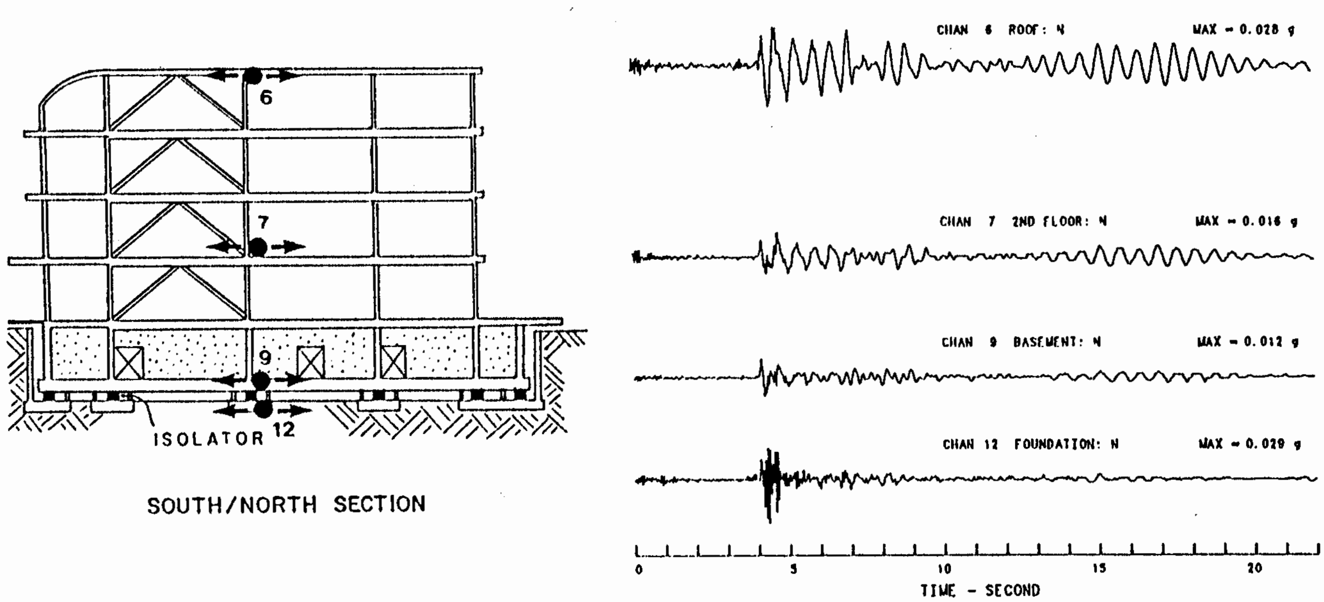

Fig. 2 Cross-section of the base-isolated County Law and Justice building near San Bernardino, and accelerograms obtained at the roof, the 2nd floor, and above and below the isolators during the Redlands earthquake of October 2, 1985.

TABLE 1. CSMIP 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

Table 1 shows that 8 high-priority dense arrays remain to be installed. These arrays will be designed to measure specific wave propagation or source radiation effects. The soil response array at Turkey Flat, near Parkfield, California, part of a test project described in these proceedings (Ref. 2), is such an array, and includes surface as well as downhole instruments. A similar, more extensive array has been deployed jointly with the Electric Power Research Institute (Ref. 3) at Stone Corral, also near Parkfield.

Building Instrumentation Building instrumentation systems are characterized by distributed sensors cabled to a centrally-located recorder. At the time of the 1971 San Fernando earthquake, instrumented buildings usually had three separate triaxial 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. Analyses of the San Fernando earthquake data indicated that the records would be of much greater value if the time axis for the records from each sensor were common and if recordings were obtained from more than just three points in the building. With a 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 together.

As indicated in Table 1, 91 buildings have been instrumented by CSMIP. 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 a portion of the sensor layout for a structure is given in Fig. 2. The building (the Law and Justice Center of San Bernardino County, California) is base-isolated, with rubber isolators placed between the foundation and the 5-story superstructure. Sensors were placed to record the relative motion across the isolators, as well as the motion of the superstructure itself. A total of 16 sensors were used to instrument the structure. Several records have been obtained in the building during earthquakes in the vicinity, but no motion stronger than 0.05 g at the base has occurred. The records are very interesting nonetheless (Fig. 2), since they show a reduction in high frequency motion across the isolators. The motions have so far been too small to excite the non-linear response of the isolation system.

Over 60 records with peak accelerations exceeding 15% g have been recorded in well-instrumented buildings by CSMIP. The most important building records are those from the County Services Building in El Centro, California. These records 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 investigate the details of the failure process (e.g., Ref. 4). Other recent records from well-instrumented buildings are discussed later in this paper.

Lifeline Instrumentation   Lifeline instrumentation is similar to building instrumentation except that the instrumentation is often not as environmentally protected as in a building. In addition, the total installation may have a significant linear dimension. Bridges, dams and power plants are included in this category. Because the sensors and cabling are often exposed to the weather, maintenance is generally more of a problem than with buildings. Table 1 lists the number instrumented in several categories and the number remaining in the highest priority categories.

NETWORK OPERATION AND MAINTENANCE

Network 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. Some aspects of effective network maintenance are practical details, such as housing batteries outside of the instrument itself so the corrosive effects of the gas generated by the batteries are avoided. Solar panels provide very reliable power, though they may lead to shortened battery life because of the repeated charging cycles. Recording the trigger time on an accelerogram is very important for data analysis, though the method for achieving that is not completely solved. The reception of WWVB time code broadcast at 60 KHz, dependent on atmospheric conditions, is insufficiently reliable, and internal clocks require management of the time drift. An internal clock which is periodically updated by a radio time signal appears to be the best option, and such units are now becoming available.

Instrument maintenance is a significant component of total instrumentation costs. In some cases, funding for a project may only cover the instrument installation, leaving long term maintenance as an outstanding problem. Experience indicates a direct relation between the amount and quality of instrument maintenance and the performance factor of the instrument when an earthquake occurs.

For a program like CSMIP, which continuously installs new instruments as well as maintains previously installed instruments, it is important to study the budget balance between installation and maintenance. An instrument installed one year increases the maintenance costs for the next year. This cost increase can be computed as

$$M_{n+1} = M_n + mN$$

where M_n is the total maintenance cost in year n, N is the number of instruments installed in year n, and m is the average annual maintenance cost of an instrument. The budget amount available for new installations in year n, I_n, is

$$I_n = B - M_n$$

where B is the annual instrumentation budget available, assumed constant. This relationship makes it possible to project the available installation budget for a given year. Considered as a continuous function of time, the relationship can be expressed as a differential equation, as first noted by Iwan (Ref. 5),

$$dI(t)/dt = - I(t)(m/i), \text{ with solution}$$

$$I(t) = I_o\, e^{-(m/i)t}, \quad \text{or} \quad M(t) = M_o + I_o\,(1 - e^{-(m/i)t})$$

where I_o and M_o are the installation and maintenance budgets, respectively, in some initial year, and i is the installation cost of one instrument. The budget available for installation of new instruments, I(t), is an exponentially decaying function if the total instrumentation budget is fixed. As installation continues, maintenance costs, M(t), keep increasing until, for certain conditions, there is no money available for installation, and the network becomes static. Component parts of the total budget for CSMIP, including installation and maintenance, are shown in Fig. 3 as projected for over next 15 years.

Instrument maintenance costs are predictable and depend on personnel and travel costs, the desired performance factor, and the overall average reliability of the instrument type. Another maintenance aspect, not readily apparent, is station maintenance. Stations, as opposed to instruments, need to be occasionally moved and reinstalled. Recent experience of the CSMIP program is that 1% to 2% of existing stations have to be abandoned and re-installed each year due to change of property ownership, changing physical conditions at the site, or similar factors. As more stations are installed, even if the percentage remains fixed, the number that must be reinstalled keeps increasing, reducing even faster the installation budget function I(t) above.

Accelerogram Processing and Data Utilization CSMIP developed an in-house digitization capability in 1981. The digitization system used is patterned after that developed by Trifunac and Lee in 1979 (Ref. 6). In this system the film accelerogram is scanned, while mounted on a rotating drum, by a traveling photodensitometer. The processing procedure is described in processed-data reports produced by the program. Studies of the system noise are used to develop signal-to-noise ratios to guide record filtering during processing (Ref. 7).

An effort to increase the application of the data collected by CSMIP to the improvement of building codes and improved seismic safety for lives and property in California has been recently initiated. In this effort, studies are 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 under study. These projects are aimed at solving specific problems in ground-response and the response of structures through the utilization of existing strong-motion data.

IMPORTANT RECENT DATA

The Whittier Narrows earthquake of October 1, 1987, east of Los Angeles, was a moderate magnitude (M_L 5.9) event which was recorded by many strong-motion stations in southern California. Over 100 stations of the CSMIP network, including 63 ground-response stations, 27 buildings, eight dams, and one suspension bridge recorded the event. In total, more than 500 records were recovered from stations of the CSMIP and other networks.

Ground-Response Data Peak acceleration in the epicentral area was generally between 0.4 g and 0.7 g. On average, the peak accelerations from the earthquake are higher than predicted by the Joyner-Boore model (Ref. 8) for a magnitude 6 event. The data of the CSMIP network (Ref. 9) and the U.S. Geological Survey network (Ref. 10) are plotted against epicentral distance in Fig. 4. The mean and +/- 1 standard deviation curves of Joyner and Boore have been included for comparison. The distribution of the Whittier data appears to be biased high compared to the Joyner-Boore curves.

A very interesting record was recovered at the Tarzana station, northwest of Los Angeles, 44 km from the epicenter. A peak acceleration of 0.62 g was recorded although many stations 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 accelerogram and response spectrum are shown in Fig. 5. The spectrum shows a strong spectral peak at 3 Hz; this peak is absent in spectra from nearby stations. The site is located in a region of low rolling

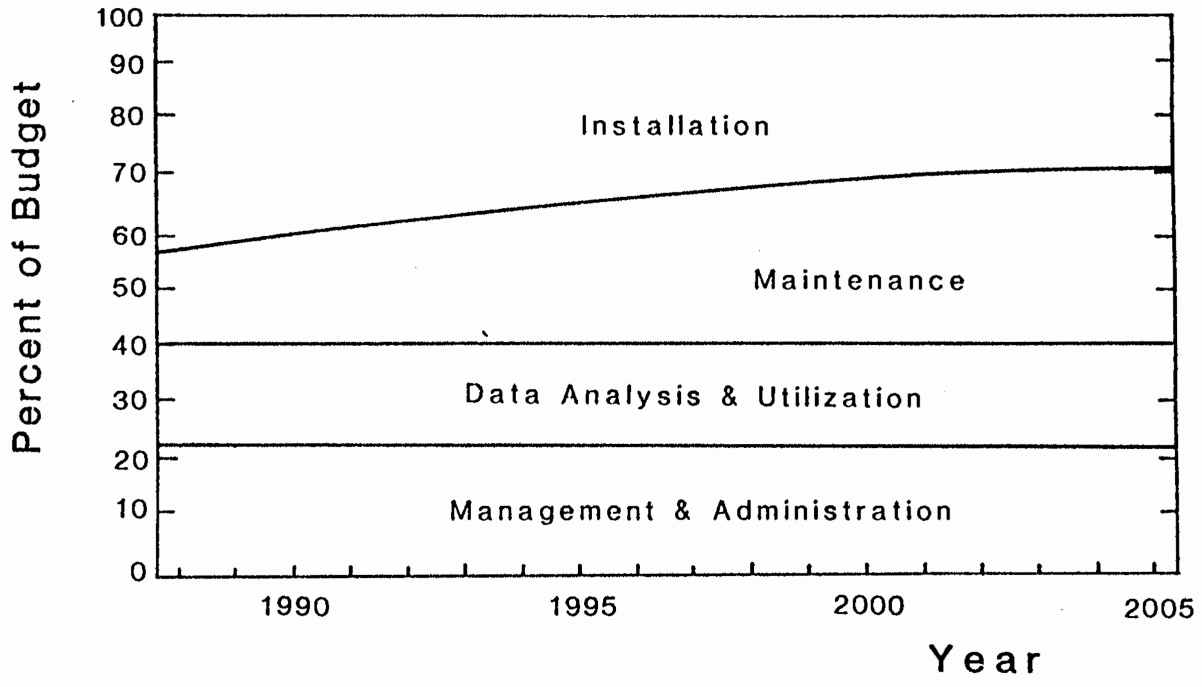

Fig. 3 Component parts of CSMIP budget projected for the next 15 years.

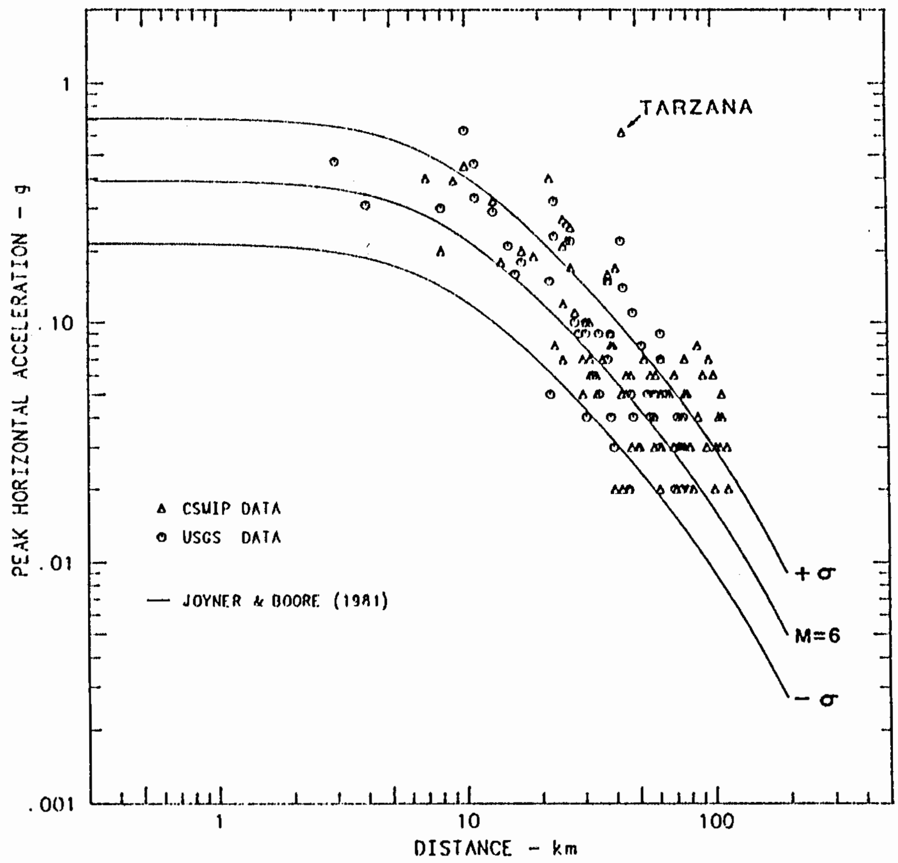

Fig. 4 Peak acceleration data for the Whittier Narrows earthquake plotted against epicentral distance.

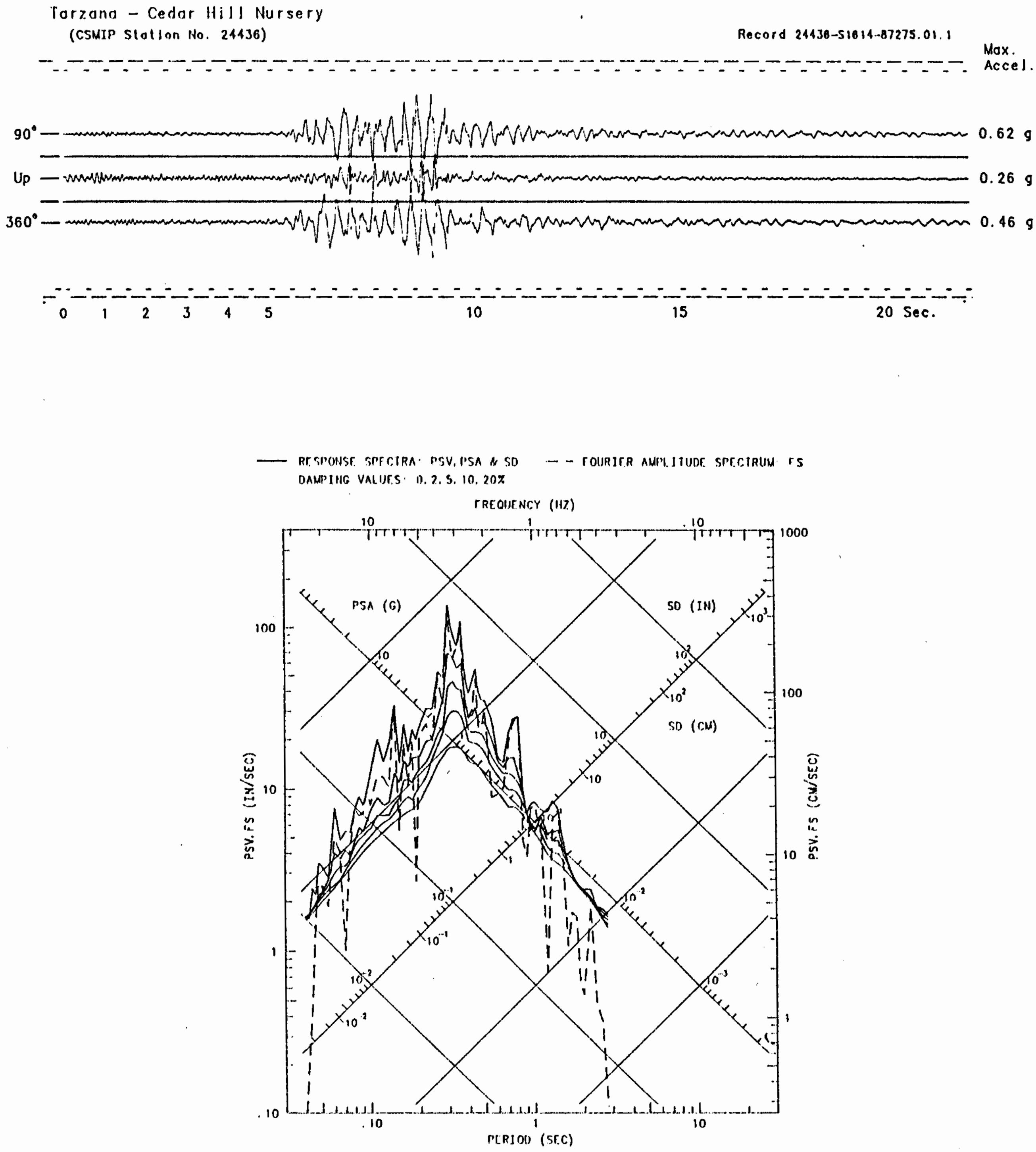

Fig. 5 Accelerogram recorded at Tarzana during the Whittier Narrows earthquake, and response spectrum of channel 1.

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 known yet. The station meets current ground-response installation standards described above so instrument-housing effects should be minimal.

Structural-Response Records Strong-motion records were recovered from a total of 38 structures instrumented by CSMIP with up to 26 centrally-recorded remote sensors per structure. Two records of particular interest are presented here, although many other records are equally interesting.

The Administration Building of the California State University at Los Angeles (CSULA) is a 9-story reinforced concrete structure, located 9 km from the epicenter. 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 16 sensors in the CSULA building and the accelerogram recorded in the Whittier Narrows earthquake are shown in Fig. 6. The maximum acceleration in the record 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. The CSULA record has less long period energy and is shorter in duration than the 1979 record. 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. Preliminary analysis of the digitizing results indicates that the building's first mode in the transverse direction had a period of 1.4 seconds; the second transverse mode had a period of 0.5 second. In the longitudinal direction, the first and second modes are at 1.5 seconds and 0.5 second, respectively.

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. Fig. 7 shows the locations of the sensors on the bridge structure and the record obtained in the Whittier Narrows earthquake, which is the first significant strong-motion record ever obtained from a long-span suspension bridge. The maximum amplitude of motion at the base of the towers was 0.08 g. The motion of the suspended deck in the side-span reached 0.28 g. A preliminary calculation indicates that in the middle of one side span the deck edge moved about 10 cm vertically as the deck oscillated in torsion during the earthquake 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 for predicting the response of the bridge during strong shaking to be improved.

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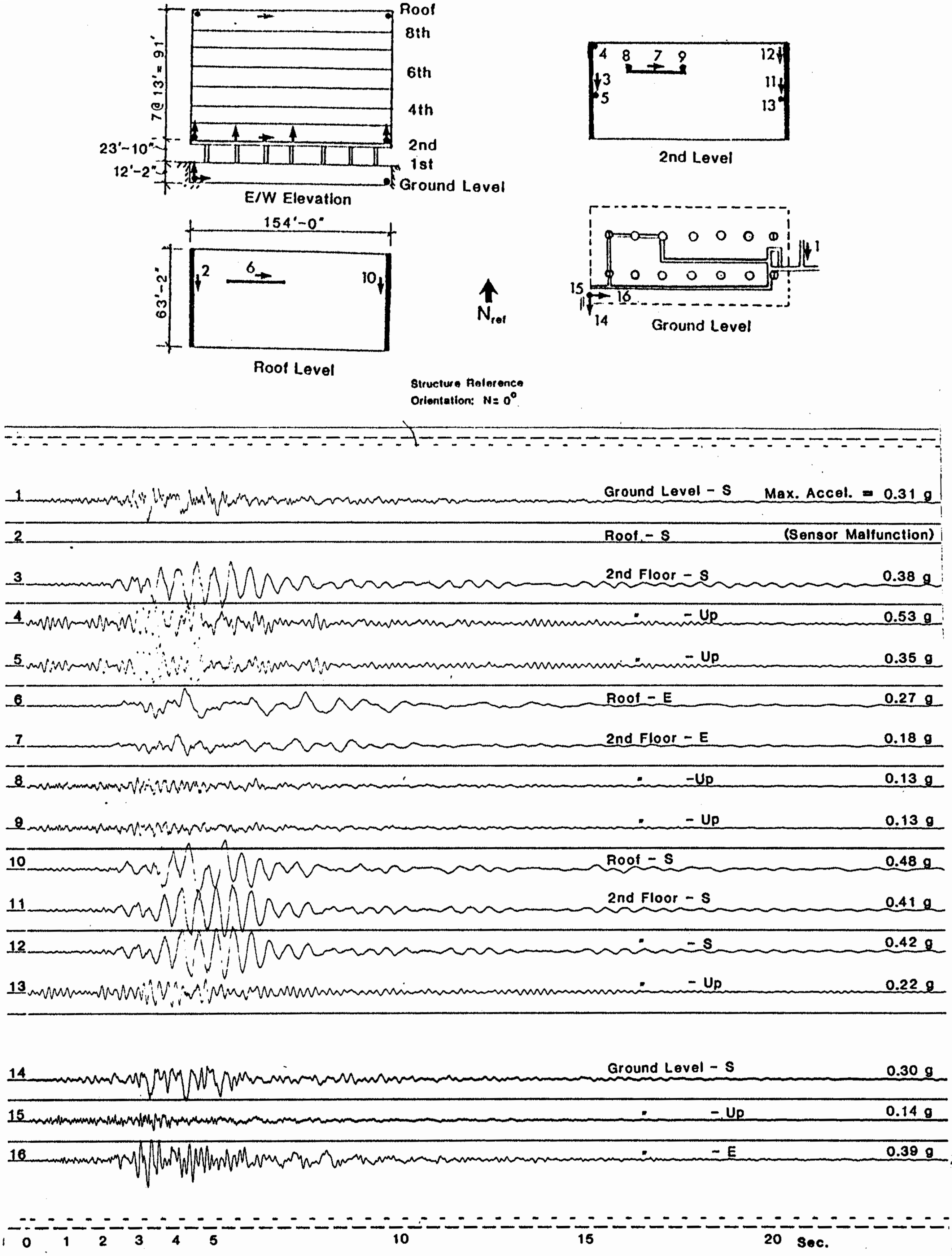

Fig. 6 Sensor locations and accelerogram recorded at the CSULA Administration building in the Whittier Narrows earthquake.

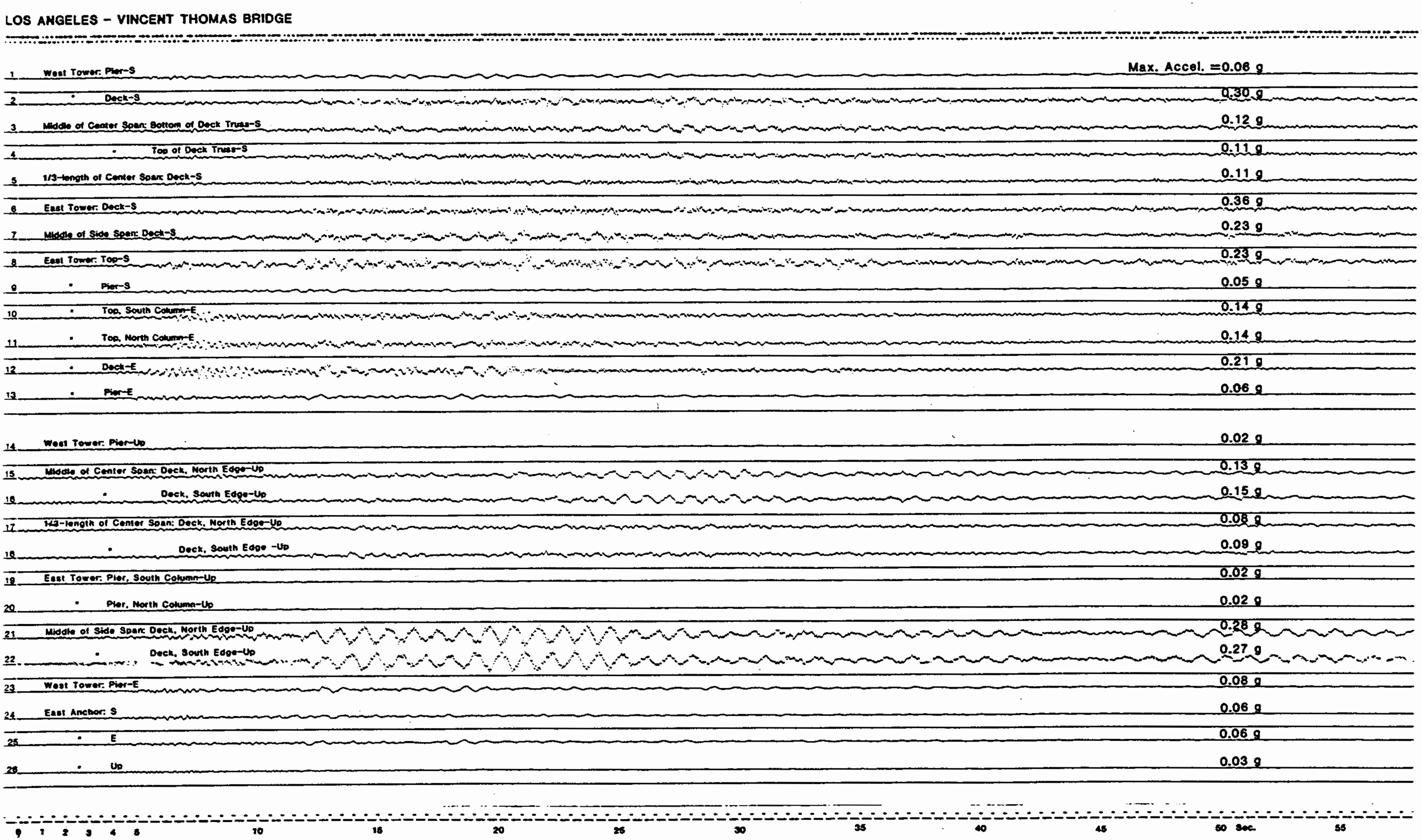

Fig. 7a Accelerogram recorded at the Vincent Thomas suspension bridge near Long Beach during the Whittier Narrows earthquake.

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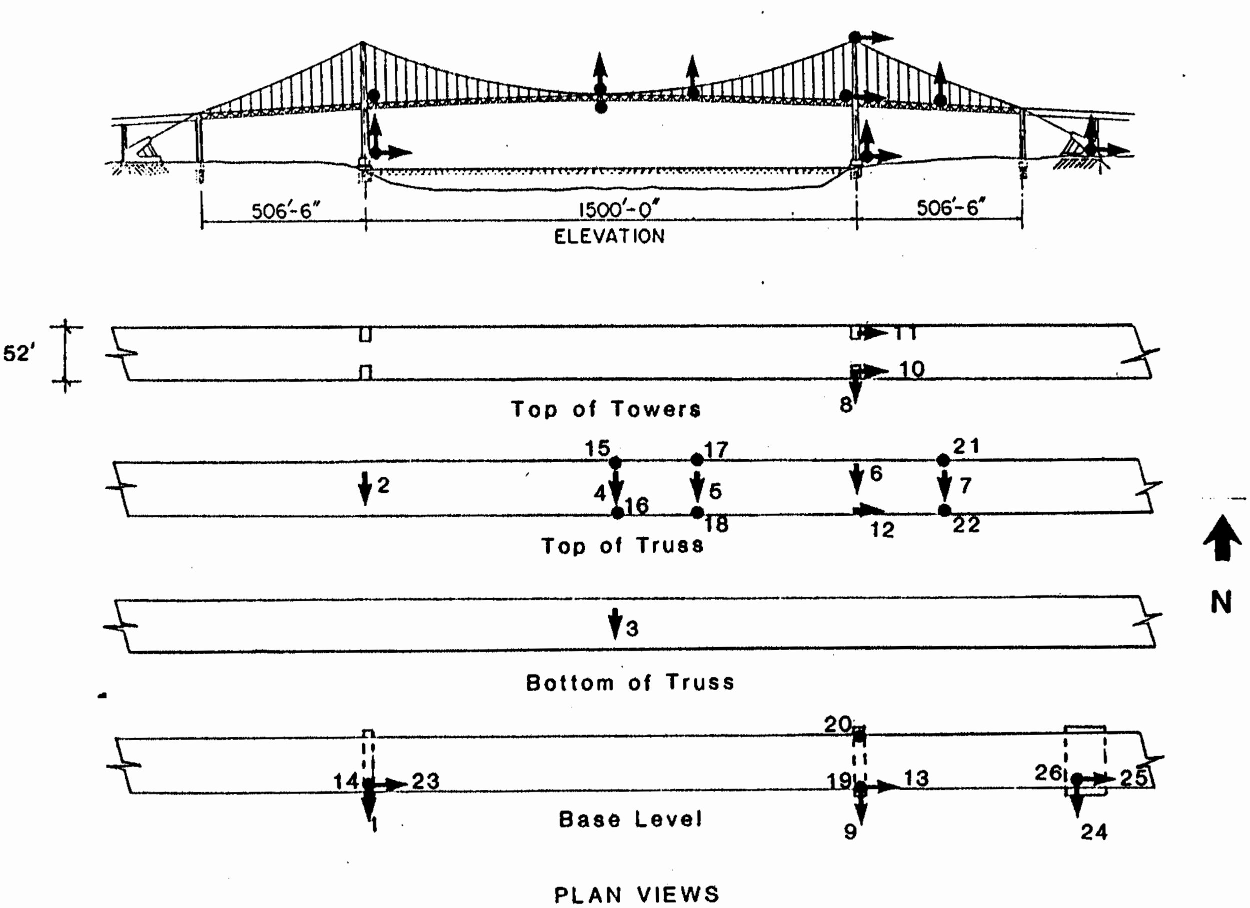

Fig. 7b Location of sensors on the Vincent Thomas suspension bridge.